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PARAMETRIC STUDY OF TRANSPORT AIRCRAFT SYTEMS FOR ESTIMATION OF ERJ-145ER COMPONENTS WEIGHTS

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Summary. *This paper presents a brief study for estimation of the ERJ-145ER components weights, that was developed based on the "Parametric Study of Transport Aircraft Systems Cost and Weight". Weight and technical data were collected, analyzed and used to develop for the weights statistical equations (WSE) for the 19 commercial aircraft. The use of these statistical database, added and adapted with the knowledge of the EMBRAER previous products, enabled the specific software development which uses part of this study on the preliminary calculation of the ERJ-145ER "fig. 01" design weights.*

Keywords: Statistical weight analysis, Weight estimated, Design weights.

1. Introduction

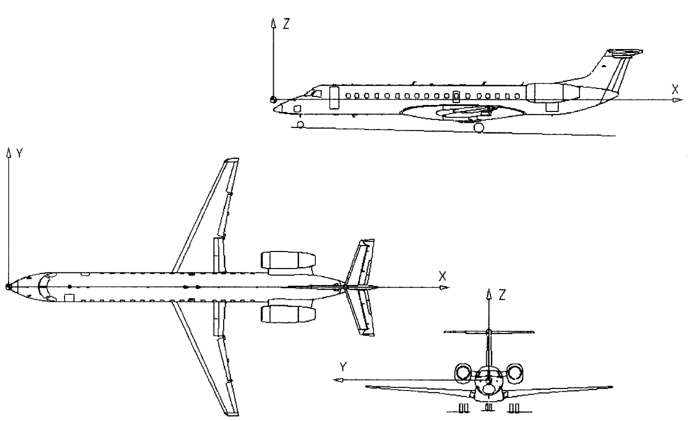

Fig.01-Airplane reference system (ERJ-145ER)

The estimation of the weight of an aircraft in the conceptual design phase is a critical part of the design process. At the beginning of the design, target weights are established for all the groups of structure and systems composing the aircraft. The weight must be strictly controlled during all the design evolution using the target weights as a "guide". The weight control is one of the most important tools for the success of an airplane and it is a matter of great concern in the aeronautical industry. In fact, lower structure and systems weights take to a payload increase, resulting directly in a more profitable aircraft.

In order to effectively implement the weight control, the weight groups needs to have a close interface with all the other engineering groups, since the conceptual until the serial production phase. Being so, it is required from the weight engineer to have a high background in aeronautical structures and systems, mechanical engineering, material and other disciplines.

There are two main levels of weight analysis. For the first level there is a methodology for a fast estimation of airplane component weights for a given Maximum take-off weight, MTOW (see table 01). They are used in conjunction with the first stage in the preliminary design process and are only suitable for “first-pass” analysis. This technique is useful for initial weight and balance calculations and can be used to check the results of the more detailed statistical methods.

For the 2nd level more sophisticated methods can also be used weight equations that allow they are based on a more detailed weight derivation of aircraft components and groups. These equations have a statistical basis associated to the many experience years. They allow the designer to account for fairly detailed configuration design parameters. To use these more sophisticated methods it is necessary to have a V-n diagram (Fig. 02 / 03), a preliminary structural arrangement and to have decided on all systems, which are needed for the operation of the airplane under study. This technique is sufficiently detailed to provide credible estimate of the weights of each major component group. Those weights are usually grouped as defined by MIL-STD-1374A; However by the use of the manufacturer practice, some small variations are accepted. A typical summary format appears in table 02, where the equipped empty weight (EEW) is considered as being composed of three major groups (structure, power plant and general systems).

The weight estimating equations can be used for conceptual studies where approximated weight estimates are required, but where limited design data are available. These weight estimating equations can also be used as the basis for determining the weights required for the airframe cost estimates, through the use of the cost estimating relationships (NASA, Raymer).

The AMPR (Aeronautical Manufacturers Planning Report) weight is as important tool for cost estimation, and can be understood as the weight of the parts of the aircraft really manufactured (structure and general installation) not including only the purchased items. In accordance with MIL-STD-1374A, the AMPR weight is equal to the EEW less the weights of the avionics, air conditioning, auxiliary power unit, batteries, brakes, cooling fluids, electrical power supplies/converters, engines, instruments, starters, tires and wheels.

