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A Review of Aircraft Wing Mass Estimation Methods

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Abstract

In this paper, the current state of the art of aircraft wing mass estimation methods is reviewed. The phases of aircraft design and the development process are discussed. The open literature on the subject of wing mass estimation methods and their applications in the aerospace industry is discussed, and relevant data are presented to provide the reader with background information on the field. Special attention is given to classifications of wing mass estimation methods. Current challenges and technological difficulties in wing mass estimation methods are identified, and perspectives are drawn and used to propose several key ideas for future research in the field.

Keywords: Wing Mass Estimation; Aircraft Design process; Empirical Methods

Nomenclature

Acronyms

ACSYNT	AirCraft SYNThesis
AFaWWE	Analytical Fuselage and Wing Weight Estimation
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CFRP	Carbon Fibre Reinforced Polymers
CRM	Common Research Model
FAME-W	Fast and Advanced Mass Estimation Wing
FEA	Finite Element Analysis
FEM	Finite Element Method
FRP	Fibre Reinforced Plastic
GUESS	Genetic Unknown Estimator in Structural Sizing
MDCAD	Multidisciplinary Concept Assessment and Design
MDO	Multidisciplinary Design Optimisation

MTOM	Maximum Take-Off Mass
NeoCASS	Next generation Conceptual Aero-Structural Sizing Suite
OEW	Operating Empty Weight
PrADO	Preliminary Aircraft Design and Optimisation Program
SMARTCAD	Simplified Models for Aeroelasticity in Conceptual Aircraft Design
WAATS	Weight Analysis of Advanced Transportation Systems

Roman Symbols

STSPAN	Structural Span (ft)
SWING	Gross Wing Area (ft^2)
TROOT	Theoretical Root Thickness
W_{Wing}	Wing Weight (lbs)
WTO	Gross Weight (lbs)
XLF	Ultimate Load Factor

1. Introduction

In recent years, air traffic has experienced an average global growth rate of approximately 4-5% per annum [1] and the demand for aviation transportation is expected to continue and even increase in the future. The continued growth in air travel has led to substantial increases in the emission of gases attributed to global warming, including carbon dioxide, and given the increasing importance of climate change within the global political agenda, there is a general demand to reduce the environmental impact of transportation, including aviation. Aircraft manufacturers have made significant efforts and have issued ambitious goals for the reduction of emissions in air traffic and transportation. Over the last decade, different concepts and technologies, ranging from completely new aircraft design concepts, like the box wing aircraft [2,3] and the blended wing body [4,5], to the implementation of new technologies in more conventional aircraft designs, have been suggested to face the increased economic and environmental challenges. Examples of key enabling technologies are the use of advanced materials, such as composite materials and carbon fibre reinforced polymers (CFRP), high aspect ratio laminar flow wings [6,7], and wing configurations utilising high lift device concepts to decrease aircraft noise during take-off and landing [8]. Furthermore, innovative detailed technologies, like the NASA shape-changing wing [9] and aircraft equipped with novel morphing technology that allows air-vehicles to alter their characteristics to achieve improved flight performance and manoeuvering control authority [10] have to be considered for the new generation of aircraft.

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During recent years, aircraft manufacturers and research institutes have been focusing on environmentally friendly and aerodynamically efficient aircraft concepts that require new wing designs. The design of an efficient aircraft wing featuring new technologies has always represented a substantial challenge for aircraft designers, especially when the proposed novel concept challenges the existing knowledge base, and the accuracy of normally used empirical methods and statistical data collected from previously constructed aircraft. During the development of new aircraft, the structural mass of an aircraft has a big influence on the overall performance and cost development of the aircraft at the initial design stages. Reducing the structural mass has the effect of lowering the operating empty weight (OEW), allowing the aircraft to fly higher payloads at a greater range. The wing of a modern transport aircraft is one of the heaviest structural components, and therefore a particular focus has always been placed on the accurate estimation of wing structural mass. Figs. 1 and 2 show the planform and mass breakdown, respectively, of a conventional transport aircraft wing.

