19.5.1 Trade Study Categories

In Table 19.1 Raymer refers to the growth sensitivities to dead weight, i.e. weight that does not contribute to aircraft design or performance. If dead weight is added and the same aircraft performance (such as takeoff and landing distance) must be maintained, most of the aircraft (such as wing, landing gear, and empennage, and possibly fuselage weight if payload is added) must increase in size and weight. The ratio of the increase in MTOGW to the unit increase in fixed weight is called the aircraft weight growth factor, and depends on the mission flown. There are two methods of calculating weight growth factors: the "exact" method which can be used on designs which are still in the preliminary design stage, and the simplified method, which can be used on existing designs (although it is, of course, too late to actually change the design).

Exact Method of Calculating Weight Growth Factor

The exact method of calculating weight growth factor is to use a detailed mission sizing computer program with detailed component weight estimation equations. Methods are described in this chapter, using weight equations such as those in Chapter 15.

Simplified Method of Calculating Weight Growth Factor

To use the simplified method, an important assumption must be made. That is that empty weights can be broken down into two categories. The first category is proportional to MTOGW, and the second category is independent of MTOGW. This assumption is fairly close to reality. It enables the derivation of a simple equation to determine what the growth factor would have been for an existing aircraft. There is no need to calculate empty weights or to simulate a mission. This equation can be derived using two approaches. The first is an algebraic approach, and the second is a graphical approach, which may be more intuitive. In both cases a small arbitrary weight W_x is added to the baseline configuration, and the aircraft is resized to accommodate the addition of the arbitrary weight. In the resizing it is assumed that the aircraft takeoff and landing performance is unchanged, which implies that the values of airplane thrust/weight (T/W) and wing loading (W/S) remain constant. To the first order, propulsion system weight is assumed proportional to thrust, and thus to MTOGW. Similarly, wing weight is assumed proportional to wing area, and is therefore also proportional to MTOGW. The empennage sizes roughly with the wing dimensions, so its weight is also proportional to MTOGW.

Algebraic Approach

The following method is taken from Ref. 19.5.1.1. For commercial aircraft the MTOGW can be broken down into five categories:

$W_{e_{var}}$ = Variable empty weight proportional to MTOGW (eg, landing gear, wing, etc)

$W_{e_{payload}}$ = Empty weight proportional to payload (eg, cabin crew, seats, toilets)

$W_{e_{fixed}}$ = Fixed weight (flight deck crew, flight deck, avionics)

$W_{payload}$ = Payload weight

W_{fuel} = Fuel weight

For a Boeing 707-320B (weights are in lb and are approximate)

$$\begin{aligned} W_{TO} &= W_{e_{Var}} + W_{e_{payload}} + W_{e_{fixed}} + W_{payload} + W_{fuel} \\ &= 98{,}000 + 7{,}000 + 43{,}000 + 35{,}000 + 153{,}000 \\ &= 336{,}000 \end{aligned} \tag{19.5.1.1}$$

The numerical values above were determined by the author of Ref. 19.5.1.1. Weight growth factors are normally based on a fixed payload, unless the weight growth is being calculated specifically for payload weight growth, in which case fuselage weight will be included in variable weights.

From the Breguet range equation we know that for a constant range

$$ln\left(\frac{W_{TO}}{W_{LDG}}\right) = \text{constant so } \frac{W_{TO}}{W_{LDG}} = \text{constant} \tag{19.5.1.2}$$

$$\text{So } \left(\frac{W_{TO}}{W_{TO} - W_{fuel}}\right) = \left(\frac{1}{1 - \frac{W_{fuel}}{W_{TO}}}\right) = \text{constant} \tag{19.5.1.3}$$

$$\text{So } \frac{W_{fuel}}{W_{TO}} = \text{constant} \tag{19.5.1.4}$$

If we designate the original MTOGW with the suffix 1 and the MTOGW of the configuration with the extra weight, W_x, with the suffix 2, then

$$W_{TO_1} = W_{e_{var}} + W_{e_{payload}} + W_{e_{fixed}} + W_{payload} + W_{fuel} \tag{19.5.1.5}$$

$$W_{TO_2} = W_{e_{var}}\left(\frac{W_{TO_2}}{W_{TO_1}}\right) + W_{e_{payload}} + W_{e_{fixed}} + W_{payload} + W_{fuel}\left(\frac{W_{TO_2}}{W_{TO_1}}\right) + W_x \tag{19.5.1.6}$$