Table 01 – Approximate transport aviation empty weight buildup (Raymer, Roskam)

Item	**Factor**	**Multiply by (a)**	**Approximate location**
Wing (c)	40 – 50 [kg/m^2]	Wing area (b)	35 - 40% MAC
Horizontal Tail (c)	18 - 27 [kg/m^2]	H. Tail area (b)	40% MAC
Vertical Tail (c)	22 - 27 [kg/m^2]	V. Tail area (b)	40% MAC
Fuselage (c)	15 - 25 [kg/m^2]	Wetted area (b)	45 - 50% (f)
Landing Gear group	3.5 - 4.5%	MTOW	---
Installed engine (d)	1.30 - 1.50	Dry engine weight	---
Missing items (e)	30 - 35%	MTOW	40-50% (f)

Notes

(a) Results are in kg
(b) Exposed plan form [m^2]
(c) Structure part only
(d) Including Nacelles, thrust reverses and engines equipped.
(e) For the remaining items of the EEW
(f) Fuselage length

Table 02 - Summary of typical components Weight list

Main Groups	
1- Structure	**3- General Systems**
Wing	Flight Controls
Tail Group	Hydraulics
Body	Electrical
Alighting Gear	Pneumatic
Nacelle	Air Conditioning
	Auxiliary Power
2- Power plant	Anti-Icing
	Furnishings and Equipment
Engines	Instruments
Fan Thrust Reverser	Avionics
Engine Exhaust Reverses and Nozzles	Loading and handling
Fuel System	
Engine Systems	
Total: Equipped Empty Weight (EEW)	

Flight Maneuver and Gust conditions

The V-n diagrams are used to determine the design limit and the design ultimate load factors as well as the design airspeeds for which the aircraft structure is designed. The use of the statistical weight analysis will be illustrated in the example applicable directly to the wing of the ERJ-145ER.

The referred diagrams are simplified versions of those ones defined in accordance with FAR 25.333 until 25.341 “fig. 02 and 03”.

2. DETAILED STATISCAL WEIGHT ANALYSIS

A preliminary estimation for MTOW was obtained during the conceptual design phase in accordance with the description in the table 01, associated to the statistical weight analysis that commented in the next paragraphs. A more refined estimation is obtained through the use of statistical equations derived from sophisticated regression analysis from the references.

The development of these equations represents a major effort and normally the manufacturer develops, modifies or adapts the equations in accordance with its our design requirements.

To acquire an statistical database for these equations “Eq. 01”, detailed group weight statements for several airplane were obtained from the references, from EMBRAER products, aeronautical magazines and other publications about the referred subject “fig. 04”.

