Aircraft weight estimation in interactive design process

Omran Al-Shamma

Dr. Rashid Ali

University of Hertfordshire

Abstract

Amongst all the design modules employed in aircraft design process, weight module is the most significant one. Evaluating aircraft performance is dependent on a suitable aircraft weight in order to carry out its intended mission. In interactive design process, the weight design engineers usually follow one particular published methodology such as that proposed by Roskam or Torenbeek or etc.

The main drawback of these methodologies is their limited accuracy to be applied to the vast variation of civilian aircraft. Furthermore, the non-availability of component-weight data, which may be used in evaluating maximum take-off weight, makes the design process difficult.

Hence, new weight module has been applied to interactive design process. It suggests that many equations of different methodologies are applied to each aircraft component instead of applying one analyst's methodology. Simultaneously, any formula that has secondary variables, which may not be available in the early stages of aircraft design, is rejected. The equation that gives the lowest average value is selected. The new module results show that the accuracy of the estimated operating empty weight and the maximum take-off weight is better than 5%.

Nomenclatures

$AR_h = Horizontal\ tail\ aspect\ ratio$

$AR_v = Vertical\ tail\ aspect\ ratio$

$AR_w = Wing\ aspect\ ratio$

$D_{fus} = Fuselage\ diameter$

$\frac{H_t}{H_v} = 0.0\ for\ conventional\ tail; 1.0\ for\ T\ tail$

$L_{fus} = Fuselage\ length$

$N_{eng} = Number\ of\ engines$

$N_{ft\_att} = Number\ of\ flight\ attendants$

$N_{ft\_crew} = Number\ of\ flight\ crew$

$N_{gust} = Gust\ factor$

$(N_{gust})_{ult} = Ultimate\ gust\ factor$

$N_{manu} = Manoeuvre\ factor$

$(N_{manu})_{ult} = Ultimate\ manoeuvre\ factor$

$N_{pas} = Number\ of\ passengers$

$N_{ult} = Ultimate\ load\ factor$

$S_e = Elevator\ area$

$S_{flap} = Flap\ area$

$S_{fuswet} = Wetted\ fuselage\ area$

$S_h = Horizontal\ tail\ area$

$S_{he} = Exposed\ horizontal\ tail\ area$

$S_w = Wing\ reference\ area$

$S_v = Vertical\ tail\ area$

$Th = Total\ take-off\ thrust$

$V_{dive} = Designed\ dive\ speed$

$W_{acic} = Air\ conditioning\ and\ anti-icing\ weight$

$W_{apu} = Auxiliary\ power\ unit\ weight$

$W_{apu\_dry} = Dry\ APU\ engine\ weight$

$W_e = Empty\ weight$

$W_{ele} = Electrical\ systems\ weight$

$W_{eng} = Engine\ weight$

$W_{ft\_att} = Flight\ attendant\ weight$

$W_{ft\_crew} = Flight\ crew\ weight$

$W_{furn} = Furnishing\ weight$

$W_{fus} = Fuselage\ weight$

$W_{ht} = Horizontal\ tail\ weight$

$W_{hyd} = Hydraulic\ system\ weight$

$W_{ins} = Instruments\ and\ avionics\ weight$

$W_{mg} = Main\ gear\ weight$

$W_{nac} = Nacelle\ group\ weight$

$W_{ng} = Nose\ gear\ weight$

$W_{op\_it} = Operating\ items\ weight$

$W_{oxy} = Oxygen\ system\ weight$

$W_{pay} = Payload\ weight$

$W_{pnt} = Paint\ weight$

$W_{pro} = Propulsion\ group\ weight$

$W_{pro\_sys} = Propulsion\ system\ weight$

$W_{sur} = Surface\ controls\ weight$

$W_{sys} = Systems\ weight$

$W_t = Tail\ weight$

$W_{to} = Designed\ take-off\ weight$

$W_{uc} = Undercarriage\ weight$

$W_{vt} = Vertical\ tail\ weight$

$W_w = Wing\ weight$

$W_{zf} = Designed\ zero\ fuel\ weight$

$b = Wing\ span$

$b_h = Horizontal\ tail\ span$

$b_v = Vertical\ tail\ span$

$cos\Lambda_{1/4} = Cosine\ wing\ sweep\ angle$

$cos\Lambda_v = Cosine\ vertical\ tail\ sweep\ angle$

$cwr = Wing\ root\ chord$

$l_{cab} = Cabin\ length$

$l_h = Distance\ from\ wing\ aerodynamic\ centre\ to\ tail\ aerodynamic\ centre$

$l_v = Distance\ from\ wing\ aerodynamic\ centre\ to\ vertical\ tail\ aerodynamic\ centre$

$mac_w = Wing\ mean\ aerodynamic\ chord$