We define the total growth in MTOGW as

$$\Delta W_{TO} = W_{TO_2} - W_{TO_1} \tag{19.5.1.7}$$

Subtracting Eq. (19.5.1.6) from Eq. (19.5.1.5) we get

$$\Delta W_{TO} = W_{e_{var}}\left(\frac{W_{TO_2}}{W_{TO_1}} - 1\right) + W_{fuel}\left(\frac{W_{TO_2}}{W_{TO_1}} - 1\right) + W_x$$
$$= W_{e_{var}}\left(\frac{\Delta W_{TO}}{W_{TO_1}}\right) + W_{fuel}\left(\frac{\Delta W_{TO}}{W_{TO_1}}\right) + W_x \qquad (19.5.1.8)$$

Rearranging terms we get

$$\Delta W_{TO}\left(1 - \frac{W_{e_{var}}}{W_{TO_1}} - \frac{W_{fuel}}{W_{TO_1}}\right) = W_x \qquad (19.5.1.9)$$

By definition, the growth factor is

$$\boxed{\frac{\Delta W_{TO}}{W_x} = \frac{1}{1 - \frac{W_{e_{var}}}{W_{TO_1}} - \frac{W_{fuel}}{W_{TO_1}}} = \frac{1}{\left(1 - \frac{W_{fuel}}{W_{TO_1}}\right) - \frac{W_{e_{var}}}{W_{TO_1}}}} \qquad (19.5.1.10)$$

The reason for re-ordering the terms in the denominator will become apparent later.

Plugging in the numbers for the example Boeing 707 we get

$$\text{Growth factor} = \frac{1}{1 - \frac{153{,}000}{336{,}000} - \frac{98{,}000}{336{,}000}}$$
$$= 4.0 \qquad (19.5.1.11)$$

Note that the smaller the fuel fraction, $\frac{W_{fuel}}{W_{TO}}$, or the ratio of variable empty weight to TOGW, $\frac{W_{e_{var}}}{W_{TO}}$, the smaller the growth factor. This suggests that for short range airplanes the application of advanced weight-saving technology does not offer such a large payoff as for long range airplanes.

For aircraft with very small payload and crew fractions and large fuel fractions, such as the National AeroSpace Plane (NASP), the denominator is small and the growth factor becomes very large. For this class of airplane, very small changes in structural fraction or fuel fraction have a very large effect on MTOGW. It is almost impossible to estimate MTOGW with any level of confidence.

Graphical Approach

The second approach is based on analysis of airplane sizing and sensitivity described in Ref. 19.5.1.2. Figure 19.5.1.1 shows the empty weight of an aircraft as a function of MTOGW. As for the algebraic method, airplane empty weight is be broken down into two parts - one part is proportional to TOGW, and the other part is constant.

