15.4 Additional Considerations in Weights Estimation

Raymer Fig. 15.4 shows the typical percentage increase in empty weight from a reference value at the start of detail design. Another potential weight growth may occur during the conceptual or preliminary design phase due to change in requirements. In these design phases of an aircraft, a fixed weight added to (or subtracted from) the airplane does not simply add (or subtract) the same value of the weight to the takeoff gross weight (TOGW) to achieve the same payload and range. If weight is added, then to meet performance requirements most of the aircraft (such as wing, landing gear, and empennage) must increase in size and weight. The ratio of the increase in TOGW to the unit increase in fixed weight is the aircraft weight growth factor, and this 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. Empty weight available is based on detailed mission analysis, and empty weight required is calculated using component weight buildup with detailed empirical equations for each component (Fig. 15.4.1). A small arbitrary weight is added to the empty weight, and the required value of TOGW recalculated.

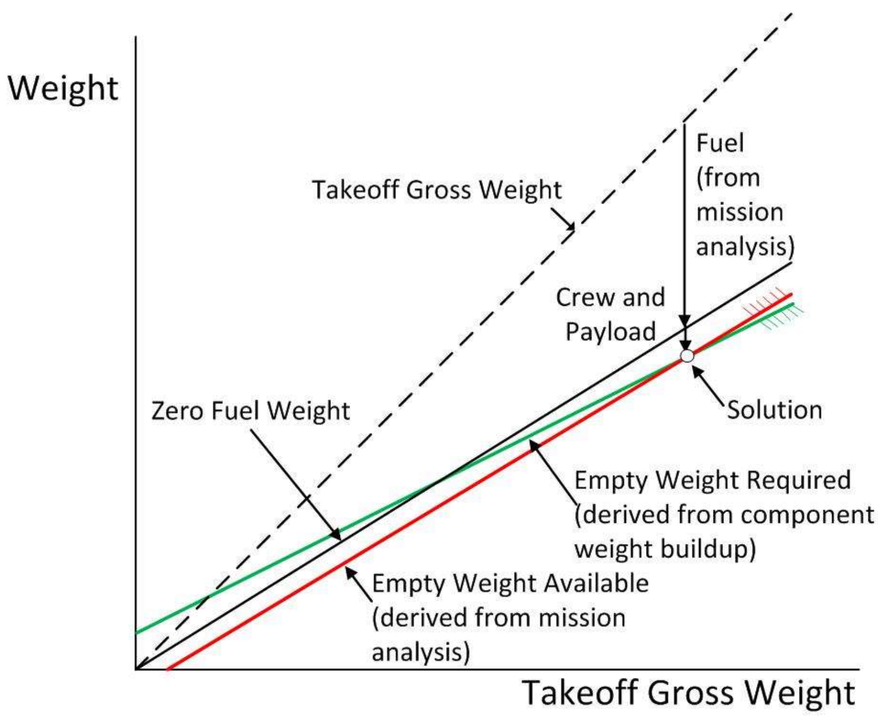

Fig. 15.4.1 Matching Empty Weight Required to Empty Weight Available

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 TOGW, and the second category is independent of TOGW. 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 TOGW. Similarly, wing weight is assumed proportional to wing area, and is also considered proportional to TOGW. The empennage sizes roughly with the wing dimensions, so its weight is proportional to TOGW.

Algebraic Approach

The following method is taken from Ref. 15.4.1. For commercial aircraft, TOGW can be broken down into five categories:

$$
\begin{aligned}
&W_{E_{Var}} = \text{Variable empty weight proportional to TOGW} \left(\text{e.g. , landing gear, wing, etc}\right)\\
&W_{E_{Payload}} = \text{Empty weight proportional to payload} \left(\text{e.g. , cabin crew, seats, toilets}\right)\\
&W_{E_{Fixed}} = \text{Fixed weight} \left(\text{flight deck crew, flight deck, avionics}\right)\\
&W_{Payload} = \text{Payload weight}\\
&W_{Fuel} = \text{Fuel weight}
\end{aligned}
$$

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

$$
\begin{aligned}
W_{TO} &= W_{E_{Var}} + W_{E_{Payload}} + W_{E_{Fixed}} + W_{Payload} + W_{Fuel}\\
&= 98{,}000 + 7{,}000 + 43{,}000 + 35{,}000 + 153{,}000\\
&= 336{,}000
\end{aligned}
\tag{15.4.1}
$$

The numerical values above were determined by the author of Ref. 15.4.1.