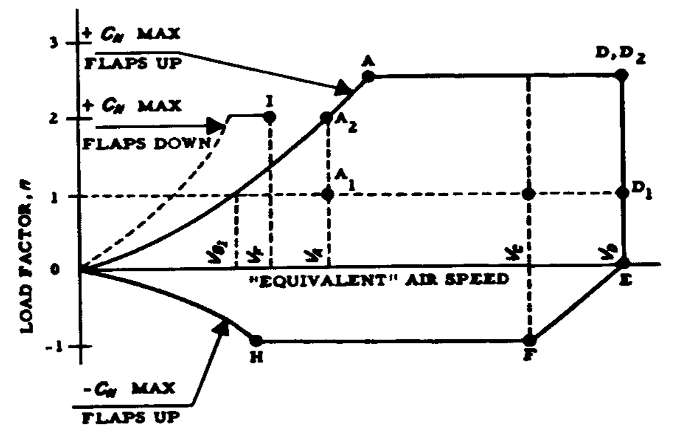

Fig. 02 - Maneuvering envelope

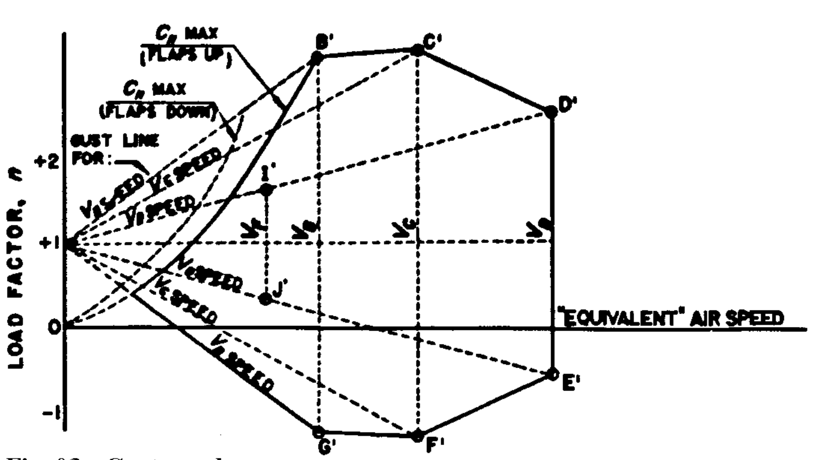

Fig. 03 - Gust envelope

The method presented herein has an iterative procedure (Roskam). Almost all the airplane component weights are a function of the MTOW and are derived based on it.

Being so, any changes affecting the MTOW will affect the weight of the components and vice-versa.

The following step-by-step procedure, used to estimate the weight of the aircraft components that will be added to the obtain the EEW equipped empty weight, EEW.

The recommended procedure is:

1. Input all aircraft characteristics, design parameters and weights already known. This information are obtained from the mission requirements and category that better represents the airplane (see table 03).
2. To adjusted mission fuel.
3. Compute the limit maneuvering load factors (n_{man}) and gust loads (n_{gust}).
4. Compute all aircraft components for which the weights will have to be estimated (see table 02) and obtain the estimated EEW.
5. Determine the Zero Fuel Weight (ZFW) and the MTOW.

6. Use this new estimate for MTOW to repeat the iterate process from steps 3 to 6 until the input and output MTOW values have a difference of less than 0.1%
7. MTOW estimated (= EEW + Operations Items + Payload + Fuel).

Since the payload and design mission are know, the fuel weight is also know and the take-off weight will be obtained by the sum of the all main groups composing the EEW, the operation items, the payload and the mission fuel.

If the equipped empty weight is higher than expected, the fuel to complete the mission will be reduced. This must be corrected by adjusting and optimizing the aircraft as described in Raymer and Roskam, not by simply increasing fuel weight for the designed condition.

In the following section it will be show an example related to the derivation of the basic wing structure weight in order to method demonstrate the method, by the use of this important and representative aircraft component.