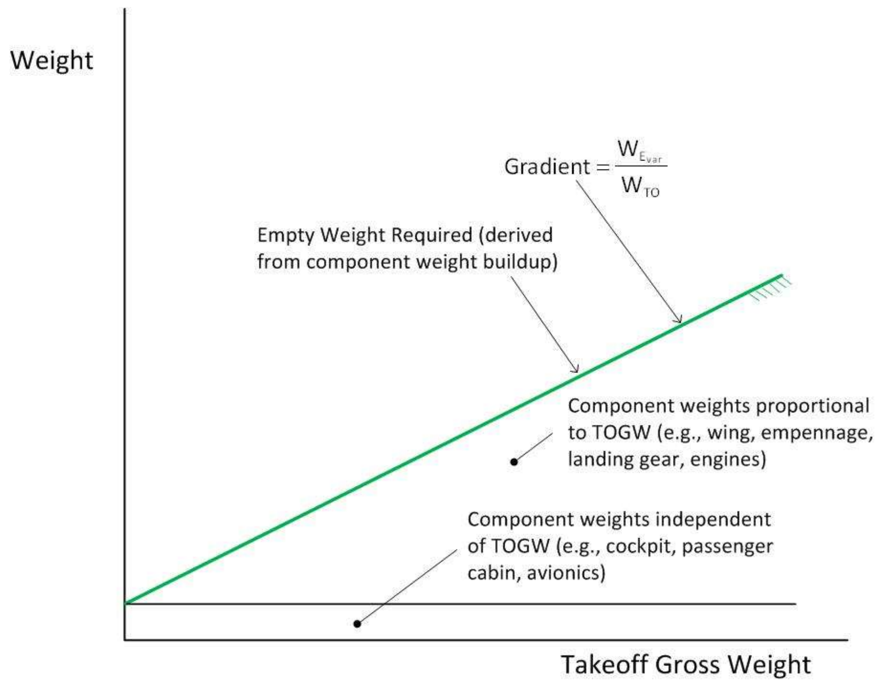

Figure 19.5.1.1 Empty Weight Required as a Function of Takeoff Gross Weight

In order to design an airplane to meet a required mission, the empty weight required must be equal to the empty weight available when the airplane is flown on the design mission, all the fuel (including reserves) is burned, and crew and payload then removed, as illustrated in Figure 19.5.1.2. Depending on how weights are allocated, crew may be considered as part of empty weight required; the weight of the converged solution does not change. Often for military aircraft the crew is not considered part of the empty weight required, but for commercial aircraft the crew is part of the operating empty weight. The gradient of the empty weight available line is the same as that of the zero-fuel line.

Figure 19.5.1.3 shows a matching point between empty weight required and empty weight available. In the conceptual design process, a computer program is available to the designer which calculates the empty weight required based on component weight buildup, and calculates empty weight available by "flying" the airplane on a the design mission. The intersection of the two empty weight lines is found by iteration.

The figures show the procedure for finding the TOGW of a configuration that meets the mission requirement. For our situation, the airplane has already been sized. In fact it's already flying, so we can go straight to the solution point. To calculate the weight growth factor, the intersection point may be examined in more detail, and the arbitrary weight W_x may be added graphically to the empty weight required line.