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

$$\ln\left(\frac{W_{TO}}{W_{LDG}}\right) = \text{constant} \quad \text{so} \quad \frac{W_{TO}}{W_{LDG}} = \text{constant} \tag{15.4.2}$$

$$\text{So} \quad \left(\frac{W_{TO}}{W_{TO} - W_{Fuel}}\right) = \left(\frac{1}{1 - \dfrac{W_{Fuel}}{W_{TO}}}\right) = \text{constant} \tag{15.4.3}$$

$$\text{So} \quad \frac{W_{Fuel}}{W_{TO}} = \text{constant} \tag{15.4.4}$$

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

$$W_{TO_1} = W_{E_{Var}} + W_{E_{Payload}} + W_{E_{Fixed}} + W_{Payload} + W_{Fuel} \tag{15.4.5}$$

$$W_{TO_2} = W_{E_{Var}}\left(\frac{W_{TO_2}}{W_{TO_1}}\right) + W_{E_{Payload}} + W_{E_{Fixed}} + W_{Payload} + W_{Fuel}\left(\frac{W_{TO_2}}{W_{TO_1}}\right) + W_x \tag{15.4.6}$$

We define the total growth in TOGW as $\Delta W_{TO} = W_{TO_2} - W_{TO_1}$ (15.4.7)

Subtracting Eq. (15.4.6) from Eq. (15.4.5) we get

$$\begin{aligned} \Delta W_{TO} &= W_{E_{Var}}\left(\frac{W_{TO_2}}{W_{TO_1}} - 1\right) + W_{Fuel}\left(\frac{W_{TO_2}}{W_{TO_1}} - 1\right) + W_x \\ &= W_{E_{Var}}\left(\frac{\Delta W_{TO}}{W_{TO_1}}\right) + W_{Fuel}\left(\frac{\Delta W_{TO}}{W_{TO_1}}\right) + W_x \end{aligned} \tag{15.4.8}$$

Rearranging terms we get

$$\Delta W_{TO}\left(1 - \frac{W_{E_{Var}}}{W_{TO_1}} - \frac{W_{Fuel}}{W_{TO_1}}\right) = W_x \tag{15.4.9}$$

By definition, the growth factor is

$$\boxed{\frac{\Delta W_{TO}}{W_x} = \frac{1}{1 - \dfrac{W_{E_{Var}}}{W_{TO_1}} - \dfrac{W_{Fuel}}{W_{TO_1}}} = \frac{1}{\left(1 - \dfrac{W_{Fuel}}{W_{TO_1}}\right) - \dfrac{W_{E_{Var}}}{W_{TO_1}}}} \tag{15.4.10}$$

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

$$\text{Growth factor} = \frac{1}{1 - \frac{153{,}000}{336{,}000} - \frac{98{,}000}{336{,}000}} = 4.0 \tag{15.4.11}$$

Note that the larger the fuel fraction, $\frac{W_{Fuel}}{W_{TO}}$, or the ratio of variable empty weight to TOGW, $\frac{W_{E_{Var}}}{W_{TO}}$, the larger the growth factor. This suggests that for long range airplanes the application of advanced weight-saving technology offers a greater payoff as compared with short 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 TOGW. It is almost impossible to estimate TOGW with any level of confidence.

Graphical Approach

The second approach is based on analysis of airplane sizing and sensitivity described in Ref. 15.4.2. Fig. 15.4.2 shows the required empty weight of an aircraft as a function of TOGW. As for the algebraic method, airplane empty weight assumed to be broken down into two parts - one part is proportional to TOGW, and the other part is constant. Note that a detailed component weight buildup is not required in this simplified method.