$stage = stage\ length$

$(t/c) = Average\ wing\ thickness\ ratio$

$\lambda = Wing\ taper\ ratio$

Introduction

Amongst all the design variables used in aircraft design, three are most important, they are weight, weight and weight. Performance of the aircraft is dependent on the aircraft having a suitable weight in order for it to carry out its intended mission. Cost of aircraft which is another major parameter for customers (airliners) depends mainly on aircraft weight. Therefore, manufacturers are always trying seriously to make the aircraft as light as possible. Accurate weight estimation at early stage of aircraft design process is a hard and difficult task. When the detail design drawings are complete, the aircraft weight can be calculated accurately by evaluating each part and adding them all up, and that is really done. The methodologies used for weight estimation are expanded synchronously with the design phases. In conceptual design phase, these methodologies are very simple in nature and have significant uncertainty [1] which estimate the aircraft weight as a whole (MTOW). In preliminary design phase where the MTOW breaks down into components and sub-components, the methodologies becomes more complicated and accurate. More specifically, as information becomes more accessible in this phase, the accuracy increased from 10-15% to 5-10%.

The weight methodologies are classified into three categories: Empirical, Analytical, and Semi-analytical. Empirical methods are used to generate fast and accurate empty weight (EW) (and in turn MTOW) [2] and to predict weights of different configurations of aircraft [3]. Analytical methods tend to be more accurate than empirical methods and its ability to incorporate new technologies, materials, and concepts. More details about weight methodologies are found in Ref. [4]. Semi-analytical have the highest accuracy than the others and it required less data compared to analytical methods [5]. In interactive aircraft design, it is normal for design engineers to follow one particular estimation methodology, for instance as proposed by Raymer [6] or Torenbeek [7] or even the method proposed by NASA [3].

The limitation of the existing methodologies is that they cannot be applied to the vast variation of civilian aircraft that exist or indeed likely to be designed due to the changing demands or indeed their utility. In fact, Roskam [8] describes three different methodologies that yield different values which differ as much as 25%. What makes the process difficult also is the non-availability of data that could be used to compare aircraft component weights. Although the overall weight figures (such as operating empty weight (OEW) and MTOW) are available, there is a scarcity of information on the detailed component, sub-system and system level.

Hence, instead of applying complete formulae set of one methodology, the weight module which has been implemented in Ref. [9], is suggested as a new approach for accurate weight estimation in interactive design process. This module evaluates each aircraft component weight by applying many formulae of different methodologies and trying at the same time to avoid using any formula that have secondary variables which may not be available in the early stages of aircraft design. The one that gives the lowest average value is selected.

New Module Details

Since the body of the aircraft (Wing, Fuselage, and tail) forms 50-60% of the empty weight, the new module uses three formulae sets to each component of the existing Airbus and Boeing aircraft. The one that gives the lowest average value is selected. Two of these three sets are Ramer's set [6] (which is the newest one) and the other is Torenbeek's set [7] (which is the most famous and widely used).