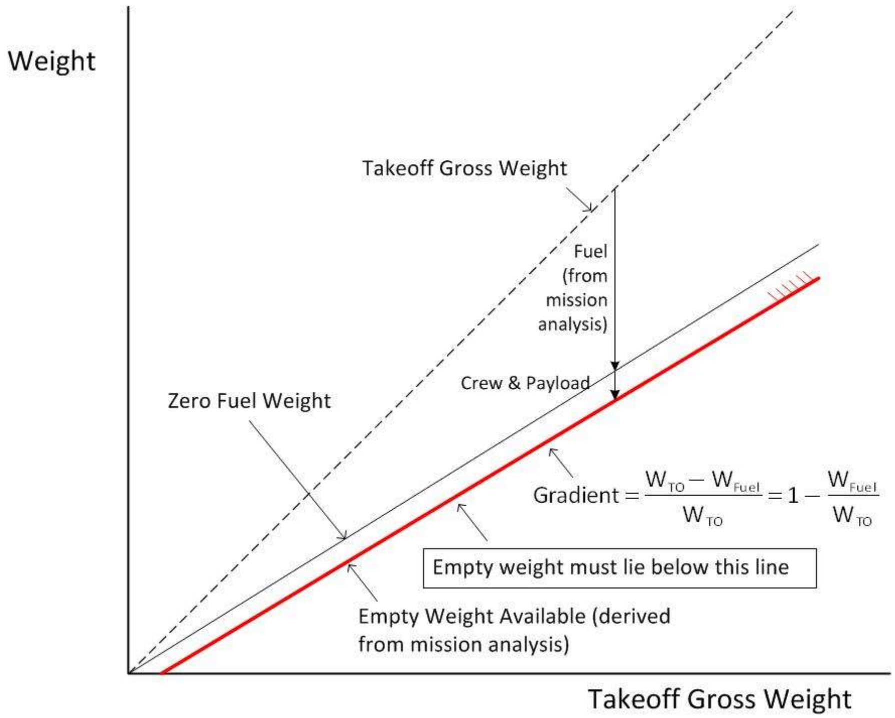

Figure 19.5.1.2. Empty Weight Available from Mission Analysis

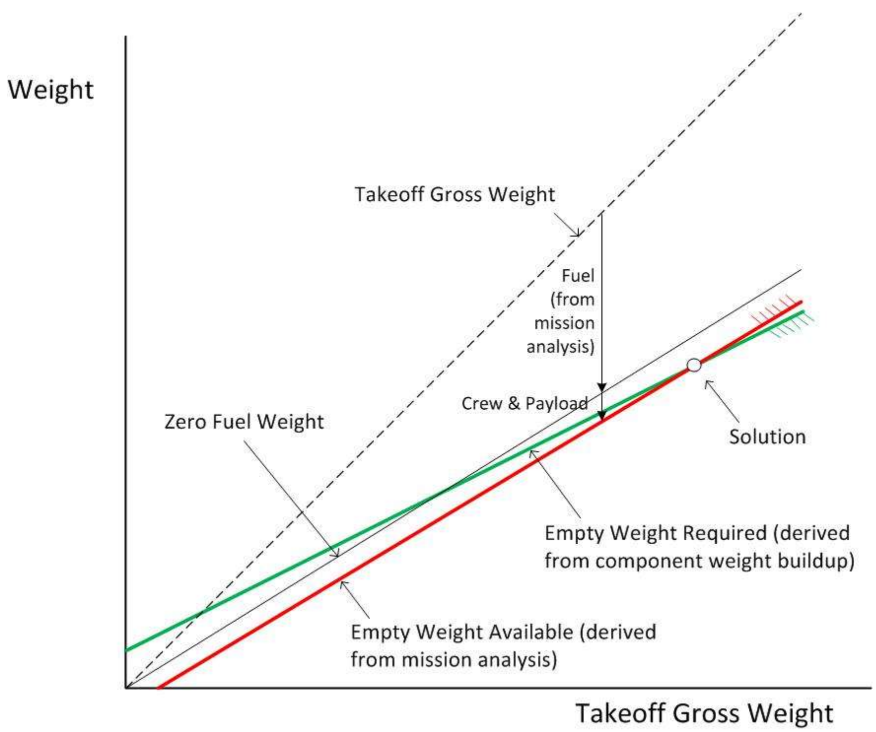

Figure 19.5.1.3 Finding a Match between Empty Weight Required and Empty Weight Available