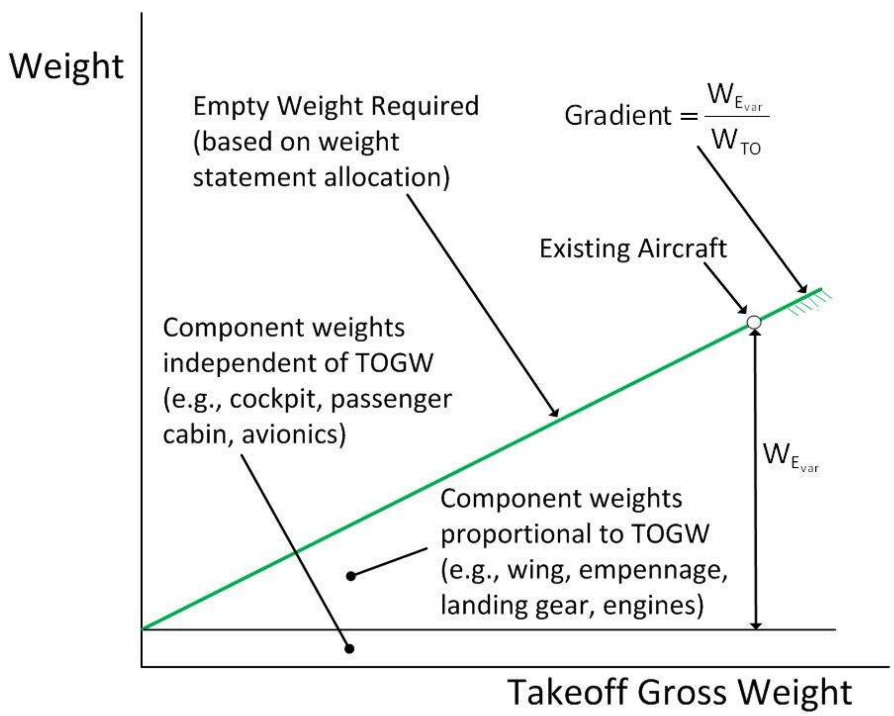

Fig. 15.4.2 Empty Weight Required as a Function of Takeoff Gross Weight

Fig. 14.4.3 shows the gradient of empty weight available as a function of TOGW based on the aircraft weight statement.

