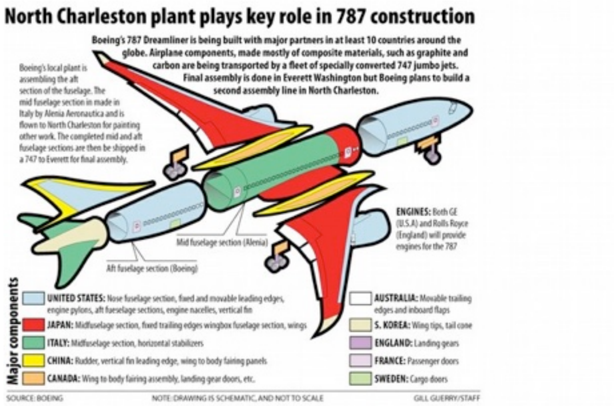
1



Refined sizing using group weight estimates

Recommended reading:

Howe: Chapter 6 and Addendum 4
Nicolai & Carichner: Chapter 20
Torenbeek: Chapter 8
Raymer: Chapter 15

2

Refined weight estimation/group weights

1. At some point in the design process a breakdown of empty weight into groups of components is required. There are a number of reasons, besides the fact that weight is a critical issue:
   a. This enables a more precise gross weight estimate, reducing the reliance on a noisy curve-fit for W_{empty}/W_0 as a function on W_0. Hence we will also gain more precise estimates of T_0 and S.
   b. We need to find weights and locations of the various components in order to balance the aircraft longitudinally.
2. <u>Three main groups: Structures, Propulsion and Equipment.</u> These are then further broken down into subgroups (wing, tail, ...). Sometimes an assignment to one group or another is somewhat arbitrary; this is unimportant so long as we include all significant items.

Note that as well as the weight of each group we are interested in its position from the nose of the aircraft.

This is for CG calculation.

	Weight, lb	Loc., ft	Moment, ft-lb
Structures	**4,526**		**106,879**
Wing	1,459.4	23.3	34,004
Horizontal tail	280.4	39.2	10,992
Vertical tail		0	0
Ventral tail		0	0
Fuselage	1,574	21.7	34,156
Main landing gear	631.5	23.8	15,030
Nose landing gear	171.1	13.0	2,224
Other landing gear		0	0
Engine mounts	39.1	33.0	1,290
Firewall	58.8	33.0	1,940
Engine section	21	33.0	693
Air induction	291.1	22.5	6,550
			0
			0
			0
Propulsion	**2,354**		**70,931**
Engine(s)—installed	1,517	33.0	50,061
Accessory drive			0
Exhaust system			0
Engine cooling	172	33.0	5,676
Oil cooling	37.8	33.0	1,247
Engine controls	20	33.0	660
Starter	39.5	15.7	620
Fuel system/tanks	568	22.3	12,666
			0
			0
			0
			0

	Weight, lb	Loc., ft	Moment, ft-lb
Equipment	**4,067**		**80,646**
Flight controls	655.7	21.7	14,229
APU		0	0
Instruments	122.8	10.0	1,228
Hydraulics	171.7	21.7	3,726
Pneumatics		21.7	0
Electrical	713.2	21.7	15,476
Avionics	989.8	10.0	9,898
Armament		0	0
Furnishings	217.6	6.2	1,3497
Air conditioning	190.7	15.0	2,860.5
Anti-icing			0
Photographic			0
Load and handling	5.3	15.0	79.5
Misc. equipment and We	1,000	31.8	31,800
Empty weight allowance	547	23.6	12,9237
Total weight empty	**11,495**	**23.6**	27,1379
Useful load	**4,985**		
Crew	220	15.0	3,300
Fuel—usable	3,836	22.3	85,551
Fuel—trapped	39	22.3	864
Oil	50	33.0	1,650
Passengers			0
Cargo/payload	840	21.7	18,228
Guns			0
Ammunition	0	21.7	0
Misc. useful load			
Takeoff gross weight	**16,480**	**22.0**	362,744

Raymer

3

Refined weight estimation/group weights

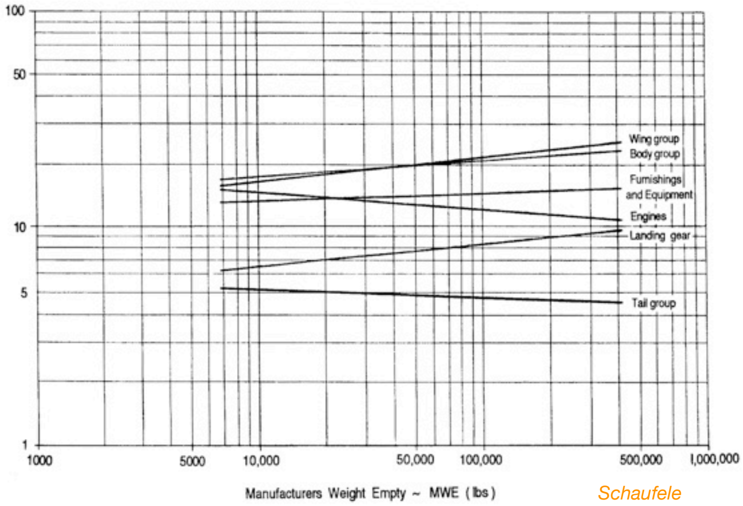
3. Typically the group weight fractions (proportions of W_e) are weak functions of W_0, like our earlier correlations W_e/W_0.
4. Assuming the fuel weight fraction W_f/W_0 and the payload weight W_p remain constant, we have to iterate W_0 (hence also, T_0 and S) until the weight budget comes into balance:

$$W_0 = W_{\text{payload}} + W_{\text{fuel}} + W_{\text{empty}}$$

$$= W_p + \frac{W_f}{W_0} W_0 + W_e(S, T_0, W_0)$$

$$\left(1 - \frac{W_f}{W_0}\right) W_0 = W_p + W_e(S, T_0, W_0)$$

fixed — fixed — correlations



Schaufele

5. While ultimately in the detail design stage the actual masses could be estimated from parts drawings, at the conceptual design level correlations for group masses are used. These are significantly more accurate than the type-level correlation previously used for W_e/W_0, hence the overall estimate of W_0 ends up closer to the final value.
6. A number of different sets of group weight correlation functions exist in the textbooks (e.g. Raymer, Howe, Nicolai, Roskam, Jenkinson et al., Torenbeek), and each manufacturer would have its own. If possible, it is best to compare results from the various published correlations. We will (later) use Howe.

4

Refined weight estimation/group weights

6. Detailed weight correlation functions are difficult to generalise; each text is a little different (and many do not use SI units). We will consider an example from Raymer.

Fighter/Attack Weights (British Units, results in pounds)

$$W_{\text{wing}} = 0.0103\, K_{dw} K_{vs} (W_{dg} N_z)^{0.5} S_w^{0.622} A^{0.785} (t/c)_{\text{root}}^{-0.4} \times (1+\lambda)^{0.05} (\cos\Lambda)^{-1.0} S_{csw}^{0.04} \quad (15.1)$$

$$W_{\text{horizontal tail}} = 3.316 \left(1 + \frac{F_w}{B_h}\right)^{-2.0} \left(\frac{W_{dg} N_z}{1000}\right)^{0.260} S_{ht}^{0.806} \quad (15.2)$$

$$W_{\text{vertical tail}} = 0.452\, K_{rht} (1 + H_t/H_v)^{0.5} (W_{dg} N_z)^{0.488} S_{vt}^{0.718} M^{0.341} \times L_t^{-1.0} (1 + S_r/S_{vt})^{0.348} A_{vt}^{0.223} (1+\lambda)^{0.25} (\cos\Lambda_{vt})^{-0.323} \quad (15.3)$$

$$W_{\text{fuselage}} = 0.499\, K_{dwf} W_{dg}^{0.35} N_z^{0.25} L^{0.5} D^{0.849} W^{0.685} \quad (15.4)$$

$$W_{\text{main landing gear}} = K_{cb} K_{tpg} (W_l N_l)^{0.25} L_m^{0.973} \quad (15.5)$$

$$W_{\text{nose landing gear}} = (W_l N_l)^{0.290} L_n^{0.5} N_{nw}^{0.525} \quad (15.6)$$

$$W_{\text{engine mounts}} = 0.013\, N_{en}^{0.795} T^{0.579} N_z \quad (15.7)$$

$$W_{\text{firewall}} = 1.13\, S_{fw} \quad (15.8)$$

$$W_{\text{engine section}} = 0.01\, W_{en}^{0.717} N_{en} N_z \quad (15.9)$$

$$W_{\text{air induction system}} = 13.29\, K_{vg} L_d^{0.643} K_d^{0.182} N_{en}^{1.498} (L_s/L_d)^{-0.373} D_e \quad (15.10)$$

where K_d and L_s are from Fig. 15.2.

$$W_{\text{tailpipe}} = 3.5 D_e L_{tp} N_{en} \quad (15.11)$$

$$W_{\text{engine cooling}} = 4.55 D_e L_{sh} N_{en} \quad (15.12)$$

$$W_{\text{oil cooling}} = 37.82 N_{en}^{1.023} \quad (15.13)$$

$$W_{\text{engine controls}} = 10.5 N_{en}^{1.008} L_{ec}^{0.222} \quad (15.14)$$

$$W_{\text{starter (pneumatic)}} = 0.025 T_e^{0.760} N_{en}^{0.72} \quad (15.15)$$

$$W_{\text{fuel system and tanks}} = 7.45 V_t^{0.47} \left(1 + \frac{V_i}{V_t}\right)^{-0.095} \times \left(1 + \frac{V_p}{V_t}\right) N_t^{0.066} N_{en}^{0.052} \left(\frac{T \cdot \text{SFC}}{1000}\right)^{0.249} \quad (15.16)$$

$$W_{\text{flight controls}} = 36.28 M^{0.003} S_{cs}^{0.489} N_s^{0.484} N_c^{0.127} \quad (15.17)$$

$$W_{\text{instruments}} = 8.0 + 36.37 N_{en}^{0.676} N_t^{0.237} + 26.4 (1 + N_{ci})^{1.356} \quad (15.18)$$

$$W_{\text{hydraulics}} = 37.23 K_{vsh} N_u^{0.664} \quad (15.19)$$

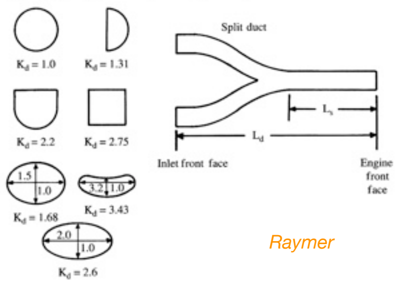
$$W_{\text{electrical}} = 172.2 K_{mc} R_{kva}^{0.152} N_c^{0.10} L_a^{0.10} N_{gen}^{0.091} \quad (15.20)$$

$$W_{\text{avionics}} = 2.117 W_{uav}^{0.933} \quad (15.21)$$

$$W_{\text{furnishings}} = 217.6 N_c \text{ (includes seats)} \quad (15.22)$$

$$W_{\text{air conditioning and anti-ice}} = 201.6 [(W_{uav} + 200 N_c)/1000]^{0.735} \quad (15.23)$$

$$W_{\text{handling gear}} = 3.2 \times 10^{-4} W_{dg} \quad (15.24)$$



Raymer

Fig. 15.2 Inlet duct geometry.