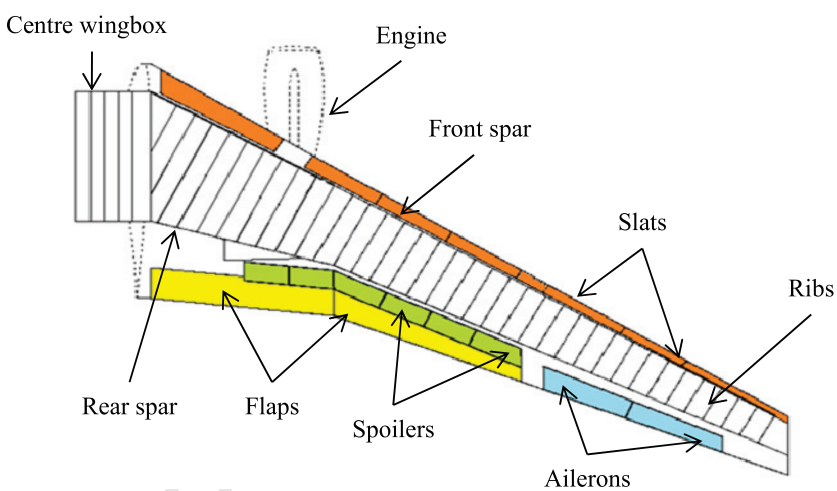

Fig. 1 Wing planform of a conventional transport aircraft

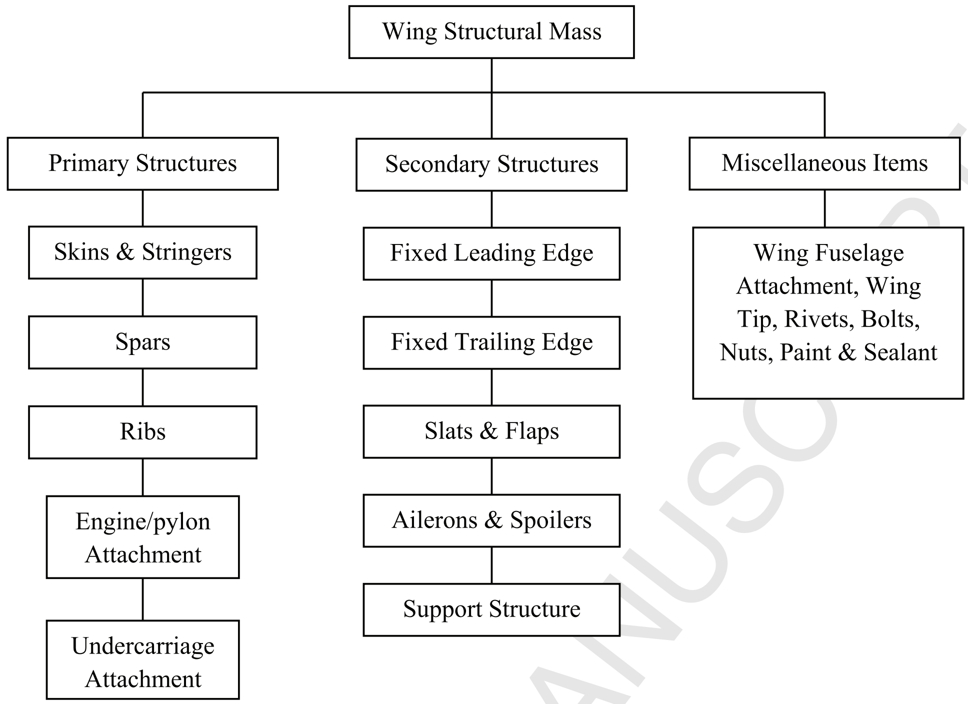

Fig. 2 Wing mass breakdown of a conventional transport aircraft

The aim of this paper is to review relevant publications in order to identify the state-of-the-art trends and challenges in estimating the mass of newly designed aircraft wing equipped with key technologies. To achieve this aim, this paper presents an overview of the aircraft design process. This will be followed by a comprehensive review of aircraft wing mass estimation methods. Finally, conclusions and future trends of wing mass estimation will be discussed.

2. An overview of the aircraft design process

Aircraft design and development is a complex and fascinating process. It is the academic engineering process of creating a flying machine to a certain set of specifications and requirements established by either a prospective user or pioneering innovative ideas and technology. The aircraft design process is described in many aircraft design textbooks [11-13]. According to these textbooks, the process, which requires design experience as well as good intuition, takes place in three distinct phases. Fig. 3 shows the aircraft design and development phases [13].

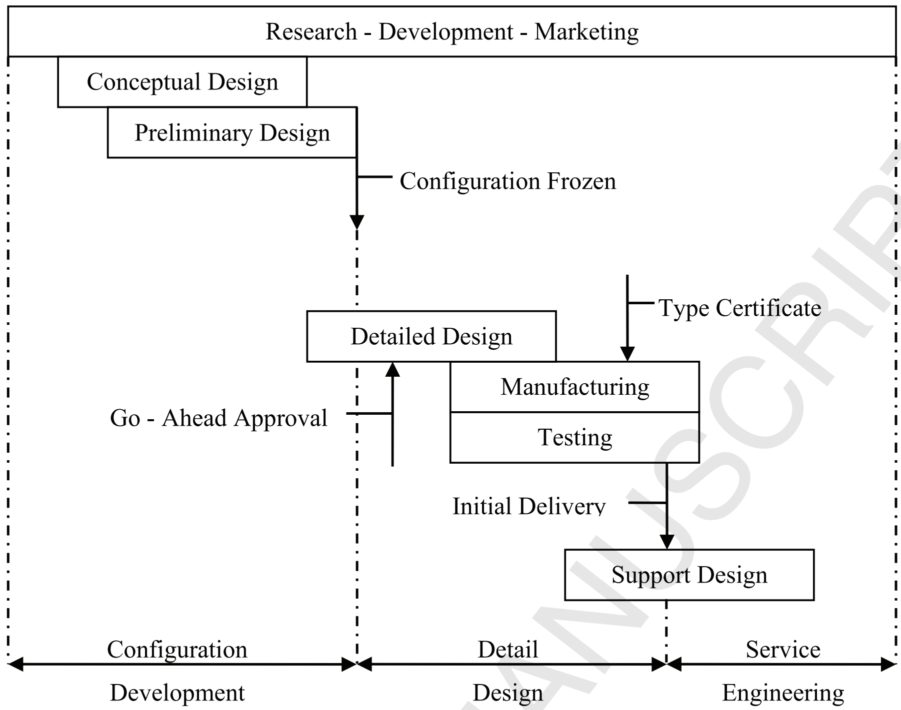

Fig. 3 Development phases of the aircraft design process

During the first phase, the conceptual design, the overall size, shape, weight, and performance of the aircraft are determined, yielding the general layout. Throughout this stage, the configuration of the aircraft is developed using simple methods and tools that require only a few input parameters and are therefore well suited to this particular design phase. The second phase, the preliminary design, involves structural and control system analysis, detailed wind-tunnel testing and computational fluid dynamics calculations. During this stage, the aircraft concept remains largely unchanged and only minor modifications are made. The detailed design phase is the last phase in which the precise designs of each individual part of the aircraft are prepared for production. The size, number, and locations of aircraft structural elements and fasteners are decided and manufacturing tools are designed. At each phase of the design process, each design decision is evaluated for its impact on overall performance, weight and unit cost of the aircraft, since an accurate prediction of aircraft weight during the initial stages is essential in achieving an optimum and successful configuration [13].

3. Classifications of aircraft wing mass estimation methods

The conventional approach to aircraft wing mass estimation at the early stages of the design process is mostly based on statistical data from previously investigated or constructed aircraft of the same type and manufacturer. Historically, determining the mass of an aircraft wing for which the database is insufficient or non-existent has been limited to two very expensive methods:

1. Detailed finite element modelling and analysis of the aircraft wing structure, integrated with a corresponding knowledge of the as-built structural design and manufacturing process definition [14,15];

2. Design and construction of aircraft wing prototypes.

The use of finite element models for aircraft component structural design and mass estimation was always considered by the aerospace industry as a costly approach in terms of time and resources. Compared to the first approach, the construction of prototypes is considered even more expensive, especially for large transport and military aircraft. However, new technology in computer processors, recent advancements in computer-aided design, finite element analysis software and optimisation techniques have paved the way not only for possible reconsideration of the first approach, but also for the development of multidisciplinary integrated design optimisation methods and tools for the mass prediction of aircraft wings. In the literature, great efforts have been put into and reported on developing wing mass prediction methods. This is because of the well-defined structural role of the wingbox as a primary load-carrying component and the importance of optimum wing design as a significant subject of the preliminary design phase [16].