The main input variables (key drivers) that are used in this module are: W_{to}, S_{ref}, $V_{dive,}$ l_{fus}, D_{fus}, and AR_w. Other input variables such as N_{ult}, b, and S_{fuswet} are already consist of these main key derivers. On the other hand, the effects of composites or other advanced materials are taking into account by applying suitable user-controlled factors to each individual weight components. These factors are used to overcome the shortage of some empirical methodologies as mentioned above. For the reason that all formulae work in terms of mass rather than weight, some traditional weight-style abbreviations such as OEW, MTOW, etc are used interchangeably for convenience. SI units are used unless it is mentioned. In order to calculate component weights, pre-calculations for the load factors (limit and ultimate) were required as in follow:

Initially, the limit load factor which is the greater of the gust and manoeuvre factors is evaluated. These load factors are determined in accordance with airworthiness requirements [10]. The following relationships [11] are used: -

$$N_{gust} = \frac{1 + 6.3AR_w S_{ref} V_{dive}}{W_{to}(2 + AR_w)} \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$N_{manu} = 2.1 + \frac{10900}{4530 + W_{to}} \ldots\ldots\ldots\ldots\ldots\ldots (2a)$$

$$N_{manu} = 2.5 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2b)$$

$N_{manu} = the\ greatest\ of\ (2a)\ and\ (2b).$

The second step is to calculate the ultimate load factors of both gust and manoeuvre:-

$$(N_{gust})_{ult} = 1.5N_{gust} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$(N_{manu})_{ult} = 1.65N_{manu} \ldots\ldots\ldots\ldots\ldots .\ldots\ldots\ldots\ldots (4)$$

$N_{ult} = the\ greatest\ of\ (3) and\ (4).$

The weight module evaluates the aircraft weight (MTOW) by breaking down into the following sections:

1- Empty weight.
2- Operating empty weight.
3- Zero fuel weight.

<u>1-Empty Weight (EW):</u>

Evaluation of EW is done by breaking down into its components as in the following sub-sections:-

<u>1-a- Wing:</u> Wing weight represents about 17-27% of the EW. The following formulae (5, 6, & 7) are for Kroo [12], Torenbeek [7], and Raymer [6] respectively:

$$W_w = 4.22S_{ref} + 1.642 \times 10^{-6} \times \frac{N_{ult} b^3 (1+2\lambda)\sqrt{W_{to}W_{zf}}}{(t/c)\, cos^2\Lambda_{\frac{1}{4}}\, S_{ref}\,(1+\lambda)} \ldots\ldots\ldots\ldots\ldots (5)$$

$$W_w = 0.00667 N_{ult}^{0.55} \left({}^{t}/_{c} \times cwr\right)^{-0.3} \times \left(\frac{b}{cos\Lambda_{\frac{1}{2}}}\right)^{1.05} \times \left(1 + \sqrt{\frac{1.905 \times cos\Lambda_{1/2}}{b}}\right) \times \left(\frac{W_{zf}}{S_{ref}}\right)^{-0.3} W_{zf} \ldots\ldots (6)$$

$$W_w = 0.0051 {S_{ref}}^{0.649} {S_{flap}}^{0.1} \times \frac{(N_{ult}W_{to})^{0.557}\,(1+\lambda)^{0.1}\,{AR_w}^{0.5}}{\left(\frac{t}{c}\right)^{0.4}\; cos\Lambda_{\frac{1}{4}}} \ldots\ldots (7)$$

Note that equations (5 & 7) are in English units.

Raymer's formula is selected for the reason that it gives the lowest average value.

1-b- Fuselage: Nicolai [13], Torenbeek [7], & Raymer [6] formulae are used to calculate the fuselage weight as follows:

$$W_{fus} = 0.0737 \times \left(2D_{fus}\, V_{dive}^{0.338}\, L_{fus}^{0.857} \times (W_{to}\, N_{ult})^{0.286}\right)^{1.1} \ldots\ldots\ldots (8)$$

$$W_{fus} = 0.23 \times S_{fuswet}^{1.2} \times \sqrt{\frac{V_{dive} l_h}{2D_{fus}}} \ldots\ldots\ldots\ldots (9)$$

$$W_{fus} = 0.4886\,\sqrt{W_{to}N_{ult}}\; l_{fus}^{0.25}\; S_{fuswet}^{0.302}\,(1 + kws)^{0.4} \ldots\ldots\ldots\ldots\ldots (10)$$

Where:

$$kws = 0.75 \times \frac{\left(\frac{(1+2\lambda)}{(1+\lambda)}\right)\left(AR_W\, S_{ref}\right)^2\, tan\Lambda_{1/4}}{l_{fus}}$$

Note that equation (10) is in English units. Typically, Raymer's formula gives the lowest average value.