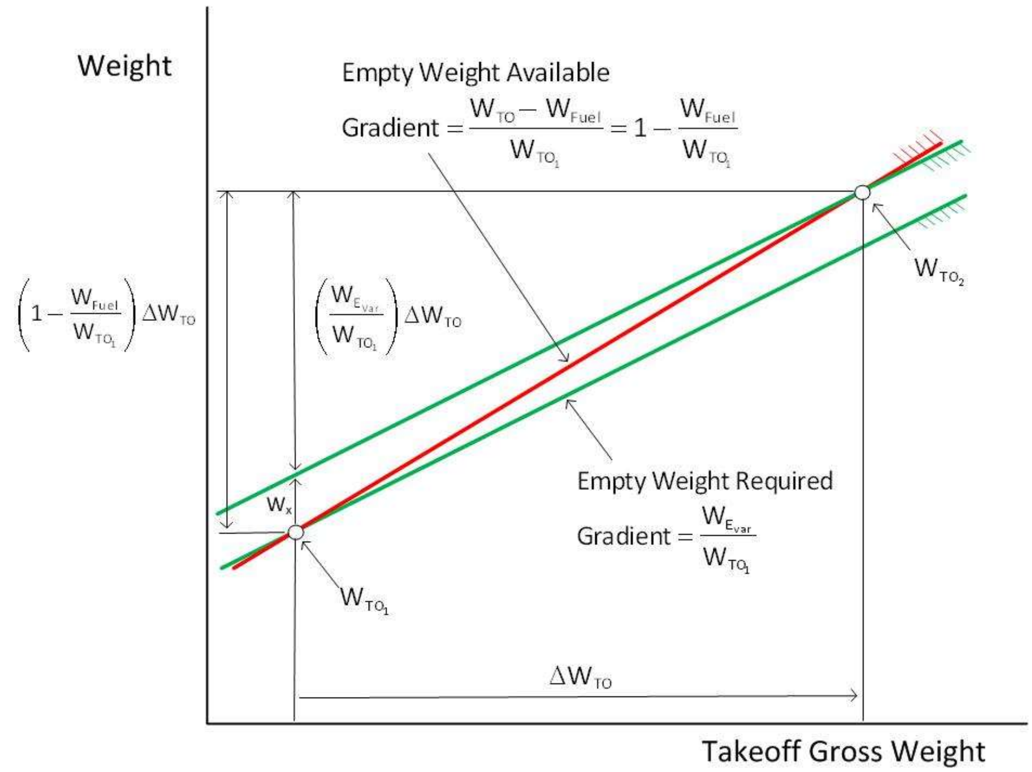

Figure 19.5.1.4 Adding an Arbitrary Weight W_x

This is illustrated in Figure 19.5.1.4. The initial solution is located at W_{TO_1}. The addition of the weight W_x moves the solution to W_{TO_2}. An examination of the increase in empty weight (i.e., vertical component of the displacement of the solution) shows that

$$W_x = \left(1 - \frac{W_{fuel}}{W_{TO_1}}\right)\Delta W_{TO} - \left(\frac{W_{e_{var}}}{W_{TO_1}}\right)\Delta W_{TO} \qquad (19.5.1.12)$$

Rearranging:

$$\frac{W_x}{\Delta W_{TO}} = \left(1 - \frac{W_{fuel}}{W_{TO_1}}\right) - \frac{W_{E_{var}}}{W_{TO_1}} \qquad (19.5.1.13)$$

And inverting:

$$\boxed{\frac{\Delta W_{TO}}{W_x} = \frac{1}{\left(1 - \frac{W_{fuel}}{W_{TO_1}}\right) - \frac{W_{e_{var}}}{W_{TO_1}}}}$$

This is the same as Equation 19.5.1.10 above.

Examples

This equation can be used to estimate the weight growth factors for different classes of aircraft by examining the weight breakdown of existing aircraft. In the example above for the Boeing 707-320B, empty weights were allocated by the author of Ref. 19.5.1.1 as fixed or variable. Note that in the table below, weights are for the Boeing 707-320C, for which weights are different. The -320B has a range of 5,000 nmi, whereas the -320C has a range of 2,900 nmi. It is possible allocate weights for other aircraft, as illustrated in Table 19.5.1.1. Weights were taken from Refs. 19.5.1.3 and 19.5.1.4, with minor modification. The payloads shown here are estimated design payloads, which are somewhere between the maximum payload and payload at maximum fuel capacity, but often hard to find in references. For the most part group weights were used in the calculation, but for the Fixed Equipment Group, the definition of "Fixed" is not the same as for calculating weight growth factors. Within the Fixed Equipment Group, weights were allocated to the fixed or variable categories based on knowledge of typical component growth. To some extent, component growth is a function of the type of design so this allocation may not be appropriate for every design.