Many authors have developed different classifications for aircraft wing mass estimation methods in recent years. A number of these key classifications are presented at the beginning in this section to provide the reader with some background information on the field. In his study, Murphy [17] places mass estimation methods into three classes: purely statistical, hybrid analytical-statistical and purely analytical methods. Fig. 4 shows a typical example of purely statistical wing mass estimation method [17]. In the case where the component of interest is the wing, the first step is to collect sufficient values of wing weights for a specific class and type of aircraft. Later on, curve fitting techniques like least squares are used to find the best-fitting curve to the set of collected values of wing weights. The case illustrated in Fig. 4 is applied to high-speed aircraft of aluminium construction, and curve fitting gives the following relationship:

$$W_{wing} = 110 \times \frac{(WTO)(XLF)(STSPAN)(SWING)^{0.77}}{(TROOT)} \times 10^{-6} \tag{1}$$

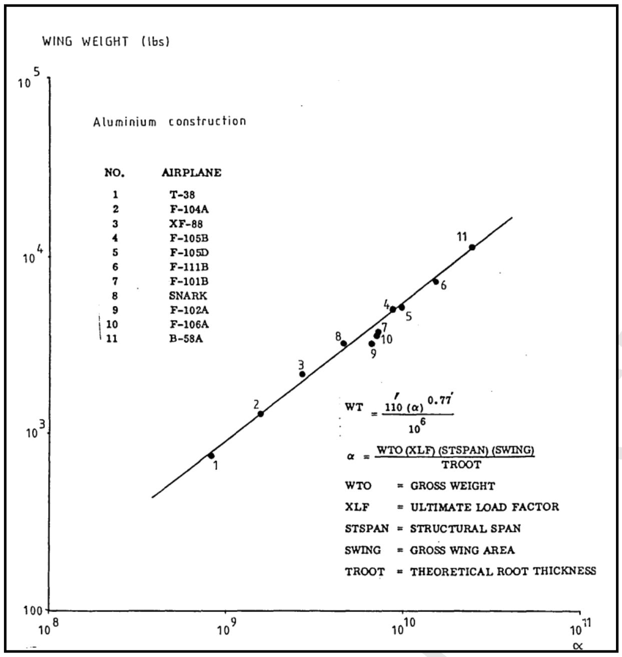

Fig. 4 Wing weight of high-speed aircraft [17]

Ardema et al. [18] classify wing mass prediction methods by increasing order of complexity and accuracy as empirical regression, detailed finite element structural analysis, and classical plate theory based methods. Fig. 5 shows an example of empirical regression wing mass estimation method [18]. It is considered as the simplest wing weight estimation tool and it requires the knowledge of wing weights from a number of similar existing aircraft in addition to various key configuration parameters of these aircraft in order to produce a linear regression. This regression is a function of the configuration parameters of the existing aircraft and then is scaled to give an estimate of wing weights for aircraft under investigations.

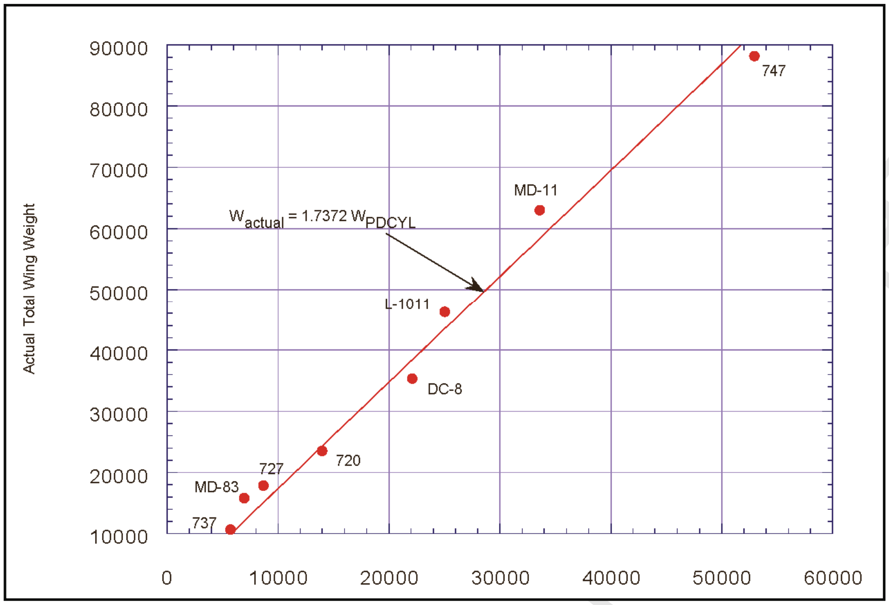

Fig. 5 Wing total weight and linear regression [18]

Kundu [19] divides weight estimation methods at the conceptual design level into three methods, addressed as:

1. The rapid method, based on empirically determined weight fractions used to estimate the weight of major aircraft components. The mass is expressed in terms of percentage of the maximum take-off mass (MTOM). For example, Table 1 shows the values of components weight fraction for passenger aircraft as percentage of MTOM;

Table 1 Mass fractions of passenger aircraft as percentage of MTOM [19]

	Mid-sized 2 engines aircraft		Large turbofan aircraft	
Group	Turboprop	Turbofan	2-Engine	4-Engine
Fuselage	9-11	10-12	10-12	9-11
Wing	7-9	9-11	10-12	11-12
H-Tail	1.2-1.5	1.8-2.2	1-1.2	1-1.2
V-Tail	0.6-0.8	0.8-1.2	0.6-0.8	0.7-0.9
Nacelle	2.5-3.5	1.5-2	0.7-0.9	0.8-0.9
Pylon	0-0.5	0.5-0.7	0.3-0.4	0.4-0.5
Undercarriage	4-5	3.4-4.5	4-6	4-5

2. The graphical method, statistically based on weight equations, obtained using regression analysis, for existing aircraft used to predict the weight of major components such as a wing;

3. The semi-empirical method, usually consisting of analytically based equations derived from a theoretical foundation, which is adjusted using statistical correlations from historical data.