1-c- Tail: Similar to the wing weight estimation, Kroo [12], torenbeek [7], & Raymer [6] formulae (11, 12, & 13 repectively) are used here to calculate the horizontal and vertical tail weights as in the following:

$$W_{ht} = 5.25S_{he} + 0.8 \times 10^{-6}\, \frac{N_{ult}\, b_h^3\, W_{to}\, mac_w \sqrt{S_{he}}}{(t/c)\, cos\Lambda_{1/4}^2\, l_h\, S_h^{1.5}} \ldots\ldots\ldots\ldots (11a)$$

$$W_{vt} = 2.62S_v + 1.5 \times 10^{-5}\, \frac{N_{ult}\, b_v^3 \left(8.0 + 0.44\frac{W_{to}}{S_{ref}}\right)}{(t/c)\, cos\Lambda_{1/4}^2} \ldots\ldots\ldots (11b)$$

$$W_t = W_{ht} + W_{vt} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11c)$$

$$W_t = 0.051\, \frac{V_{dive}\,(S_h + S_v)^{1.2}}{\sqrt{cos\Lambda_{1/4}}} \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

$$W_{ht} = 0.0379\, W_{to}^{0.639}\, N_{ult}^{0.1}\, l_h^{-1.0}\, S_h^{0.75} \times (0.3l_h)^{0.704}\, cos\Lambda_{1/4}^{-1.0}\, AR_h^{0.166} \times \left(1 + \frac{D_{fus}}{b_h}\right)^{-0.25} \times \left(1 + \frac{S_e}{S_h}\right)^{0.1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13a)$$

$$W_{vt} = 0.0026\, W_{to}^{0.556}\, N_{ult}^{0.1}\, l_v^{-0.5}\, S_v^{0.5} \times (0.3l_v)^{0.875} AR_v^{0.35}\, cos\Lambda_v^{-1.0} \times (t/c)^{-0.5} \times \left(1 + \frac{H_t}{H_v}\right)^{0.225} \ldots\ldots\ldots\ldots\ldots\ldots (13b)$$

$$W_t = W_{ht} + W_{vt} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

Note that all equations are in English units except equation (12).

1-d- Propulsion system: The major deriver in evaluating the weight of propulsion system (propulsion & nacelle groups) is the engine dry weight. This weight has been estimated accurately using the following state-of-art formula which is based on engines data given by Harris [14]:

$$W_{eng} = 0.4054 \times Th^{0.9255} \dots\dots\dots\dots\dots\dots\dots (14a)$$
$$for\ Th < 10000\ lbs$$

$$W_{eng} = 0.616 \times Th^{0.886} \dots\dots\dots\dots\dots\dots\dots (14b)$$
$$for\ Th < 10000\ lbs$$

The weight of the propulsion group which includes the engines, engine exhaust, reverser, starting, controls, lubricating, and fuel systems are handled together as the total propulsion group weight. Torenbeek [7] suggests the following formula for estimating the propulsion group weight:

$$W_{pro} = 1.377 \times W_{eng} \times N_{eng} \dots\dots\dots\dots\dots (15a)$$

While his formula for nacelle group weight is:

$$W_{nac} = 0.055 \times Th \times N_{eng} \dots\dots\dots\dots\dots\dots (15b)$$

The total weight of propulsion system is:

$$W_{pro\_sys} = W_{pro} + W_{nac} \dots\dots\dots\dots\dots\dots\dots (15)$$

Note that all weights in this sub-section are in pounds (*lbs*).