Refined weight estimation/group weights

Weights Equations Terminology

A = aspect ratio
B_h = horizontal tail span, ft
B_w = wing span, ft
D = fuselage structural depth, ft
D_e = engine diameter, ft
F_w = fuselage width at horizontal tail intersection, ft
H_t = horizontal tail height above fuselage, ft
H_t/H_v = 0.0 for conventional tail; 1.0 for "T" tail
H_v = vertical tail height above fuselage, ft
I_y = yawing moment of inertia, lb-ft^2 (see Chap. 16)
K_{cb} = 2.25 for cross-beam (F-111) gear; = 1.0 otherwise
K_d = duct constant (see Fig. 15.2)
K_{door} = 1.0 if no cargo door; = 1.06 if one side cargo door; = 1.12 if two side cargo doors; = 1.12 if aft clamshell door; = 1.25 if two side cargo doors and aft clamshell door
K_{dw} = 0.768 for delta wing; = 1.0 otherwise
K_{dwf} = 0.774 for delta-wing aircraft; = 1.0 otherwise
K_h = 0.05 for low subsonic with hydraulics for brakes and retracts only; = 0.11 for medium subsonic with hydraulics for flaps; = 0.12 for high subsonic with hydraulic flight controls; = 0.013 for light plane with hydraulic brakes only (and use M = 0.1)
K_{Lg} = 1.12 if fuselage-mounted main landing gear; = 1.0 otherwise
K_{mc} = 1.45 if mission completion required after failure; = 1.0 otherwise
K_{mp} = 1.126 for kneeling gear; = 1.0 otherwise
K_{ng} = 1.017 for pylon-mounted nacelle; = 1.0 otherwise
K_{np} = 1.15 for kneeling gear; = 1.0 otherwise
K_p = 1.4 for engine with propeller or 1.0 otherwise
K_r = 1.133 if reciprocating engine; = 1.0 otherwise
K_{rht} = 1.047 for rolling horizontal tail; = 1.0 otherwise
K_{tp} = 0.793 if turboprop; = 1.0 otherwise
K_{tpg} = 0.826 for tripod (A-7) gear; = 1.0 otherwise
K_{tr} = 1.18 for jet with thrust reverser or 1.0 otherwise
K_{uht} = 1.143 for unit (all-moving) horizontal tail; = 1.0 otherwise
K_{vg} = 1.62 for variable geometry; = 1.0 otherwise
K_{vs} = 1.19 for variable sweep wing; = 1.0 otherwise
K_{vsh} = 1.425 for variable sweep wing; = 1.0 otherwise
K_{ws} = $0.75\,[(1+2\lambda)/(1+\lambda)]\,(B_w \tan\Lambda/L)$
K_y = aircraft pitching radius of gyration, ft ($\cong 0.3L_t$)
K_z = aircraft yawing radius of gyration, ft ($\cong L_t$)
L = fuselage structural length, ft (excludes radome cowling, tail cap)
L_a = electrical routing distance, generators to avionics to cockpit, ft
L_d = duct length, ft
L_{ec} = length from engine front to cockpit—total if multi-engine, ft
L_f = total fuselage length
L_m = extended length of main landing gear, in.
L_n = extended nose gear length, in.
L_s = single duct length (see Fig. 15.2)
L_{sh} = length of engine shroud, ft
L_t = tail length; wing quarter-MAC to tail quarter-MAC, ft
L_{tp} = length of tailpipe, ft
M = Mach number
N_c = number of crew (use 0.5 for UAV)
N_{ci} = number of crew equivalents: 1.0 if single pilot; = 1.2 if pilot plus backseater; = 2.0 pilot and copilot
N_{en} = number of engines
N_f = number of functions performed by controls (typically 4–7)
N_{gen} = number of generators (typically = N_{en})
N_{Lt} = nacelle length, ft
N_l = ultimate landing load factor; = $N_{gear} \times 1.5$
N_m = number of mechanical functions (typically 0–2)
N_{mss} = number of main gear shock struts
N_{mw} = number of main wheels
N_{nw} = number of nosewheels
N_p = number of personnel onboard (crew and passengers)
N_s = number of flight control systems
N_t = number of fuel tanks
N_u = number of hydraulic utility functions (typically 5–15)
N_w = nacelle width, ft
N_z = ultimate load factor; = 1.5 × limit load factor
q = dynamic pressure at cruise, lb/ft^2
R_{kva} = system electrical rating, kV · A (typically 40–60 for transports, 110–160 for fighters and bombers)
S_{cs} = total area of control surfaces, ft^2
S_{csw} = control surface area (wing-mounted), ft^2
S_e = elevator area, ft
S_f = fuselage wetted area, ft^2
S_{fw} = firewall surface area, ft^2
S_{ht} = horizontal tail area
S_n = nacelle wetted area, ft^2
S_r = rudder area, ft^2
S_{vt} = vertical tail area, ft^2
S_w = trapezoidal wing area, ft^2
SFC = engine specific fuel consumption—maximum thrust
T = total engine thrust, lb
T_e = thrust per engine, lb
V_i = integral tanks volume, gal
V_p = self-sealing "protected" tanks volume, gal
V_{pr} = volume of pressurized section, ft^3
V_t = total fuel volume, gal
W = total fuselage structural width, ft
W_c = maximum cargo weight, lb
W_{dg} = flight design gross weight, lb (typically 50–60% of internal fuel for military aircraft)
W_{ec} = weight of engine and contents, lb (per nacelle), $\cong 2.331 W_{engine}^{0.901} K_p K_{tr}$
W_{en} = engine weight, each, lb
W_{fw} = weight of fuel in wing, lb (if zero, ignore this term)
W_l = landing design gross weight, lb
W_{press} = weight penalty due to pressurization, = $11.9(V_{pr}P_{delta})^{0.271}$, where P_{delta} = cabin pressure differential, psi (typically 8 psi)
W_{uav} = uninstalled avionics weight, lb (typically = 800–1400 lb)
Λ = wing sweep at 25% MAC
λ = taper ratio (wing or tail)