Recently Elham [20] logically divided mass estimation techniques into four categories:

- Class I methods, termed fractions methods, where mass of each aircraft component is defined as a fraction of the maximum take-off mass of the aircraft. To establish ratio of the mass of a particular component (e.g. wing) to the aircraft mass, a number of existing aircraft designs of the same class and category as the aircraft under study are analysed. Typically, these techniques are used at initial stages of aircraft design process.
- Class II methods, where in addition to coefficients obtained by statistical analysis of existing aircraft, aircraft parameters such as design speeds, load factors, geometrical dimensions, configuration aspects, etc. are included into sets of empirical equations to calculate mass of every fundamental aircraft component. Fig. 6 shows an example of class II wing weight functions for three different aircraft categories [21];

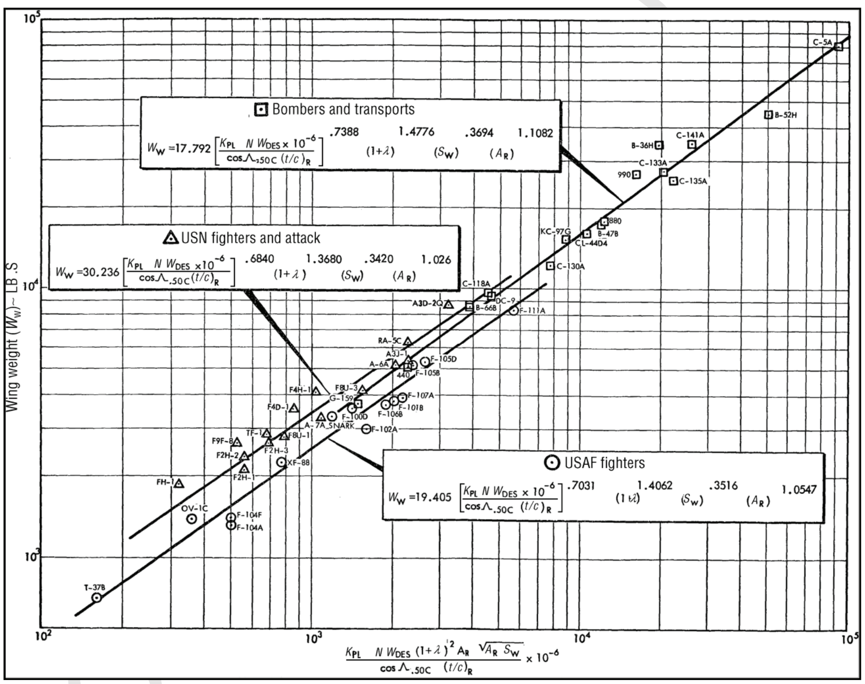

Fig. 6 Wing weight functions for three different aircraft categories [21]

- Class II & 1/2 methods, based on estimation of the mass of material, required to withstand a certain loads applied to a particular aircraft component. In order to calculate the required amount of material, basic strength/stiffness analysis is applied to simplified structural model of the load-carrying component. The use of statistical and experimental data may be considered to improve performance of these methods. These methods allow studying the influence of particular design decisions on the estimated mass of aircraft component or group of components.

- Class III methods, in these methods the mass of the aircraft primary structure is calculated using Finite Element Method (FEM). Since the influence of the secondary and non-structural masses on the aircraft structural loading is not computed in FEM, other analytical and empirical methods are still required. Fig. 7 shows an example of wing design procedure to estimate the wingbox mass [22].

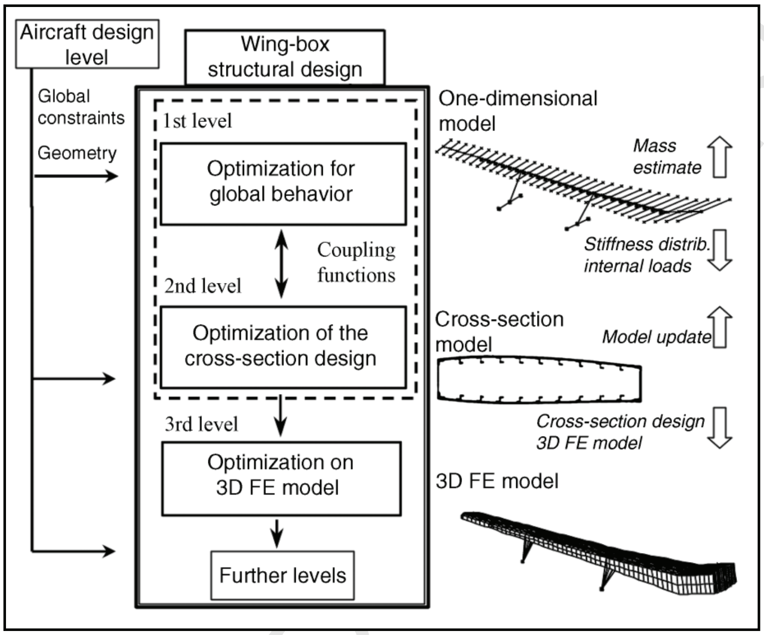

Fig. 7 Multilevel structural optimisation for wingbox mass estimation [22]

In summary, wing mass estimation methods can be logically separated between three categories: Empirical, Analytical and based on Finite Element Analysis, although each category can be divided into sub-categories. Advantages and drawbacks of methods falling in these categories will be compared in sections 3.1-3.4.

3.1 Empirical and semi-empirical methods

A great and valuable contribution to the field of aircraft design is attributed to Raymer [11], Roskam [12] and Torenbeek [13]. The empirical wing mass estimation methods developed by these authors are still in use by many aerospace manufacturing research centres and university researchers in the field of aeronautical engineering today. A typical example of a purely statistical-based method is WAATS (Weight Analysis of Advanced Transportation Systems) - A Statistical Based Prediction Method, given by Murphy [17]. The method was fully explained and coded for use on computers by Glatt [23]. According to Ardema [18], however, the implementation and accuracy level of statistical-based methods in predicting wing mass depends primarily on the amount and quality of the data available for existing aircraft, in addition to how closely the presented aircraft matches the design and configuration concept, mission profile and weight of the aircraft under investigation. These conditions make statistical-based methods of limited practical use to the designers of an innovative design concept, where the novelty is in the configuration or the material used. As an example, the wing mass prediction method of Torenbeek [24] presents remarkably good results, but it is limited to subsonic transport aircraft only. Shevell [25] developed a statistical method based on a wing weight index, which is related to the weight of a fully-stressed wingbox. The weight index was proportional to the compressive and tensile loads due to the bending moments at the root of the wing in the skin and the spar caps. The amount of material required to resist the applied bending loads represented the primary wing weight. The LTH (Luftfahrttechnisches Handbuch) method is another example of statistical methods developed by Dorbath on behalf of LTH organization [26].