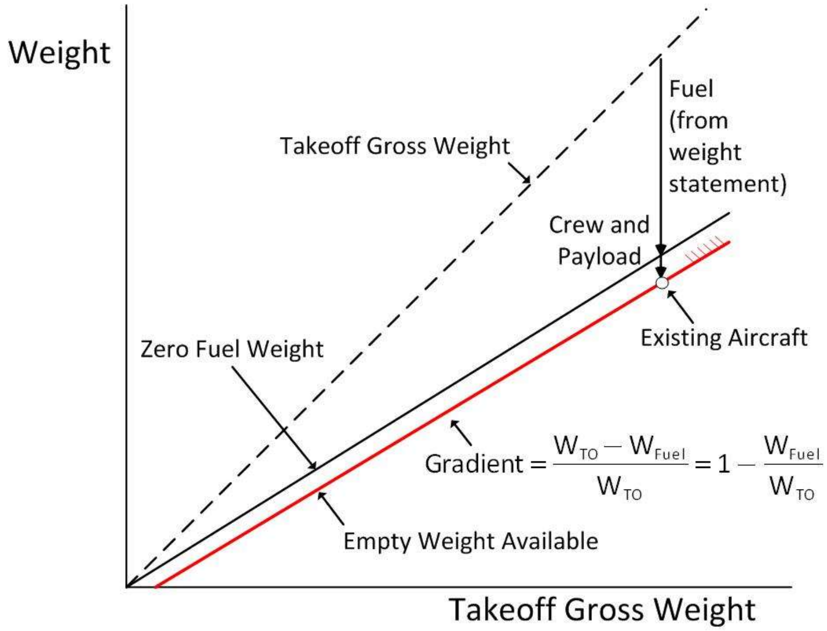

Fig. 15.4.3. Empty Weight Available

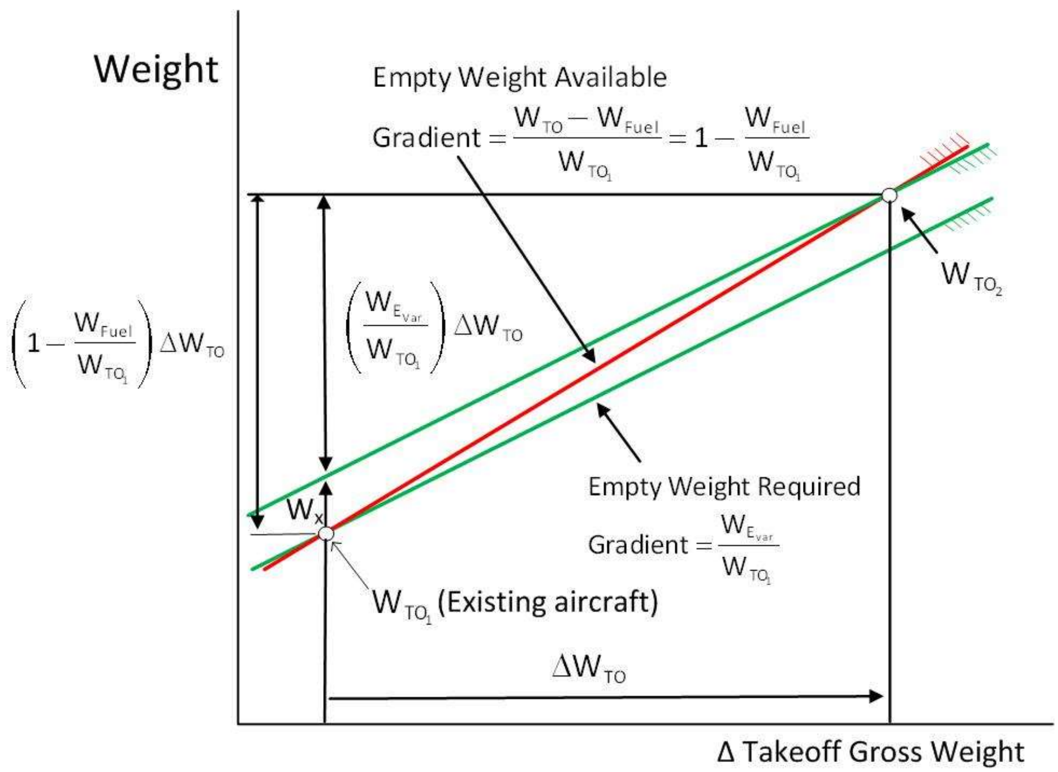

Figure 15.4.4 Adding an Arbitrary Weight W_x

This is illustrated in Figure 15.4.4. 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

$$W_x = \left(1 - \frac{W_{Fuel}}{W_{TO_1}}\right)\Delta W_{TO} - \left(\frac{W_{E_{Var}}}{W_{TO_1}}\right)\Delta W_{TO} \tag{15.4.12}$$

Rearranging:

$$\frac{W_x}{\Delta W_{TO}} = \left(1 - \frac{W_{Fuel}}{W_{TO_1}}\right) - \frac{W_{E_{Var}}}{W_{TO_1}} \tag{15.4.13}$$

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 (15.4.10) 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 707-320, empty weights were allocated by the author of Ref. 15.4.1 as fixed or variable. It is possible to do this for other aircraft, as illustrated in Table 15.4.1. Weights were taken from Refs. 15.4.3 and 15.4.4, with minor modification. The tables in the references show "Maximum Payload". This may be greater than the design payload, but depending on the required design flexibility, the difference is normally not large. 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 (shown indented in the table), 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 V	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	4,680	319	6,245	71,845	26,937	823	1,410	6,911
Nacelle Group	V	1,430	22	9,528	1,841	129	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	151			
Paint	F				150							
Operating Items	F	2,700										
Fixed Equipment Group		18,880	102	44,049	7,442	498	5,758	63,062	24,456	1,851	1,351	7,721
Oil and Trapped Fuel										221		644
Empty Weight		58,070	978	363,174	26,602	3,030	27,347	318,313	130,809	8,099	8,244	57,040
Fuel (= W_0 - W_E - W_{PL})		26,355	124	205,826	7,898	614	7,482	299,027	170,191	11,201	8,238	79,729
Max Payload		23,575	398	200,000	9,500	1,186	2,571	92,660	35,000	1,000	518	3,981
Design Gross Weight		108,000	1,500	769,000	44,000	4,830	37,400	710,000	336,000	20,300	17,000	140,750
(Variable Weight)/(Gross Weight)		0.29	0.45	0.28	0.36	0.47	0.44	0.27	0.25	0.28	0.35	0.33
(Fuel Weight)/(Gross Weight)		0.24	0.08	0.27	0.18	0.13	0.20	0.42	0.51	0.55	0.48	0.57
Weight Growth Factor		**2.1**	**2.1**	**2.2**	**2.2**	**2.5**	**2.8**	**3.3**	**4.1**	**5.9**	**6.0**	**9.4**

Table 15.4.1 Simplified Weight Growth Factor Calculations for Existing Designs

The assumptions made by the author of Ref. 15.4.1 for the Boeing 707-320 were slightly different from those shown in Table 15.4.1, so the result for this airplane does not agree exactly with the result shown in the algebraic approach. The fuel values shown in this table are derived values and not indicative of the tank capacity.

References:

15.4.1 Robinson, A.C., Mass Properties Engineering, Lockheed-California Course LX3196 notes (unpublished), Sept 1980 - Feb 1981.
15.4.2 Hays, Anthony P., Zen and the Art of Airplane Sizing, SAE Paper 931255, May 1993.
15.4.3 Roskam, Jan, Airplane Design Part V: Component Weight Estimation, Roskam Aviation and Engineering Corp., 1985.
15.4.4 Nicolai, L.M., and Carichner, G.E., Fundamentals of Aircraft and Airship Design Volume 1 - Aircraft Design, AIAA Educational Series, 2010