Raymer

Refined weight estimation/group weights

7. While detailed group weight estimates are ultimately required, we could take a simpler approach, which is to combine more reliable correlations for W_{empty}/W_0 with statistical values for group weight fractions.
8. First the correlations. These more accurate correlations (from Raymer) use the values of T_0/W_0 and W_0/S, which we now have available following the constraint analysis. In addition they involve the aircraft maximum speed. Raymer states the standard deviation of the estimate to be only about half that of the relationships previously used.
9. Note that the correlations use Imperial units. Since they produce a dimensionless result but use dimensional values, conversion factors are required.
10. We could use the correlations for another iteration through the mission analysis (to re-estimate W_0): hopefully somewhat more accurate than the initial correlation we used.
11. Next we will examine group weight fractions.

Table 6.1 Empty weight fraction vs W_0, A, T/W_0, W_0/S, and M_{max}

$$W_e/W_0 = (a + bW_0^{C1}A^{C2}(T/W_0)^{C3}(W_0/S)^{C4}M_{max}^{C5})K_{vs}$$

fps units	a	b	$C1$	$C2$	$C3$	$C4$	$C5$
Jet trainer	0	4.28	−0.10	0.10	0.20	−0.24	0.11
Jet fighter	−0.02	2.16	−0.10	0.20	0.04	−0.10	0.08
Military cargo/bomber	0.07	1.71	−0.10	0.10	0.06	−0.10	0.05
Jet transport	0.32	0.66	−0.13	0.30	0.06	−0.05	0.05

K_{VS} = variable sweep constant = 1.04 if variable sweep = 1.00 if fixed sweep

Raymer

Correlations use Imperial units. To convert to SI, multiply the values of b by: (and take W_0 in Newtons).

$$\left(\frac{1}{4.448}\right)^{C1}\left(\frac{1}{47.88}\right)^{C4}$$

Table 6.2 Empty weight fraction vs W_0, A, hp/W_0, W_0/S, and V_{max} (knots)

$$W_e/W_0 = a + bW_0^{C1}A^{C2}(\mathrm{hp}/W_0)^{C3}(W_0/S)^{C4}V_{max}^{C5}$$

fps units	a	b	$C1$	$C2$	$C3$	$C4$	$C5$
Sailplane—unpowered	0	0.76	−0.05	0.14	0	−0.30	0.06
Sailplane—powered	0	1.21	−0.04	0.14	0.19	−0.20	0.05
Homebuilt—metal/wood	0	0.71	−0.10	0.05	0.10	−0.05	0.17
Homebuilt—composite	0	0.69	−0.10	0.05	0.10	−0.05	0.17
Gen. Av.—single engine	−0.25	1.18	−0.20	0.08	0.05	−0.05	0.27
Gen. Av.—twin engine	−0.90	1.36	−0.10	0.08	0.05	−0.05	0.20
Agricultural aircraft	0	1.67	−0.14	0.07	0.10	−0.10	0.11
Twin turboprop	0.37	0.09	−0.06	0.08	0.08	−0.05	0.30
Flying boat	0	0.42	−0.01	0.10	0.05	−0.12	0.18

Multiply b by: (take V_{max} in m/s).

$$\left(\frac{1}{4.448}\right)^{C1}\left(\frac{4.448}{746}\right)^{C3}\left(\frac{1}{47.88}\right)^{C4}\left(\frac{1}{0.5148}\right)^{C5}$$

Refined weight estimation/group weights

12. Group weight fractions give a breakdown of W_{empty}, based on historical data for comparable aircraft types. These group weights may or may not include the operational items, such as non-consumable fluids, which can be considered part of the payload.