1-e- Landing gear: The total landing gear weight which includes structure, actuating system, and rolling assembly, is about 3.5-4% of MTOW for aircraft whose weight exceeds 4500 kg. Landing gear weight estimation can be break down into main gear weight and nose gear weight. The following formulae developed by Torenbeek [7] are employed due to their good estimation (around 3.7% of MTOW):

$$W_{mg} = 40 + 0.16W_{to}^{0.75} + 0.019W_{to} + 1.5 \times 10^{-5}W_{to}^{1.5} \dots\dots\dots\dots\dots (16a)$$

$$W_{ng} = 20 + 0.1W_{to}^{0.75} + 2 \times 10^{1.5}W_{to}^{1.5} \dots\dots (16b)$$

The total weight is:

$$W_{uc} = W_{mg} + W_{ng} \dots\dots\dots\dots\dots\dots\dots\dots\dots (16)$$

Note that all weights are in English units.

1-f- Surface controls: The weight of the surface controls are the systems associated with control surface actuation and depends mainly on the tail area, Torenbeek [7] suggests the following formula related to take-off weight instead:

$$W_{sur} = 0.4915 \times W_{to}^{2/3} \dots\dots\dots\dots\dots\dots\dots\dots (17)$$

Add 20% for leading flaps or slots and 15% for control dampers if used.

1-g- Systems: To breakdown the systems, different analysts have their different categories. Therefore, it is better to select only one formulae set of any analyst. Raymer set [6] for example is good but it requires many detail information which may not be available or decided in early design stages. Torenbeek [7] set has been used for a long time and hence it is used here. Systems are break down into seven sub-categories as follows:

<u>1-g-1- *Auxiliary power unit (APU):*</u> The installed APU weight is dependent mainly on the dry engine weight of APU as in the following formula:

$$W_{apu} = 2.2 \times W_{apu\_dry} \dots\dots\dots\dots\dots (18a)$$

In the absence of the uninstalled APU weight, Kudu [15] formula is:

$$W_{apu\_dry} = 0.001 \times W_{to} \dots\dots\dots\dots\dots\dots\dots\dots (18a1)$$

<u>1-g-2- *Instruments and Avionics:*</u> This weight is estimated based on both take-off weight and stage length:

$$W_{ins} = 0.347 \left(\frac{W_{to}}{2}\right)^{0.555} \left(\frac{stage}{1000}\right)^{0.25} \dots\dots (18b)$$

1-g-3- *Hydraulics and Pneumatics:* The weight of hydraulic systems is related directly with the take-off weight:

$$W_{hyd} = 0.015\left(\frac{W_{to}}{2}\right) + 272 \dots\dots\dots\dots\dots\dots\dots (18c)$$

1-g-4- *Electrical system:* This weight depends only on cabin length (l_{cab}) and fuselage diameter (D_{fus}):

$$W_{ele} = 10.8 \times \left(\pi l_{cab}\left(0.9D_{fus}\right)^2\right)^{0.7} \times \left(1 - 0.18\left(\pi l_{cab}\left(0.9D_{fus}\right)^2\right)^{0.7}\right) \dots\dots\dots.. (18d)$$

Note that formula (18d) is in English units.

1-g-5- *Air conditioning and Anti-icing:* Again this weight depends on cabin length (l_{cab}) only:

$$W_{acic} = 14 \times l_{cab}^{1.28} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (18e)$$

1-g-6- *Oxygen system:* This weight related to cruise altitude and range. If the altitude is less than 25000 feet, the following formula is used:

$$W_{oxy} = 20 + 0.5N_{pas} \dots\dots\dots\dots\dots\dots\dots\dots\dots (18f1)$$

If the altitude is higher than 25000 feet, the following formulae are used:

$$W_{oxy} = 30 + 1.2N_{pas} \dots\dots (18f2) \quad for\ short\ range$$

$$W_{oxy} = 40 + 2.4N_{pas} \dots\dots (18f3) \quad for\ long\ range$$

1-g-7- *Paint and Miscellaneous:* This weight represents 0.006 of the take-off weight:

$$W_{pnt} = 0.006 \times W_{to} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (18g)$$