Aircraft Type	F or	Douglas DC-9-30	Cessna 150	Lockheed C-5A	de Havilland DHC-7	Cessna 310C	McDonnell F-15C	Boeing 747-100	Boeing 707-320C	Boeing Condor	Lockheed U-2	Lockheed SR-71
Wing Group	V	11,400	216	100,015	4,888	453	3,642	86,402	32,255	2,519	2,034	14,054
Empennage Group	V	2,780	36	12,461	1,318	118	1,104	11,850	6,165	253	320	1,503
Fuselage Group	F	11,160	231	118,193	2,580	319	6,245	71,845	26,937	823	1,410	6,911
Nacelle Group	V	1,430	22	9,528	1,841	139	0	10,031	4,183		0	1,068
Landing Gear Group	V	4,170	104	38,353	1,732	263	1,393	31,427	12,737	243	263	3,486
Power Plant Group	V	8,250	267	40,575	4,701	1,250	9,205	43,696	24,076	2,189	2,866	21,653
Avionics and Instruments	F	1,450	3	3,823	850	46	151	1,909	515	530	57	372
Surface Controls	V	1,620	31	7,404	710	66	810	6,982	3,052	295	362	1,682
Hydraulic System	V	480		4,086	493		433	4,471	1,086		66	1,222
Pneumatic System	V	280										
Electrical System	F	1,330	34	3,503	1,651	121	607	3,348	4,179	319	290	898
Electronics	F			992			1,787	4,429	2,338		166	1,427
Armament	F						627					
Oxygen System	F	150		308	0							75
Air Con Systems	F	1,120		3,416	550	46	685	3,969	3,608		135	
Anti-Ice System	V	480	1	229	176					157		1,325
Furnishings	F	8,450	33	19,272	2,862	154	294	36,824	9,527		82	520
Auxiliary Gear	F			29		65	119			550	193	200
Photographic	F						24					
Ballast	F						221					
APU	F	820		987				1,130	836			
Paint	F				150							
Operating Items	V	2,700										
Fixed Equipment Group		18,880	102	44,049	7,442	498	5,758	63,062	25,141	1,851	30,135	7,721
Fuel (= W_0 - W_E - W_{PL})		26,355	124	205,826	9,998	604	7,482	271,687	142,106	11,401	8,238	79,729
Oil and Trapped Fuel										221		644
Payload		23,575	398	200,000	9,500	1,186	2,571	120,000	60,000	1,500	518	3,981
Design Gross Weight		108,000	1,500	769,000	44,000	4,830	37,400	710,000	333,600	21,000	17,000	140,750
(Variable Weight)/(Gross Weight)		0.29	0.45	0.28	0.36	0.47	0.44	0.27	0.25	0.27	0.35	0.33
(Fuel Weight)/(Gross Weight)		0.24	0.08	0.27	0.23	0.13	0.20	0.38	0.43	0.54	0.48	0.57
Weight Growth Factor		**2.1**	**2.1**	**2.2**	**2.4**	**2.5**	**2.8**	**2.9**	**3.1**	**5.3**	**6.0**	**9.4**

Growth Factor calcs rev 1.xlsx

Table 19.5.1.1 Simplified Weight Growth Factor Calculations for Existing Designs

Advanced Material Weight Reductions

It is possible to estimate the reduction in W_0 due to the application of carbon-epoxy composite materials to the aircraft structure. This method is reasonably valid for transport aircraft, and not so much for other types. The first step is to decide which parts of the structure will be made of composites. The weight reductions (taken from References 4 and 5) for various group weight are shown in Table 19.5.1.2.

Weight Group	Reduction Factor (Nicolai)	Reduction Factor (Raymer)	Group %MWE	Reduced Group %MWE
Wing	0.80	0.85 - 0.90	25.0	22.5
Tails	0.75	0.83 - 0.88	4.5	4.0
Fuselage	0.75	0.90 - 0.95	23.0	21.9
Landing gear	0.92	0.95 - 1.00	9.5	9.5
Nacelles		0.90 - 0.95	3.5	3.3
Engines			11.0	11.0
Furnishings and Equipment			16.0	16.0
Systems (derived value)			(7.5)	(7.5)
Total			100	95.6

Table 19.5.1.2 Composite Material Weight Reduction

The next step is to estimate what percentage of the empty weight is represented by each weight group. If you have already obtained a value of empty weight for a baseline configuration with aluminum primary structure, use Fig 19.5.1.5 to find the breakdown of MWE by group.