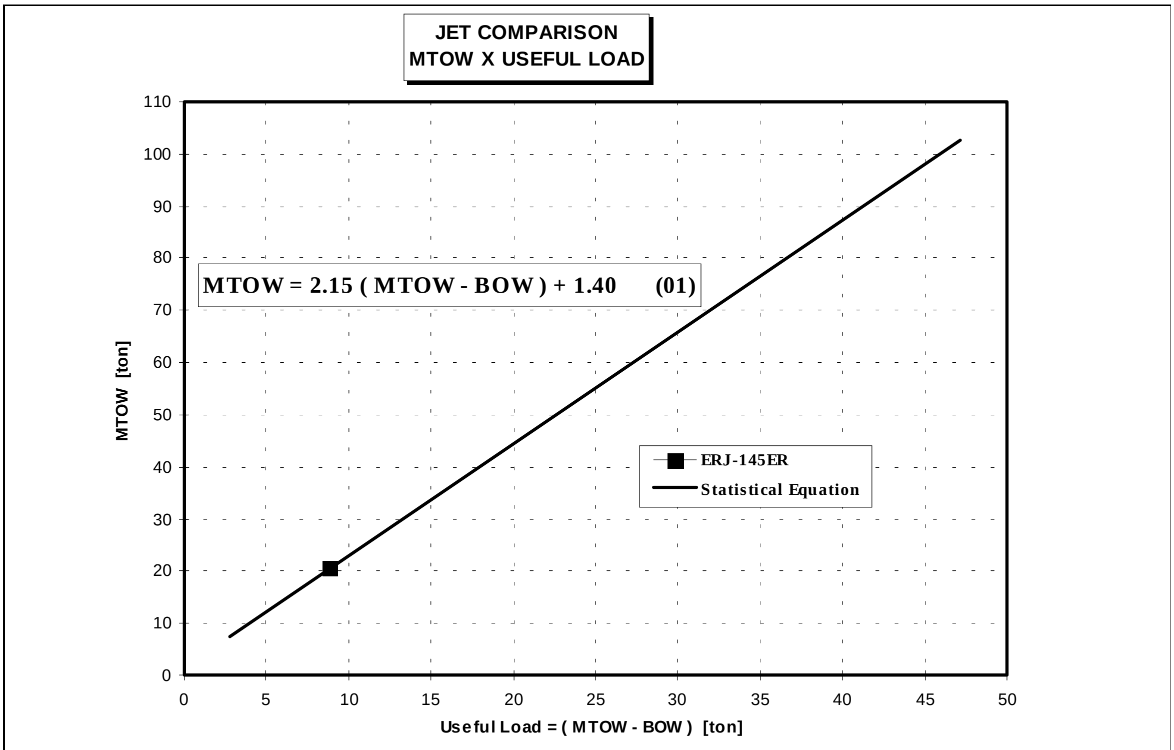

Fig. 04 - Statistical of Jet Comparison

Weight statistical equation (WSE)

Wing:

The symbols used in the weight estimating method are:

AR	-	Aspect ratio (W_{span}^2 / S_w)
I_w	-	Bending material weight index
S_w	-	Wing Area [m^2]
TOGW	-	Takeoff Gross Weight [kg]
t/c	-	Average wing thickness to chord ratio
U	-	Ultimate load factor
ZFW	-	Zero Fuel Weight [kg]

W_{span}	-	Wing span [m]
W/S	-	Wing loading [kg / m^2]
λ	-	Wing taper ratio (chord tip / chord root)
$\Omega_{c/4}$	-	Sweep angle of quarter chord [degrees]
WCF	-	Wing Correction Factor (Corrective factor depending of the EMBRAER know-how)

The wing weight is sensitive to several wing design parameters and geometric characteristics. It has been shown that these variables can be combined into a wing design equation as presented bellow (NASA).

$$I_w = \frac{U\,(AR)^{1.5}\,(ZFW/TOGW)^{0.5}\,(1+2\lambda)\,(W/S)\,Sw^{1.5}}{(t/c)\,(\cos\Omega_{c/4})^{2}\,(1+\lambda)} \qquad (02)$$

For small aircraft (S_w< 84 m^2 and passengers numbers lower than 100) the statistical wing weight formula used was:

$$W_w = (13.911\ I_w + 2.783\ S_w)\ WCF \qquad [kg] \qquad (03)$$

The index I_w is related to the wing box structure "fig. 05".weight; the higher the index, the higher the wing box structure weight required. The remaining of the wing weight, i.e., the secondary structure weight, is related to the wing area (S_w).

In contrast to medium and large airplane, I_w is considerably more important than S_w for predicting the weight of small aircraft. This is possibly the result of less sophisticated control surfaces and lighter secondary structure. The WSE are valid only for transport aircraft, which are similar in design to those which were used in the formulation of the WSE (NASA).

Because the calculation to determine the I_w is more complex, an alternative equation were developed by EMBRAER weight group to determine quickly the wing weight, as function only of the wing area. The alternative equation is:

$$W_w = S_w\ (0.15\ S_w + 35) \qquad [10^3\ kg] \qquad (04)$$

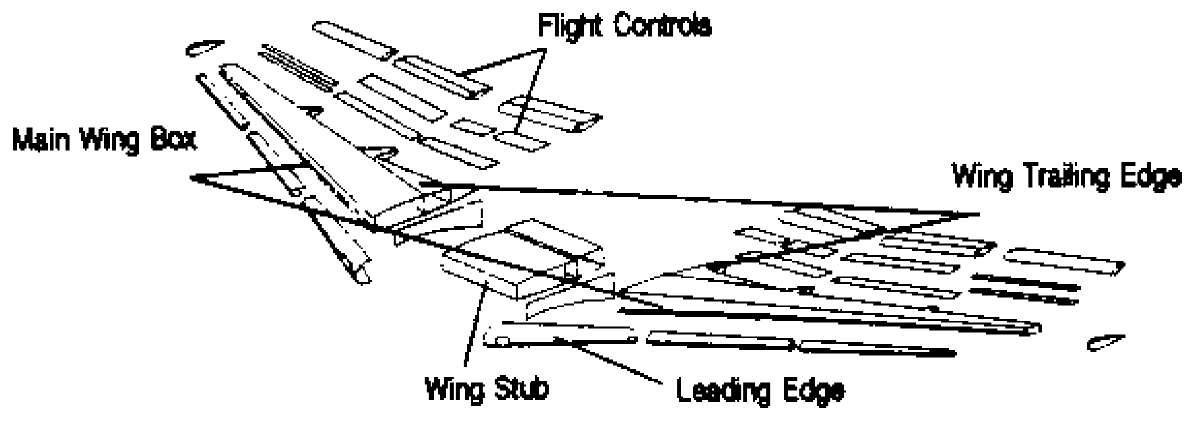

Fig. 05 - ERJ-145ER, Wing structure breakdown

Table 03 – ERJ-145ER, Characteristics and design parameters

ACF.....AIRCRAFT....(1=SMALL, 2=MEDIUM AND LARGE)...........	1.0000
TOGW....TAKEOFF GROSS WEIGHT..............................KG	0.0000
ZFW.....ZERO FUEL WEIGHT..................................KG	0.0000
EEWA....OPERATION EMPTY WEIGHT............................KG	0.0000
PLW.....PAYLOAD WEIGHT....................................KG	5000.0000
OPIT....OPERATING WEIGHT..................................KG	600.0000
WENG....DRY ENGINE..KG	730.0000
WCREW...CREWMEMBER WEIGHT............................KG/CREW	88.5000
WAH.....STEWARDESS WEIGHT..............................KG/AH	68.0000
WPAX....WEIGHT PER PAX................................KG/PAX	100.0000
NOQ.....NORMAL OIL QUANTITY...............................KG	24.0000
PSE.....PASS SERV EQUIP INCLUD WASHING POTAB WATER ETC....KG	0.0000
WDEM....DEMOUNTABLE WEIGHT OF POWER PLANT.............KG/ENG	0.0000
TR......ENGINE THRUST ....LB/ENG	7040.0000
GL......TOTAL FUEL VOLUME..................................L	5146.0000
HFEET...ALTITUDE..FT	20000.0000
XMC.....MACH NUMBER (20.000 FT) OR SEA LEVEL................	0.7800
VB......MAX. GUST INTENSITY SPEED........................M/S	131.2000
VCEMS...MAX. DESIGN CRUISE SPEED EQUIVALENT..............M/S	164.6000
VDMS....DESIGN DIVE SPEE.................................M/S	192.9000
NP......NUMBER OF PAX.......................................	50.0000
NENG... NUMBER OF ENGINE....................................	2.0000
NCREW...NUMBER CREWMEMBER...................................	2.0000
NAH.....NUMBER STEWARDESS...................................	1.0000
LFUS....FUSELAGE STRUCTURAL LENGTH.........................M	27.9300
DFUS....FUSELAGE STRUCTURAL DEPTH..........................M	2.2800
WING....ALTERNATIVE EQUATION Y(1), N(0).....................	1.0000
SW......WING AREA..M^2	51.1800
WGS.....WING SPAN..M	19.9700
LAMB....TAPER RATIO(TIP CHORD/ROOT CHORD)...................	0.2543
TC......AVERAGE THICKNESS TO CHORD RATIO....................	0.1200
OMM2....SWEEP ANGLE OF MID-CHORD LINE....................DEG	18.9100
OMQ4....SWEEP ANGLE OF QUARTER CHORD.....................DEG	22.7300
SCS.....AREA CONTROL SURFACE..(>0) SIMPLE EQUATION........ M^2	19.4800
SCSW....CONTROL SURFACE AREA (WING-MOUNTED)............... M^2	10.3600
TAIL....(1=CONVENTIONAL TAIL, 2='T' TAIL)...................	2.0000
SH......GROSS HORIZONTAL TAIL AREA....................... M^2	11.2000
SV......EXPOSED VERTICAL TAIL AREA .... M^2	7.2000
NLT.....NACELLE LENGTH.....................................M	4.3330
DF......DIAMETER OF FAN....................................M	1.2875