Group weight % of MWE

Weight Element	Personal/Utility	Regional T/P	Jet Transport
Wing group	17.0	18.0	21.0
Tail group	4.0	4.0	4.5
Body group	24.0	24.0	20.0
Landing gear	8.0	8.5	8.5
Nacelle group	—	3.0	3.5
Propulsion group	4.5	4.5	4.0
Flight controls	1.5	2.0	2.5
Auxiliary power	—	—	0.5
Instruments	1.0	1.0	1.0
Hydraulic system	—	.05	1.5
Electrical system	1.0	5.0	2.5
Avionics	1.0	2.5	2.5
Furnishings	13.0	11.0	13.0
Air conditioning	0.5	1.5	1.5
Anti-icing system	—	2.0	1.5
Dry engine	24.5	12.5	12.0
	100.0	100.0	100.0

Fig. 10-6 Typical Manufacturers Weight Empty Breakdown in % of MWE

Example operational items weight

Schaufele

Operational Items	22,843 lb
Cockpit crew (2 x 170 lb)	340
Cabin crew (12 x 130 lb)	1,560
Crew baggage (14 x 20 lb)	280
Flight kits	50
Oil including Engine, Constant Speed Drive, APU and System Oil	380
Unuseable Fuel	1,059
Potable water (5 lb x 451 pass)	2,255
Lavatory fluids	135
Food, Galley Service including carts (36 F/C x 28 lbs/pass + 415 E/C x 16 lbs/pass)	7,648
Passenger Service Equipment (451 x 3 lb/pass)	1,353
Evacuation Slides/Slide-Rafts	2,079
Emergency Transmitters	13
Life Vests (451 + 14 = 465 x 1 lb each)	465
Pallets (nine 88 x 125 x 214 lbs each)	1,926
Containers (20 LD3 x 165 lbs each)	3,300

Figure 10-5 Operational Items List–Typical Long Range Jet Transport

(Simplified/model) Refined weight estimation/group weights

Mass model from Howe's *Aircraft Conceptual Design Synthesis.*

$$W_0 = M_0 g$$

$$M_0 = M_{\text{FIXED}} + M_{\text{VARIABLE}}$$

$$M_{\text{FIXED}} = M_{\text{FUS}} + M_{\text{PAY}} + M_{\text{OP}}$$ Independent of M_0.

$$M_{\text{VARIABLE}} = M_{\text{LIFTSUR}} + M_{\text{POWERPT}} + M_{\text{SYS}} + M_{\text{FUEL}}$$ Functions of M_0.

M_{FUS}	is mass of fuselage structure
M_{PAY}	is mass of the payload; this is as specified but can include directly related items if necessary, such as provisions for passengers
M_{OP}	is mass of operational items (the difference between the basic empty and operating empty masses); this item is not to be confused with operators specified items which cover a greater mass contribution and usually include furnishings, etc.
$M_{LIFTSUR}$	is the total mass of the wing and the horizontal and vertical stabiliser/control surfaces
$M_{POWERPT}$	is the total mass of the installed powerplants
M_{SYS}	is the mass of the airframe systems, equipment, landing gear, etc., not included in M_{PAY}, but see Table 6.9
M_{FUEL}	is the fuel mass required to meet the design specification

} NB: from specification (M_{FUS}, M_{PAY})

9

Fixed mass contributions – M_{FUS}

Pressurised transport, executive and related types (Eq 6.20a):

$$M_{\mathrm{FUS}} = C_2 p (9.75 + 5.84B)\left(\frac{2L}{B+H} - 1.5\right)(B+H)^2 \text{ kg}$$

where

p is the cabin maximum working differential pressure, bar
L is the overall fuselage length, m
B is the maximum width of the fuselage, m
H is the maximum height of the fuselage, m
C_2 is a coefficient which depends upon the actual type of pressurised fuselage, see Table 6.6

(Recall 1 bar = 100 kPa.)

Other aircraft (Eq 6.20b):

$$M_{\mathrm{FUS}} = C_2 \left[L(B+H)V_D^{0.5}\right]^{1.5} \text{ kg}$$

where

L is the overall length of the basic fuselage (aft of the engine bulkhead when a nose propeller engine is used), m
V_D is the design maximum (diving) speed, m/s (EAS)
C_2 is the coefficient given in Table 6.6

Table 6.6 Fuselage mass coefficient, C_2 Howe

CATEGORY OF FUSELAGE	C_2
Pressurised fuselages [Eq (6.20a)]	
Airliners, executive and feeder line aircraft of four or more abreast seating with wing-mounted landing gear	0.79
Airliners and related types with fuselage-mounted landing gear	0.81
Antisubmarine and regional airliners of less than four abreast seating	0.83
Freighter aircraft with fuselage-mounted landing gear and rear ramp door	0.87
Increment when engines are located on rear fuselage	0.01
Other fuselages [Eq (6.20b)]	
Land based combat aircraft with fuselage-mounted engines	0.04-0.036*
Naval combat aircraft with fuselage-mounted engines	0.043-0.039*
Bomber aircraft with wing-mounted engines	0.027
Single-engine light aircraft	0.06-0.04*
Twin-engine general aviation aircraft, with or without limited pressurisation	0.034

N.B. The values are all for metal construction except that those marked * make allowance for the possible benefits of using reinforced plastic materials where appropriate.

10

Fixed mass contributions – M_{OP}

M_{OP} pertains to items added to the basic empty mass to bring the aircraft to its empty operational state, including

- Crew and associated personal items
- Safety equipment, such as emergency oxygen and life rafts
- Freight equipment
- Water and food, especially on transport types
- Possibly residual fuel, but here this item is assumed to be included in the powerplant mass.

Passenger aircraft

$$M_{\mathrm{OP}} = 85 n_c + F_{\mathrm{OP}} P \text{ kg}$$

where

P is the number of passengers
n_c is the number of crew
F_{OP} is the operating items factor and is of the order of:

i)	Feeder line aircraft, very short haul	7 kg
ii)	Medium range	12 kg
iii)	Very long range and executive	16 kg

Average mass of passenger + baggage = 85 kg, perhaps a bit low?