The total systems weight is:

$$W_{sys} = W_{apu} + W_{ins} + W_{hyd} + W_{ele} + W_{acic} + W_{oxy} + W_{pnt} \dots\dots\dots\dots\dots (18)$$

1-h-Furnishings: Furnishings are mainly proportional to the number of actual passenger seats. For more accurate calculation, this weight is based on the actual division of seats between first class and coach. In the early stages of aircraft design process, the maximum number of seats of one class is used. Torenbeek [7] formula instead depends on zero fuel weight:

$$W_{furn} = 0.196 \times W_{zf}^{0.91} \dots\dots\dots\dots\dots\dots\dots\dots\dots (19)$$

Now, aircraft empty weight (EW) is the sum of all structural component weights. i.e.:-

$$W_e = W_w + W_{fus} + W_t + W_{uc} + W_{pro\_sys} + W_{sur} + W_{sys} + W_{furn} \dots\dots\dots\dots\dots (20)$$

2- Operating Empty Weight (OEW):

This weight consists of the following sub-weights: EW, operating items, flight crew, and flight attendants:

2-a- Empty weight (EW): It is calculated as above.

2-b- Operating items: Torenbeek formula [7] for short range aircraft is:

$$W_{op\_it} = 8.617 \times N_{pas} \dots\dots\dots\dots\dots\dots . \dots\dots\dots (21a)$$

While for long range aircraft, the formula is:

$$W_{op\_it} = 14.97 \times N_{pas} \dots\dots\dots\dots\dots\dots\dots\dots\dots (21b)$$

2-b- Flight crew: Torenbeek [7] suggest an average 93 Kg per flight crew. The formula is:

$$W_{fl\_crew} = 93 \times N_{fl\_crew} \dots\dots\dots\dots\dots\dots\dots\dots\dots (22)$$

2-c- Flight attendants: Typically, there are 30 passengers per attendant and Torenbeek [7] suggests 68 kg per flight attend:

$$W_{fl\_att} = 68 \times N_{fl\_att} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (23)$$

3- Zero Fuel Weight:

This weight consists of OEW and payload.

3-a- Operating empty weight (OEW): It is calculated as above.

3-b- Payload: The FAA suggests that passenger weights include *169 lbs* per passenger plus *10 lbs* for winter clothing and *16 lbs* of carry-on bags and personal items for a total of *195 lbs* per passenger. An additional *30 lbs* is assumed for checked bags, leading to the total of *225 lbs* per passenger. This is higher than what has been assumed in the past and based on recent surveys of passenger weights. The aircraft may also carry cargo as desired. An added cargo weight of 40 lbs per passenger is a reasonable in the determination of maximum zero fuel weight. Therefore, the total weight per passenger is *265 lbs* or *120 kg*:

$$W_{pay} = 120 \times N_{pas} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (24)$$

Case Study

Many case studies have been performed for the existing aircraft. For the reason of the EW and MTOW are the only published data available for now day aircraft, the new module results agree very favourably with the data of Airbus and Boeing aircraft. The accuracy is better than 5% as shown in Table 1. In particular, a full case study for Boeing 747-200B is presented here to assess the components weights with the published data in Kroo [12]. Initially, these published data which are shown in Fig. 1, are in English units (lbs). The major input variables used are taken from Ref. [16] & [17], while the calculated component weights are obtained in Fig. 2. Note that the dive speed value is not available as a published data but it was evaluated as 1.2 of the maximum cruise speed. By examining the data of Fig. 2 with Fig. 1, we can conclude that MTOW, EW, Wing, Fuselage, Propulsion system (nacelle and propulsion groups, each or overall), and Undercarriage weights give excellent accuracy of about 5%. As Kundu [15] reported that Oxygen System weight and Paint weight are included in Furnishings weight not in Systems weight. Hence, Systems weight alone accuracy is 7%, while Systems and Furnishings both together have accuracy of 2.7%. Although tail weight estimation gives 50% higher than the actual value, but Raymer's formula has the lowest value while Torenbeek formula for example gives more than twice the actual value. The tail estimated value still acceptable since it is in the range of 2-3% of MTOW.