Semi-empirical methods, on the other hand, are used when a simplified geometrical layout of the aircraft configuration becomes available. These methods are used to estimate the mass of the primary structural components of an aircraft such as the wing, fuselage, and landing gear. This is done using analytically based equations that combine geometrical parameters, load factors and aircraft design speeds, adjusted using statistical data correlations derived from the weight breakdowns of existing aircraft [19]. These methods enable the design engineers to assess the effect of geometrical design parameters such as wingspan, sweep angle, and taper ratio on wing mass. Examples of semi-empirical methods are found in most aircraft design books [11-13,16]. Howe [27] presented a method, which calculates the mass of the wing as a function of the main geometrical and operational parameters. This method was called the C_1 method, where C_1 is a coefficient dependent on the type of aircraft. The method was only applicable to wings made from light alloy and further work was needed to cover composite construction. Moreover, some experience was needed to account for any special features of the design. Although semi-empirical methods improve the accuracy of the wing mass prediction compared to statistical-based methods, the effect of the internal wing structural design configuration, like the number and location of spars, stiffeners and ribs, still cannot be evaluated at this stage.

3.2 Analytical and quasi-analytical based methods

Purely analytical structural analysis methods for mass estimation are rarely found in the literature. In 1960, Ritter [28] presented a method for obtaining a realistic wing rib mass estimate using structural analysis techniques, which could be applied to a wide range of structural configurations. A simple geometry was considered for analysing and sizing the rib and the weight was calculated by determining the amount of material necessary to satisfy structural rigidity and flexural strength requirements. The method was too complex to be used for parametric weight comparison and was only applied to proposal studies.

During the 1950s, Burt [29] and Shanley [30] presented a new mass prediction method based on elementary strength/stiffness analysis improved by statistical and experimental data. In this quasi-analytical method, the material amount required to resist the applied loads is computed using structural analysis of simplified wing models. This method has enabled mass engineers to obtain higher accuracy and better design sensitivity results. In 1954, Spath [31] derived a general form for wing mass estimation based on a simple beam representation of an airplane semi-wing. The load distribution acting on the wing was represented by bending moment and shear force distributions. The amount of material needed to resist this load at each station semi-spanwise was then estimated and the wing mass was calculated by integrating the mass of the shear and bending material over the span.

John, St. [21] illustrated the principles of analytical-statistical weight prediction methods by using the engineering analysis bending stress equation to derive a correlation expression, and statistical analysis was used to apply the correlation expression to available aircraft data. The method was considered useful at the beginning of the preliminary design stages where detailed information was available and it showed better average results than other existing methods at the time. Lewis et al. [32] made a major contribution to the area of weight estimation with the development of allowable stress estimation methods particularly tailored to preliminary design prediction methods.

Anderson and Udin [33] presented a theoretical wing mass derivation method based on a simplified concept model of a subsonic aircraft wing. The wing was divided into different components and, by analysis of the wing loads, the relative mass of the wing was estimated as a function of bending moment, twist moment and shear force. Besides being applicable for subsonic aircraft wing models only, the application of this method required too much input data, which limited its use. A number of design-sensitive mass prediction methods based on refined analytical methods for the wing structures of transport aircraft were developed by Torenbeek [24]. A theoretical method, called the *F* method, was developed by Howe [27], where the wing mass was calculated as the sum of the masses of:

- Span-wise covers, booms and shear webs of the structure;
- Ribs, the mass of high lift devices and secondary fairings;
- Assorted items e.g. power plants, store attachments, landing gear, etc.

In his early studies, Howe suggested that the mass of spanwise covers/booms and shear webs was determined by strength and stiffness considerations in order to satisfy aeroelastic requirements, and in later studies he indicated that aeroelasticity may have a local effect on some parts of the structure. This method was applicable to conventional wings made of light alloy only and gave more accurate results than the C_1 method mentioned in the previous section.

An overview of an advanced conceptual wingbox weight estimation model for transport aircraft was given by Ajaj et al. [34]. The wingbox was modelled based on linear thin-walled beam theory as a simple, swept tapered multi-element beam. The weight of the wingbox was estimated based on the sizing process, including static aeroelastic requirements. The model was validated using five different transport aircraft and showed adequately accurate and reliable results.

Macci [35] presented a method for predicting the wing mass of an aircraft at the preliminary design stage. The theory behind this method was based on the fact that the wing structural box must be designed to meet both the bending strength and the torsional stiffness requirements, due to an assumed trapezoidal lift distribution acting on a rectangular wingbox. Mathematical relations for structural sizing were developed and coded to enable the method to be used as an effective design tool for structures made from both metallic and fibre reinforced plastic (FRP) materials. He concluded that despite the accurate wing mass results provided, it would be wrong to consider this method completely accurate for establishing final design masses. He also illustrated the importance of having detailed information on the wing geometry and construction to establish an accurate wing mass prediction method for existing aircraft, as well as the need for testing the proposed method for aircraft wings made from FRP materials.

Elham et al. [36] proposed a weight prediction method for aircraft lifting surfaces, known as the EMWET method. In this method, the primary wing structure weight was predicted using an advanced analytical method that took into account the structural layout, the actual geometry of the aerodynamic surfaces, and the spanwise lift distribution calculated using the Vortex Lattice Method. The weight of the secondary wing structures was predicted using semi-empirical methods. Mathematical equations were used to relate the required structural properties of the wingbox to the specific shape of the airfoil used. By using these equations, the skin, the spar caps and the stringers of the upper and lower sides of a given wingbox were modelled as two equivalent flat panels and the effective distance from each other was calculated, making it possible to take into account the effect of the airfoil shape on stress distribution in the flat panels, thereby enabling an accurate panel weight estimation. The method was validated using data from different conventional aircraft and the method proved to achieve more accurate results than similar existing methods.