LI......LENGTH LIP TO ENGINE FRONT FACE....................M	0.7350
LF......LENGTH OF FAN......................................M	2.1560
LFEX....LENGTH OF FAN EXHAUST DUCTING (DUCTS+COWL).........M	0.0000
DC......DIAMETER COWL......................................M	0.0000
LC......CORE LENGTH ....M	0.0000
DT......DIAMETER TURBINE EXHAUST...........................M	1.0800
LPEX....LENGTH PRIMARY EXHAUST NOZZLE......................M	1.0833
BPR.....ENGINE BY-PASS RATIO................................	5.0000
FETR....FAN EXH. CASC. TR. REV. TRANS SLEEVE.......(1)Y,(0)N	0.0000
SDUCT...FOR TAIL MOUNTED NACELLE S DUCT YES(1) NOT(2).......	2.0000
TEXH....EXHAUST......SHORT DUCT NACELLE(1),LONG DUCT(2).....	2.0000
NFT.....NUMBER FUEL TANKS...................................	2.0000
NW......NACELLE WIDTH......................................M	1.5319
SN......NACELLE WETTED AREA.............................. M^2	28.8535
SPY.....AREA OF PYLON.................................... M^2	1.9400
LPY.....LENGTH OF PYLON (FUSEL - NACELLE)..................M	0.4270
HPY.....HEIGTH (THICKNESS) OF PYLON........................M	0.3660
LFTR....LENGTH FROM THRUST REVERSER........................M	0.0000
TRENC...FAN CAS(2),TG(3),TG+SEP(4),TG+MIX(5),SH DT W/TR(6)..	4.0000
FCHS....SINGLE(1) AND MULTI(2) HIDRAULIC SYSTEM.............	2.0000
AI......NAC(1),WG.NC.TF(2),WG.TF.TAIL(3),FL.TL(4),WG+TL(5)..	4.0000
AUTO....(0)WITHOUT AUTO THROTTLE,(1)WITH A. THROTTLE........	1.0000
CAT.....GEN(1),II DOM(2),II OVERW(3),III DOM(4),III OV(5)...	2.0000
LPRTI...LOW PRESSURE TIRES (0)NOT (1)YES....................	0.0000
FSISS...EACH FOOT/SECOND INCREASE IN SINK SPEED.............	0.0000
KPPID...KNEELING PRE-POSIT INFL/DEFL REQUIR (0)NOT (1)YES...	0.0000
CBRAK...CARBON BRAKES (0)NOT (1)YES.......................	1.0000
KNG.....=1.017 FOR PYLON-MOUNTED NACELLE;=1.0 OTHERWISE.....	1.0170
KP......=1.40 FOR ENGINE WITH PROPELLER;=1.0 OTHERWISE......	1.0000
KTR.....=1.18 JET WITH THRUST REVERSER;=1.0 OTHERWISE.......	1.1800
SF......FUSELAGE WETTED AREA.............................M^2	175.1501
MLBC....MAXIMUM LOADING OF THE BAGGAGE COMPARTMENT........KG	1200.0000
MAC.....MEAN AERODYNAMIC CHORD.............................M	2.8650

3. RESULTS AND DISCUSSION

An example of statistical formula application is showed bellow; it was used as parameter for the weight evaluation "fig.06". The weight of the wing structure is normally determined from historical values using for the weight per square meter of exposed plan form area (see table 01). But due to the high discrepancy between actual weight and the weight obtained by this approximate form of analysis (± 8%), the statistical equations must be used to guarantee the best result and not compromise the design weights, payload and performance.