Conclusion

In preliminary phase of the interactive design process, where the MTOW breaks down into its components and sub-components, the methodologies becomes more complicated and the accuracy increased from 10-15% to 5-10%. A new module has been developed to increase the accuracy to better than 5%. Its output results agree very favourably with the published data of current Airbus and Boeing aircraft. Boeing 747-200B has been chosen as a case study due to its published component-weight data and to show the accuracy of the new module at component level.

References

[1]- Monroe, R. W., R. A. Lepsch, & R. Unal, "*Addressing Uncertainty in Weight Estimates*", In 57th Annual Conference, Wichita, Kansas, May 18-20, 1998, Wichita, Kansas, pp. 11, Society of Allied Weight Engineers, Inc.

[2]- Scott, P. W., & Nguyen, D., "*The Initial Weight Estimate*", In 55th Annual Conference, Atlanta, Georgia, June 3-5, 1996, Atlanta, Georgia, pp. 14, Society of Allied Weight Engineers, Inc.

[3]- Mack, R. J., "*A Rapid Empirical Method for Estimating the Gross Takeoff Weight of a High Speed Civil Transport*", Technical Report NASA/TM-1999-209535, December 1999.

[4]- Bechdolt, R. W., et al, "Introduction to Aircraft Weight Engineering", S.A.W.E. Inc., 1996.

[5]- Agyepong, L., "Application of Neuro Fuzzy Systems to Aircraft Systems Weight Estimation", PhD thesis, University of Leeds, May 2012.

[6]- Raymer, D. P., "Aircraft Design: A Conceptual Approach", (4th Edition), AIAA, USA, 2006.

[7]- Torenbeek, E., "Synthesis of Subsonic Airplane Design", Delft University Press, 1982.

[8]- Roskam, J., "Airplane Design", Parts I-IIIV, DAR Corporation, Kansas, USA, 1985-2005.

[9]- Al-Shamma, O., & Ali, R., "Interactive aircraft design for undergraduate teaching", Royal Aeronautical Society Conference, Bristol, 17-19 July, 2012.

[10]- Civil Aviation Authority, "Joint Airworthiness Requests (JAR) – part 23".

[11]- Howe, D., "Aircraft conceptual design synthesis", Professional Engineering Publishing Ltd., UK, 2000.

[12]- Kroo, I., "Aircraft design: Synthesis and Analysis", Stanford University, USA, 1997-2001.

[13]- Nicolai, L. M., "Fundamentals of aircraft design", METS Inc., USA, 1984.

[14]- Harris, F., "An economic model of U.S. airline operating expenses", NASA/CR-2005-213476, 2005.

[15]- Kundu, A. K., "Aircraft design", Cambridge University Press, 2010.

[16]- Jane's All the World's Aircraft, Jane's Annual Publication, various years. See www.janes.com for list of publications.

[17]- http://en.wikipedia.org/wiki/Boeing_747

Aircraft System	747
Wing System	88,741
Tail System	11,958
Body System	68,452
Alighting Gear System	32,220
Nacelle System	10,830
Propulsion System (less Dry Engine)	9,605
Flight Controls System (less Auto Pilot)	6,886
Auxiliary Power Plant System	1,797
Instrument System	1,486
Hydraulic and Pneumatic Group	5,067
Electrical System	5,305
Avionics System (incl. Auto Pilot)	4,134
Furnishings and Equipment System	48,007
Air Conditioning System	3,634
Anti-icing System	413
Load and Handling System	228 -896**
Empty Weight (less Dry Engine)	297,867
Dry Engine Weight	35,700
Empty Weight (M.E.W.)	333,567
Takeoff Gross Weight	775,000