During the last few decades, different tools and software implementations have been developed based on analytical and quasi-analytical methods. In 1973, WP15 was developed as an improved version of the BAe Subsonic Wing Weight Program WP043. The program used analytical methods for sizing the primary structure components under bending and shear forces and empirical methods for estimating the masses of other components [37]. The program could not handle kinked leading edges and it was considered valid for wings with aspect ratios between 6 and 12. In 1987, Dijk [38] developed a program for Airbus Industry in Toulouse. The program provided a rapid weight prediction of the wing structure components based on appropriate structural parameters derived from strength considerations. These parameters were correlated with actual weight data using linear regression. The AdAstra program [39] was developed in 2002, in which the wing mass was estimated by sizing the primary structure using a stationary structural analysis approach, while a set of statistical data was used to estimate the mass of the secondary structures. The application of this program was limited to conventional transport aircraft.

In 1996, Ardema et al. [18] developed an analytical method for wing and fuselage mass estimation of transport aircraft. This method was based on estimating aircraft loads and modelling the aircraft wing and fuselage structure as an Euler-Bernoulli beam. This method was integrated into a PDCYL computer program that had been made into an ACSYNT (AirCraft SYNThesis) computer program, and was used to estimate aircraft mass in vehicle design studies. The method was limited to subsonic conventional aircraft configurations and did not account for aeroelastic effects. Terpstra [39] conducted a study to compare the accuracy of the WP15 and AdAstra programs and the methods presented by Torenbeek and Dijk for wing mass estimation. The study indicated that the accuracy of wing mass prediction methods can vary significantly. Some methods used simplified structural models to represent the wing geometry, while other methods considered a more detailed representation.

FAME-W (Fast and Advanced Mass Estimation Wing) is weight prediction software designed by Airbus Germany [40,41]. It can estimate the mass of a transport aircraft wing while considering the effects of static aeroelasticity. A beam model representation and analytical methods are used for the analysis and sizing of the wingbox structure. Despite the relatively simple geometrical and structural modelling capabilities, this tool offers a high computational efficiency and it is always revalidated against weight data from existing aircraft configurations.

3.3 Finite element based structural optimisation methods

Nisbet et al. [42] proposed one of the early attempts in the literature at using finite element techniques for aircraft mass estimation. A scheme was first proposed that used engineering bending theory as a base for simpler analysis; later on, the authors presented a finite element method based on structural optimisation. These methods were intended to produce mass values for comparison and optimisation purposes rather than for mass estimation on its own.

In their study, Hutton and Richmond [43] derived a methodology for the application of the finite element analysis method to estimate the structural system weight. This resulted in the development and testing of a numerical weight correction factoring logic, which is composed of a number of sub-factors that account for modelling assumptions, material properties and other weight-sensitive variables that are built into the finite element process as functions of the individual element's geometry. This allowed a reasonable weight estimate to be achieved as a direct result of the automated resizing process. Pincha [14] gave another study on the use of the algorithmic mass factoring approach applied at the finite element level. In his study, he derived an algorithm using modelling design and manufacturing criteria for a structural concept. He computed weight increments, each of which represented a non-optimum structural weight, by optimised sizing using geometry and material properties.

Murphy [17] developed a computerised wing mass prediction method, which did not rely on a database of existing aircraft, using finite element analysis techniques. He tested the feasibility of this method for rapidly calculating the weight of an aircraft. The weight results achieved were compared to the results obtained by the advanced analytical-empirical methods [21,32]. He concluded that a feasible solution and good accurate results can be achieved using the proposed computerised method.

Doregkamp [44] presented a technology developed by the McDonnell Aircraft Company to transform the theoretical structural finite element model, with design details such as geometry, material properties and loading, into a realistic weight estimate. In his study, he emphasised the importance of finite element method weight-estimation software for the calculation of the modelled weight and the accurate representation of the structural assembly.

Dababneh and Kayran [45] investigated the effect of implementation of various structural idealisations and the effect of assorted one- and two-dimensional finite element pairs and mesh densities on the optimised mass of wing torque box. The results of the final optimized mass of the wing models were compared with each other and with simplified method solution results. The results showed that optimized wing masses of the models are very close to each other with only slight favorable overall mass on behalf of models using beam elements in the axial members. However, the fine mesh models show a heavier wing mass configuration result when compared with coarse mesh models. This is an expected behavior since in the finest mesh case, stresses are higher and that will take into account while satisfying different design constraints.

Zaidel [46] illustrated the use of the finite element method as a viable weight- engineering tool. The finite element method was also used in the A-12 aircraft project to distribute structural target weights to enhance the accuracy of the aircraft and determine realistic structural weights, which in turn provided an early indication of potential overweight areas. Mitchell [15] described the integration process of the tools for finite element mass property analysis for Weight Engineering at Boeing in a multidisciplinary finite element analysis environment. Particular emphasis was put on the weight estimation of primary structures undergoing optimisation. The multidisciplinary approach was very useful for the success of the modelling and weight estimation efforts on the High Speed Civil Transport aircraft.

Sensmeier et al. [47] proposed a methodology for rapid and automatic structural model generation based on a parametric description of aircraft structural elements and their layout rather than the actual dimensions. Using this methodology, a finite element model of moderate fidelity based on a parametric structural model can be generated so that, changing the structural model, the finite element model is changed automatically. This model can then be used within an optimisation algorithm to allow sizing optimisation to be performed. Eventually this will result in improved accuracy in weight estimation for new aircraft designs than the one obtained by the empirical-historical data based methods.

Bindolina et al. [22] presented a multilevel structural and multidisciplinary optimisation procedure for the preliminary estimation of the wingbox weight of an aircraft for which empirical formulas and statistical analysis may not be sufficiently reliable. The procedure consisted of three design cycles running on three separate levels. In the first level, a satisfactory behaviour of the wing was granted by optimising a one-dimensional model based on beam theory. In the second level, by using the internal forces stressing the wing components and a classical wing structure analysis approach coupled with a genetic optimiser, the design and sizing of the wingbox structure was accomplished. In the last level, the finite element model of the wing structure was generated using the data available from previous levels. The procedure was compared to a wingbox weight estimation of a conventional aircraft configuration using classical semi-empirical methods and was then applied to the wing weight estimation of a nonconventional aircraft configuration. In both cases, satisfactory results were demonstrated.