Freight aircraft

$$M_{\mathrm{OP}} = 600 + 0.03(\text{Payload}) \text{ kg}$$

Other types

M_{OP} = crew provision: from 77 kg per person in light aircraft to 100 kg for combat types.

Variable mass contributions – M_{LIFTSUR}

Lifting surface mass M_{LIFTSUR} contains contributions from the wings *and* the tail surfaces. Howe also supplies a factor by which the wing mass can be isolated from the total lifting surface mass.

$$M_{\text{LIFTSUR}} =$$

$$C_1 \left[A^{0.5} S^{1.5} \sec \Lambda_E \left(\frac{1+2\lambda}{3+3\lambda} \right) \frac{M_0}{S} \bar{N}^{0.3} \left(\frac{V_D}{t/c} \right)^{0.5} \right]^{0.9} \text{kg}$$

where

- M_0 is the total aircraft mass
- A is the wing aspect ratio
- S is the wing area, m²
- Λ_E is the effective sweep, usually 0.25 chord sweep but the mean of $\Lambda_{1/4}$ and Λ_{STRUCT} if the structural sweep is significantly different from basic aerodynamic sweep
- λ is the ratio of the tip to centreline chords of the wing
- $\bar{N}$ is 1.65 times the limit maximum manoeuvre acceleration factor, as given in the requirements, unless known to be overridden by gust considerations
- V_D is the design maximum (diving) speed, m/s (EAS)
- t/c is the thickness to chord ratio at wing centreline
- C_1 is a coefficient depending on the type of aircraft

n.b. $\sec\Lambda = 1/\cos\Lambda$

Howe

Table 6.7 Lifting surface mass coefficient, C_1

[Eq (6.2b)] $C_1 = A^1 - B^1 M_0 \times 10^{-3}$

TYPE	$A^1 \times 10^3$	$B^1 \times 10^6$	typical C_1
Subsonic transport aircraft; $M_0 > 5700$ kg			
Long range (nom. range > 5000 km)	0.72	0.5	Eq (6.23a)
Short/med. range; $M_0 > 46{,}000$ kg)	0.90	0	0.00090
Short/med. range; jet powered; $M_0 \le 46{,}000$ kg	1.67	16.1	Eq (6.23b)
Short/med. range; propeller driven, $M_0 \le 46{,}000$ kg	1.49	16.1	Eq (6.23c)
Executive jets (all ranges)	1.76	16.9	0.0016
General aviation types; $M_0 \le 5700$ kg			
Propeller driven, cantilever wing;			
Single engine	2.0	100	0.00183
Twin engine	2.0	100	0.00164
Propeller driven, braced wing	1.74	112	0.0015
*Supersonic delta wings, all types			
$M_0 \le 15{,}000$ kg	0.72 or 0.81	0	0.00072 or 0.00081
$M_0 > 30{,}000$ kg	0.48 or 0.55	0.64 or 0.72	0.00042 or 0.00047
(No evidence for $15{,}000 > M_0 > 30{,}000$ kg)			
Military jet strike/interceptors; $M_0 > 10{,}000$ kg			
Typically	0.62 to 0.74	0	0.00062 to 0.00074
Variable sweep, $M_0 < 40{,}000$ kg	1.24	14.9	0.00089
Naval aircraft with inboard wing fold	0.87	0	0.00087
Naval aircraft with outboard wing fold	0.75	0	0.00075
Military jet strike/interceptors; $M_0 \le 10{,}000$ kg	1.18	50	0.00076
Military trainers and related types			
Jet powered; $M_0 < 10{,}000$ kg	1.73	105	0.0012
Propeller driven; $M_0 > 3100$ kg	1.49	0	0.00149
Propeller driven; $M_0 \le 3100$ kg	4.0	800	0.002 to 0.003
Subsonic bombers			
Long range (nom. range > 10,000 km)	0.5	0	0.0005
Medium range	0.93	0	0.00093
Military freight aircraft			
Long range jet	0.72	0.5	Eq (6.23d)
Turboprop	0.77	0.53	Eq (6.23e)

N.B.*Delta wings are defined as $A \le 2.5$ and $\lambda \le 0.15$. The first, lower, value for delta wings is for tailless aircraft configurations. The values given are all for metal construction. A reduction of 15% is suggested when full use is made of fibre reinforced plastic materials in the construction of all lifting surfaces.

Variable mass contributions – M_{LIFTSUR}

For subsonic transport and freight aircraft types, Howe offers a number of C_1 coefficient values that can be adopted without reference to the last table (dependence of C_1 on B^1 is small):

a) Long range passenger aircraft, s > 5000 km

$$C_1 = 0.00072 - 0.0005(270 + 0.05s)P \times 10^{-6}$$

s is range in km
P is number of passengers

b) Short/medium range passenger aircraft, M_0 < 46,000 kg

$$C_1 = 0.00167 - 0.016(370 + 0.03s)P \times 10^{-6}$$

c) Turboprop passenger aircraft, M_0 < 46,000 kg

$$C_1 = 0.00149 - 5.8P \times 10^{-6}$$

d) Long range jet freight aircraft

$$C_1 = 0.00072 - 0.0005(2.08 + 0.00028)\text{PAY} \times 10^{-6}$$

PAY is payload in kg

e) Turboprop freight aircraft

$$C_1 = 0.00077 - 0.00053(2.08 + 0.00028)\text{PAY} \times 10^{-6}$$

For a wing of fixed shape (but variable size) the relationship for M_{LIFTSUR} reduces to

$$M_{\text{LIFTSUR}} = \overline{C}_1 \left[S^{1.5} \frac{M_0}{S} \right]^{0.9} \text{kg} \quad \text{where} \quad \overline{C}_1 = C_1 \left[A^{0.5} \sec \Lambda_E \left(\frac{1+2\lambda}{3+3\lambda} \right) \bar{N}^{0.3} \left(\frac{V_D}{t/c} \right)^{0.5} \right]^{0.9}$$

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Variable mass contributions – M_{LIFTSUR}

Note that Howe's mass for 'lifting surfaces', M_{LIFTSUR}, includes contributions for tail surfaces.