Fig. 1- Published component weights (in pounds) for Boeing 747-200B

```
@@@@@@@@@@@ Mass calculation @@@@@@@@@@@@@@@@@@@@
Wing includes flaps  (kg) =  42511.3
Fuselage             (kg) =  29318.2
Empennage            (kg) =   8512.1
Nacelles             (kg) =   5188.9
Engines              (kg) =  16852.6
Propulsion System    (kg) =  23212.1
Propulsion (total)   (kg) =  28400.9
Undercarriage        (kg) =  14035.8
Surface Controls     (kg) =   3306.5

Auxiliary power unit                 (kg) =    773.4
Paint & Oxygen system                (kg) =   2786.0
Electrical system                    (kg) =   2120.6
Avionics & Instruments (+ AutoPilot) (kg) =   2843.7
Air conditioning & Anti-icing system (kg) =   1986.6
Hydraulic system                     (kg) =   2908.5
Systems (Total)      (kg) =  13418.8

Furnishings          (kg) =  15515.3
Empty Mass           (kg) = 155018.9

Operation Items      (kg) =   8068.8
Crew mass            (kg) =    186.0
Flight attendants    (kg) =   1156.0
Op. empty mass       (kg) = 164429.8

Passsenger Load      (kg) =  64789.5
Zero Fuel mass       (kg) = 229219.3
Total Fuel           (kg) = 110000.0

Maximum TakeOff      (kg) = 339219.3
############################################
```

Fig.2- Calculated component weights for Boeing 747-200B

Aircraft Type	Published Data		Calculated Data		% Diff. OEW	% Diff. MTOW
	OEW	MTOW	OEW	MTOW		
A319 – 100	40800	75500	38918	74670	- 4.83	- 1.11
A321 - 200	48500	95510	46934	94879	- 3.34	- 0.67
A330 – 200	119600	238000	117101	232778	- 2.13	- 2.24
A330 – 300	124500	235000	118746	233636	- 4.85	- 0.58
A340 – 300	130200	276500	124116	275505	- 4.9	- 0.36
A380 – 800	276800	571000	264111	571645	- 4.8	+ 0.11
737 – 700	38147	70305	36664	70074	- 4.04	- 0.33
737 – 800	41145	79245	41294	80512	+ 0.36	+ 1.6
737 – 900ER	44676	79245	43277	85121	- 3.23	- 0.01
767 – 200ER	84280	179625	86626	181484	+ 2.78	+ 1.03
767 – 400ER	103145	204570	99113	199189	- 4.07	- 2.7
777 – 200ER	145015	297550	139771	290660	- 3.75	- 2.24
777 – 300ER	167830	351500	164944	345056	- 1.75	- 1.87

Table 1- New approach output for current Airbus and Boeing aircraft

Aircraft Component	Published Weight (kg)	Calculated Weight (kg)	Accuracy %
Wing	40252.6	42511.3	+ 5.61
Fuselage	31049.6	29318.2	- 5.9
Tail	5424.1	8512.1	+ 56.9
Nacelle Group	4912.5	5188.9	+ 5.6
Propulsion Group	4356.8	6359.5	+ 45.96
Engines	16193.4	16852.6	+ 4.07
Propulsion (total)	25462.7	28400.9	+ 11.54
Landing Gear	14614.9	14035.8	- 4.13
Surface Controls	3123.5	3306.5	+ 5.86
1- APU	815.1	774.4	- 5.3
2- Electrical System	2406.3	2120.6	- 13.44
3- Avionics + Instruments + Autopilot	2549.2	2843.7	+ 11.57
4- Hydraulic + Pneumatic Group	2298.4	2908.5	+ 26.54
5- Air Conditioning + Anti-Icing System	1835.7	1986.6	+ 8.22
6- Oxygen System + Paint	------	2786	
SYSTEMS (total)	------	13418.8	
Furnishings	21775.8	15515.3	- 40.35
EMPTY WEIGHT	151305	155018.9	+ 2.45
Operating Items	-------	8068.8	
Crew	-------	1342	
OPERATING EMPTY WEIGHT	-------	164429.8	
Payload	--------	64789.5	
Zero-Fuel Weight	-------	229219.3	
Fuel	110000	110000	
MTOW	351537.7	339219.3	- 3.63