Hurlimann et al. [48] presented a CAD/CAE-based multidisciplinary process for the mass estimation of a transport aircraft wingbox structure. CATIA V5 was used as a multi-geometrical and multi-structural model generator and the interface capabilities of CATIA V5 were used for the generation and application of wing loads. A finite element structural algorithm was used for analysing and sizing the wingbox structure. The process was verified by performing a mass estimation of the wingbox structure of a generic long-range aircraft configuration. Hurlimann concluded that although the proposed mass estimation method that relied on modern CAD/CAE tools showed several advantages while generating and handling the geometrical and structural model of an aircraft wing, there were some disadvantages that severely limited the viability of the CAD/CAE-based approach. Such disadvantages were related to the low computational efficiency and lack of an external programming interface in CATIA V5 that caused multidisciplinary optimisation to be inapplicable. Another disadvantage was related to the use of composite materials, which was not possible in the particular version of CATIA V5 (R19).

Dababneh [49] presented a novel framework for estimating the mass of transport aircraft wing based on Finite Element Analysis (FEA) and Multidisciplinary Design Optimisation (MDO) techniques that are suitable for the preliminary stage of the design process. In his work, the consequences of using wingbox cross-section models that increase structural complexity on the wing mass estimation results for conventional aluminium alloys and composite designs have been investigated. The results showed that in a scenario where high-fidelity structural models are used to describe and represent the wingbox, these models do indeed attempt to improve the level of accuracy of the optimised masses of the wingbox.

Dorbath el at. [50] presented a WINGmass tool chain for advanced physical wing mass estimation. In this tool, the structural modeling is extended beyond the wing primary structure to include the wing secondary structures, landing gears and engine pylons. The chain includes modules for finite element wing structures model generator, models for aerodynamic, fuel, landing gear and engine loads computations, structural analysis, and sizing algorithms and post processing routines. The tool was validated by conducting a wing mass estimation of a number of novel aircraft concepts with different wing configurations. Although, the tool showed an acceptable accuracy, the computational time was relatively high. Uncertainties in the aerodynamic loads calculation and lack flutter analysis tools are other limitations of the WINGmass tool.

Another study that used an automated model generator for wing mass estimation in the initial phases of the design process was given by Wenzel et al. [51]. In their work, Wenzel et al. presented a method that uses parametric-associative geometry and finite element models created in the software environment CATIA V5 for estimation of the primary structure mass. Despite the fact that the developed tool has proven to be very useful for getting insight into the mass sensitivities of the design parameters, the mass estimation tool need validation against aircraft wing mass data.

A generic numerical modelling process for nonconventional wing configurations was developed by Seywald [52] and a simulation tool for their evaluation and mass prediction was implemented. The wingbox was modelled by a nonlinear finite element beam model coupled with a low-fidelity aerodynamic method, resulting in a quasi-static aeroelastic model that takes into account the redistribution of aerodynamic forces due to deformation. The tool had been validated on a number of conventional aircraft configurations and complex wing configurations such as the C-Wing. The wingbox predicted masses were generally a little lighter when compared to the reference values. The joined wing concept has been studied by a number of designers since 1986, when Wolkovich [53] published his concept, and since then a number of methods have been developed and reported on the wing mass estimation of joined wing aircraft configurations. Hajela [54], Miura et al. [55], and Blair and Canfield [56] describe different trends and integrated design processes for creating high fidelity weight modelling and estimation techniques realised using the finite element method.

A number of computational tools have been developed for wing mass estimations. These algorithms have been significantly improved over the past few years and their accuracy has increased with recent advances in computer technology. PrADO (Preliminary Aircraft Design and Optimisation Program) is a program that was originally developed by Heinze [57-59] at the Institute of Aircraft Design and Lightweight Structures of the TU Braunschweig. PrADO is used for the design and optimisation of the entire aircraft with respect to different aspects, e.g. operational and economical, by the use of a dedicated cost model. This program offers the user either a fast analytical method or a computationally more expensive but high-fidelity finite element based method for the structural analysis and dimensioning of either conventional-configuration aircraft structures or nonconventional configurations such as the blended wing body.

Cavagna et al. [60,61] presented a design framework called NeoCASS (Next generation Conceptual Aero-Structural Sizing Suite), developed by the Department of Aerospace Engineering of Politecnico di Milano in Italy. The framework enables the creation of efficient low-order, medium fidelity models of aircraft layouts to perform structural sizing, aeroelastic analysis, and optimisation within the conceptual design stage. NeoCASS includes two main modules, named GUESS (Genetic Unknown Estimator in Structural Sizing) and SMARTCAD (Simplified Models for Aeroelasticity in Conceptual Aircraft Design). The initial sizing of aircraft is performed by the semi-analytical module GUESS, which is based on a modified version of AFaWWE (Analytical Fuselage and Wing Weight Estimation) originally performed by Ardema [18]. During the initial sizing, the total amount of load-bearing structural weight is determined using actual isotropic material properties, realistic aircraft layout and loading conditions. Strength and stability design requirements are also considered. Once the loads are determined, using simplified aerodynamic methods or Vortex Lattice Method, the sizing is performed using fully stressed design condition, and the minimum amount of material for each component of the wingbox required to resist the applied load is calculated. The wing secondary and non-structural masses are estimated using linear regression methods. During the initial sizing phase, no aeroelastic effects are considered. At the end of the sizing process, and as the first stiffness and inertia distributions are determined, GUESS automatically generates a stick beam model, structural and aerodynamic mesh for aeroelasticity analysis. The initial structural sizing is then refined to satisfy the aeroelastic constraints, using a dedicated Multi-Disciplinary Optimisation tool available in NeoCASS. The framework has been applied to the conceptual design of a transonic cruiser aircraft. The results show a good compromise between accuracy and computational costs.

MDCAD (Multidisciplinary Concept Assessment and Design) is another program originally developed by QinetiQ for the analysis and optimisation of military and civil aircraft configurations to investigate the impact of new technologies such as novel wing configurations, composite materials and other systems on the design [62,63]. MDCAD makes use of the geometry model generator in CATIA V5 for structural modelling and the finite element solver of MSC Nastran for structural analysis.