That is fine if we're just interested in overall mass but if we need to estimate the tail or wing masses as separate values, use C_5:

Howe

Table 6.10 Lifting surface factor, C_5

TYPE OF AIRCRAFT	C_5
Tailless delta	1.10
Long haul jets transport	1.16
Short/medium haul jet transports	1.20
Executive jet aircraft	1.30
All other types	1.24

C_5 = mass of all lifting surfaces/mass of wing

$$M_{\text{LIFTSUR}} = C_5 M_{\text{WING}} = M_{\text{WING}} + M_{\text{TAIL}}$$

$$M_{\text{WING}} = \frac{M_{\text{LIFTSUR}}}{C_5}$$

$$M_{\text{TAIL}} = M_{\text{LIFTSUR}} \left(1 - \frac{1}{C_5}\right)$$

This (rather crude) partitioning can be useful when we come to balance the aircraft longitudinally but is unimportant for preliminary mass estimates.

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Variable mass contributions – M_{POWERPT}

M_{POWERPT} allows for the mass associated with engine installation: the basic engine mass, plus mounting, exhaust ducts, nacelles, pods, cowling and propeller (as appropriate), fuel system.

$$M_{\text{POWERPT}} = C_3 M_{\text{ENG}}$$

Table 6.8 Powerplant installation factors, C_3 Howe

TYPE OF AIRCRAFT	C_3
Executive jets and jet transports	1.56
Supersonic aircraft with variable geometry intakes	2.0
Turbopropeller transports	2.25
Propeller turbine trainers	2.0
General aviation, twin piston-engined types	1.80
All other types	1.40

If the basic engine mass M_{ENG} is available (from manufacturer), use this, otherwise the following approximations may be employed:

a) Military combat engines (turbojets or low BPR turbofans)

Basic dry thrust rating: $\frac{T_0}{M_{\text{ENG}} g} = 4.5 \text{ to } 6.5$

With typical afterburner attached: $\frac{T_0}{M_{\text{ENG}} g} = 7 \text{ to } 9$

With provision for vectoring nozzles, etc: $\frac{T_0}{M_{\text{ENG}} g} = 4 \text{ to } 6$

(higher values are for more recent designs.)

b) Civil transport engines (high BPR turbofans)

Static sea level rating: $\frac{T_0}{M_{\text{ENG}} g} = 5 \text{ to } 6.5$

(higher values are for large, new technology, engines)

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Variable mass contributions – $M_{POWERPT}$

c) *Turboprop engines* (including gearboxes) $\frac{P_0}{M_{ENG}g} = 0.34 \text{ to } 0.42 \text{ kW/N}$

(Larger values for larger/recent products)

d) *Turboshaft engines* (excluding reduction gearbox) $\frac{P_0}{M_{ENG}g} = 0.5 \text{ to } 0.8 \text{ kW/N}$

(Turboshaft: for helicopter use – gearbox is part of rotor system)

e) *Piston engines*

Small unsupercharged, $0 < P_0 < 150$ kW: $\frac{P_0}{M_{ENG}g} = 0.057(1 + 0.006 \text{ kW}) \text{ kW/N}$

Unsupercharged, $P_0 > 150$ kW: $\frac{P_0}{M_{ENG}g} = 0.12 \text{ kW/N}$

Supercharged, $P_0 > 150$ kW: $\frac{P_0}{M_{ENG}g} = 0.1 \text{ kW/N}$

f) *Small rotary engines* $\frac{P_0}{M_{ENG}g} = 0.135 \text{ kW/N}$

We note that typically, thrust or power *loading* will be calculated from the performance requirements, i.e. we will have required values for $T_0/W_0 = T_0/(M_0g)$ or $P_0/W_0 = P_0/(M_0g)$.

These can be combined with the above correlations to estimate values for M_{ENG} by using

$$M_{ENG} = M_0 \left(\frac{T_0}{M_0 g}\right)\left(\frac{M_{ENG}g}{T_0}\right) = M_0 \left(\frac{T_0}{W_0}\right) / \left(\frac{T_0}{M_{ENG}g}\right)$$ Thrust-characterised engines (jets)

$$M_{ENG} = M_0 \left(\frac{P_0}{M_0 g}\right)\left(\frac{M_{ENG}g}{P_0}\right) = M_0 \left(\frac{P_0}{W_0}\right) / \left(\frac{P_0}{M_{ENG}g}\right)$$ Power-characterised engines (props)

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Variable mass contributions – M_{SYS} and M_{FUEL}

M_{SYS} allows for the systems (other than fuel systems), furnishings, equipment, and landing gear.

$$M_{SYS} = C_4 M_0$$

Table 6.9 Systems factor, C_4

Includes equipment, landing gear and passenger furnishing *Howe*

TYPE OF AIRCRAFT	C_4
General aviation light single-engined types	0.12
Subsonic bombers	0.12
Subsonic freighters	0.12
Long range supersonic aircraft	0.12
Long range jet transports	0.14
Small regional transports	up to 0.22
General aviation, larger single- and twin-engine types	0.16
Executive aircraft	0.21 to 0.3*
Propeller turbine trainers	0.32
All other types	0.19

*Higher figure includes luxury furnishing.