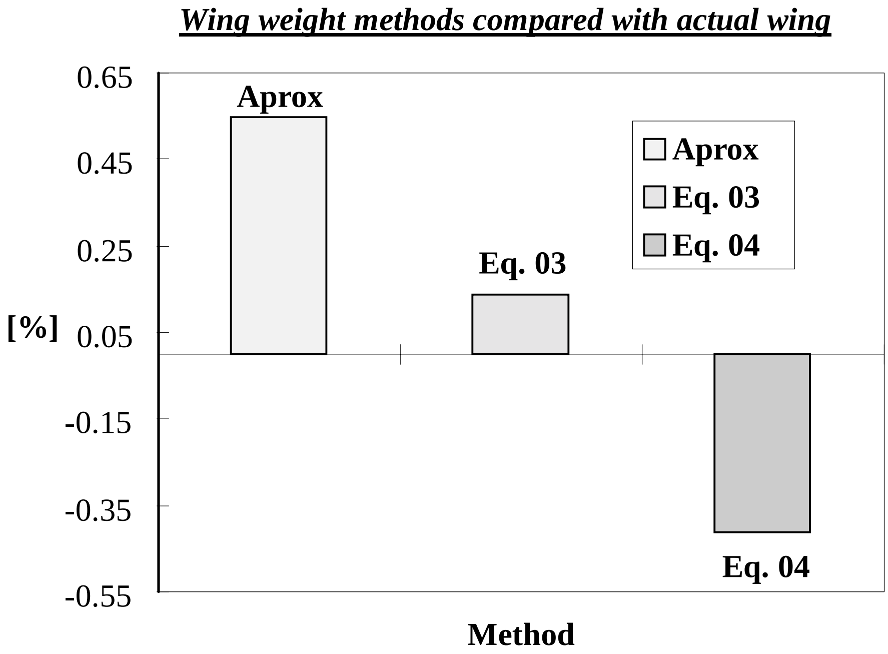

Fig.06 - ERJ-145ER, Wing weight methods comparison.

In table 04 are presents the results of raw material percentage and technology utilized on the wing assembly of ERJ-145ER.

Table 04 - Wing structure raw material percentage and technology utilized.

Material	**Total [%]**	Sheet	Chemical milling	Mechanical machined	Composite	Sealing	Others
Aluminum	**74.5**	3.1	8.1	63.3	---	---	---
Steel	**1.2**	---	---	0.1	---	---	1.1
Titanium	**1.3**	0.1	---	1.1	---	---	0.1
Composite	**12.0**	---	---	---	12.0	---	---
Sealing	**4.5**	---	---	---	---	4.5	---
Lead & Others	**6.5**	---	---	---	---	---	6.5
Total [%]	**100.0**	**3.2**	**8.1**	**64.5**	**12.0**	**4.5**	**7.7**

These equations are based upon the EMBRAER know how, on a database of existing aircraft as well as on the information and references mentioned. We have seen that the use of the statistical equations depends on many factors such as: configuration, technology used (state of the art) philosophy of the general systems principally

If the equipped empty weight was higher than expected, the fuel to complete the mission will be reduced. This must be corrected by adjusting and optimizing the aircraft as described in Raymer, Roskam and Torenbeek.

4. CONCLUDING REMARKS

The purpose of this paper is not to innovate, but to discuss the development of the weight estimation software using methods and references already used and also to show that anyone of the weight area, with access to a personal computer, can easily solve and estimate numerically the preliminary empty weight of an aircraft, in accordance with the existing categories (transport, military etc.).

The actual weight measurement involving all aircraft parts (EEW) often gives the most reliable information about the accuracy of the statistical process. Excellent values had been found: the wing weight derived using the statistical process was only 0.13% higher than actual wing weight used as example. In addition, the actual EEW obtained for the ERJ-145ER aircraft by the use of the methods enclosed 0.43% lower than the expected target weight, which is an excellent result when compared to other aircraft in the world.

However, there are many designs (novel configuration) and technology features which were not common to the majority of the airplanes data base, resulting in a poor weights estimate when using these or similar equations without this “new increment”. To allow for the prediction of those particularities, it is necessary a weight factor adjust, in such away the statistical equations need to aggregate the “fudge factors” (Raymer), that are company know how.

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