4. Discussion

Based on the studies reported in this review paper, the following key observations are highlighted:

- Empirical and semi-empirical wing mass estimation methods are mostly based on statistical data from previously investigated or constructed aircraft and rudimentary performance equations of the most significant design parameters, but it is also possible to have experimentally based methods. The simplicity of understanding and applying these methods can be of some use at the initial stages of the conceptual design process in order to approximate the mass breakdown of major components such as maximum take-off mass, payload mass and wing mass. However, the implementation and accuracy level of these methods in predicting wing mass depends primarily on the accessibility, quality, and consistency of the data available of specific classes and types of aircraft, as well as the experience gained from previous projects. In addition, these methods are limited to conventional aircraft designs constructed from light metallic alloys, and are unable to assess the relative benefits of novel wing designs concepts and the use of advanced composite materials.
- Analytical and quasi-analytical based methods make use of structural analysis methods to calculate the amount of material necessary to satisfy structural strength and stiffness requirements. These methods are considered useful at the early stages of the preliminary design process, and have shown a higher accuracy, and better design sensitivity results than other existing methods, despite the required detailed information on the wing geometry and construction. A primary limitation associated with analytical and quasi-analytical methods is their applicability only to conventional aircraft wings made of metallic alloys. In addition, they still use a simplified geometrical layout of aircraft wing [64], ignoring not only the actual aerodynamic shape of the wing but also the internal wing structure design. Unmaintained, the actual aerodynamic shape of the wing will affect the overall accuracy of the aerodynamic load calculation and distribution over the wing, which has a significant effect on the structural sizing process of the wingbox and hence it's mass. Numerous methods have been used to calculate the aerodynamic load distribution by assuming a simplified shear force and bending moment or an elliptical lift distribution based methods. The use of these methods has revealed a significant inadequacy in the existing mass estimation methods for predicting a reliable result. On the other hand, ignoring the internal wing structure design will affect the structural behaviour of the wing torque box, as the primary load-carrying structure, by having a significant effect on the accuracy of the moment of inertia and stress calculation values for each section of the wing. This will have an impact on the structural analysis technique used to size and estimate the wing structural mass components. Furthermore, it will affect the investigation of the advantages of using novel

wingbox design concepts like the curvilinear SpaRibs [65] and grid structure [66] in comparison with classical design concepts.

- Finite element based structural optimisation methods use finite element analysis and design optimisation techniques to estimate the structural mass of aircraft wings. These methods have proven to be very useful in calculating the mass of conventional and nonconventional aircraft configurations constructed from advanced composite materials. Although the computational time is relatively high, feasible designs and improved accuracy in wing mass estimation can be achieved using these methods than the one obtained by the empirical-historical data based methods or analytical methods. The accuracy of the results depend significantly on the following points:

1. The quality of the finite element wing model, consisting of a well-defined and realistic shape of the wing structure model;
2. Accurate calculation and representation of the aerodynamic loads;
3. Reasonable design requirements and practical design variables and constraints;
4. The utilised fidelity levels of the optimisation solvers and the design analysis discipline used, mainly aerodynamic and structure.

Table 2 below provides a summary of aircraft wing mass estimation methods. From Table 2, it can be seen that the choice of wing mass estimation method is design-dependent, and generally the level of accuracy and competence of the methods at each aircraft design phase play an important role in making the decision. In addition to this, the availability of key aircraft configuration parameters (wing aspect ratio, sweep angle, taper ratio, etc.) at each design stage and the computational cost can have a significant effect on the choice of the method and consequently on the accuracy of the wing mass value.

Table 2 Summary of aircraft wing mass estimation methods

Categories	Aircraft Design Phase	Fidelity and Accuracy	Computational Cost	Aircraft Configuration Input Parameters
Empirical & Semi-Empirical	Conceptual	Acceptable	Low	Small Set of Parameters
Analytical & Quasi-Analytical Based	Conceptual - Preliminary	Improved	Low-Medium	Medium Set of Parameters
Finite Element Based Structural Optimisation	Preliminary - Detailed	Enhanced	Medium-High	Detailed/Large Set of Parameters

Table 3 shows wing mass estimated results for several transport type aircraft. These values are compared with the actual wing mass values reported in the open literature. The results provided in Table 3, show that by using a high-fidelity wing mass estimation methods, mainly quasi-analytical and finite element based structural optimisation methods, these methods indeed attempt to improve the predicted masses of the aircraft wing. It should be noted that in the case where no mass values were reported for some aircraft using empirical and semi-empirical methods, the values were estimated using the well-known 12% rule, which estimates the wing mass as being 12% of the maximum take-off mass [20].

Table 3 Estimated versus actual wing mass for several transport type aircraft

Aircraft Type	Empirical & Semi-Empirical [kg]	Analytical & Quasi-Analytical [kg]	Finite Element Based Structural Optimisation [kg]	Actual Mass [kg]
B747-100	40,008 [18]	39,932 [67]	39,924 [22]	39,914 [35]
A340	32,520 [20]	35,180 [67]	-----	34,747 [35]
B737-200	4,848 [18]	3,730 [35]	-----	4,812 [35]
A320-200	9,240 [20]	-----	8,332 [52]	8,811 [52]
DLR-F11	27,636 [20]	-----	31,213 [68]	-----
NASA-CRM	31,200 [20]	-----	30,754 [49]	-----

- A large variety of software packages have been developed for wing mass estimation by different leading aircraft manufacturers and aeronautics and space research centres. These computational tools are mainly developed using in-house software [69-72], making them inaccessible for public use and limited to use by the developer company only.

5. Conclusions

In the present article, the phases of aircraft design and the development process are discussed. The open literature on the subject of wing mass estimation methods and their classifications and applications in the aerospace industry is reviewed and relevant data are presented to provide the readers with reference materials on the field. The lack of reliable and accessible wing mass prediction methods that allow assessment of the relative benefits of novel technologies that can enhance the lift-to-drag ratio of the aircraft wing, while reducing the structural wing weight, is of significant importance. It requires the development of new and generally applicable wing mass estimation methods. Determining the mass of an aircraft wing, for which the database is insufficient or non-existent or the wing design lies beyond the use of empirical methods, via fully integrated finite element analysis and design optimisation software packages appears to be a promising approach to consider at the early stages of the design process. This has been made possible over the last 10 years by the increased processing power of computers, the advancements in computer-aided design, the enhancement of multi-dimensional design space visualisations, simultaneous calculation, visual screening and representations of a variety of design analysis and optimisation results.

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A review of aircraft wing mass estimation methods

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