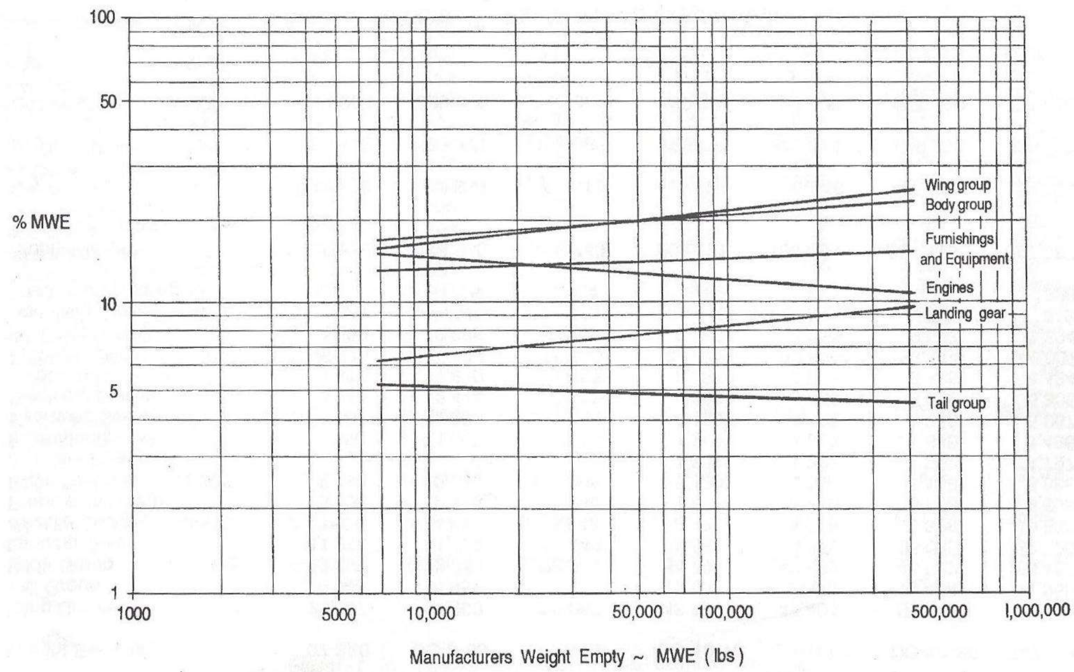

Fig. 19.5.1.5 Breakdown of Manufacturers Weight Empty by Group

Operating weight empty (OWE) is the sum of manufacturer's weight empty (MWE) and operating items, which are of the order of 5% of OWE. For this exercise, it will be assumed that the percentage weight reduction for OWE is the same as that of MWE. Multiply the weight reduction factor by the group weight percentage of MWE, and this will give you the airplane empty weight reduction for composite materials applied to a single weight group. Now apply the reduction factor for empty weight (in this example 95.6%) to the trend line for your class of aircraft and derive a new value for A in the empty weight equation.

References:

19.5.1.1 Robinson, A.C., Mass Properties Engineering, Lockheed-California Course LX3196 notes (unpublished), Sept 1980 - Feb 1981.

19.5.1.2 Hays, Anthony P., Zen and the Art of Airplane Sizing, SAE Paper 931255, May 1993.

19.5.1.3 Roskam, Jan, Airplane Design Part V: Component Weight Estimation, Roskam Aviation and Engineering Corp., 1985.

19.5.1.4 Nicolai, L.M., and Carichner, G.E., Fundamentals of Aircraft and Airship Design Volume 1 - Aircraft Design, AIAA Educational Series, 2010