The fuel mass, M_{FUEL} , is typically calculated as a proportion of M_0 as a part of mission analysis.

$$M_{FUEL} = \frac{W_f}{W_0} M_0 \equiv \frac{M_{FUEL}}{M_0} M_0$$

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Total mass from group masses

Recall:

$$M_0 = M_{\text{FIXED}} + M_{\text{VARIABLE}} = M_{\text{FIXED}} + M_{\text{LIFTSUR}} + M_{\text{POWERPT}} + M_{\text{SYS}} + M_{\text{FUEL}}$$

Now in the form

$$M_0 = M_{\text{FIXED}} + \overline{C}_1 \left[S^{1.5} \frac{M_0}{S} \right]^{0.9} + C_3 M_{\text{ENG}} + C_4 M_0 + \frac{W_f}{W_0} M_0 \quad \text{kg}$$

$$= M_{\text{FIXED}} + \overline{C}_1 \left[\left(\frac{S}{M_0} \right)^{0.5} M_0^{1.5} \right]^{0.9} + C_3 M_{\text{ENG}} + C_4 M_0 + \frac{W_f}{W_0} M_0 \quad \text{kg}$$

$$= M_{\text{FIXED}} + \overline{C}_1 \left[\left(\frac{g}{W_0/S} \right)^{0.5} M_0^{1.5} \right]^{0.9} + C_3 M_{\text{ENG}} + C_4 M_0 + \frac{W_f}{W_0} M_0 \quad \text{kg}$$

$$= M_{\text{FIXED}} + \overline{C}_1 \left[\frac{g}{W_0/S} \right]^{0.45} M_0^{1.35} + C_3 M_{\text{ENG}} + C_4 M_0 + \frac{W_f}{W_0} M_0 \quad \text{kg}$$

$$= M_{\text{FIXED}} + \overline{C}_1 \left[\frac{g}{W_0/S} \right]^{0.45} M_0^{1.35} + C_3 \left(\frac{T_0}{W_0} \right) / \left(\frac{T_0}{M_{\text{ENG}} g} \right) M_0 + C_4 M_0 + \frac{W_f}{W_0} M_0 \quad \text{kg}$$

or $\cdots + C_3 \left(\frac{P_0}{W_0} \right) / \left(\frac{P_0}{M_{\text{ENG}} g} \right) M_0 + \cdots$ as appropriate (prop aircraft)

Finally, we solve

$$M_0 = M_{\text{FIXED}} + \left[C_3 \left(\frac{T_0}{W_0} \right) / \left(\frac{T_0}{M_{\text{ENG}} g} \right) + C_4 + \frac{W_f}{W_0} \right] M_0 + \overline{C}_1 \left[\frac{g}{W_0/S} \right]^{0.45} M_0^{1.35}$$

for M_0.

The principle is the same regardless of the details of how group masses actually depend on M_0.

Note that now M_0 depends on W_0/S and T_0/W_0 as well as fuel use and payload.

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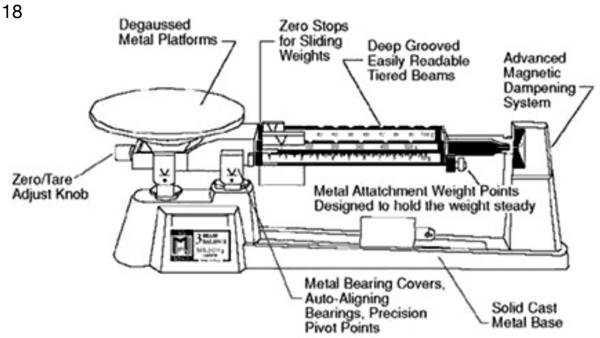


Preliminary longitudinal balance

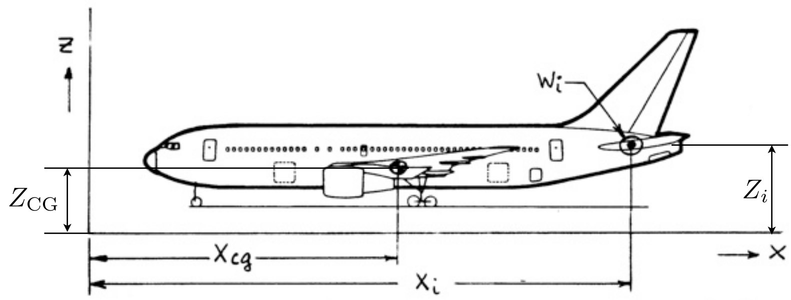
Recommended reading:

Jenkinson & Marchman: Chapter 2
Sforza: Chapter 8
Torenbeek: Chapter 8

Preliminary balance and CG location — 1

1. Once we have all the component masses (or some estimate of them) and the fuel mass, we are in a position to perform a preliminary centre of mass/gravity (CG) location. The aim is to move the masses around until the unloaded aircraft will balance longitudinally somewhere reasonably close to the CG location relative to the eventual Neutral Point, as chosen for a desired Static Margin.
2. For simplicity in some of what follows, the desired CG location is taken to be the *c*/4 point of the wing's mean aerodynamic chord (MAC), but in general it is located from the layout's stability characteristics. i.e. NP+SM (*see section on Tail Sizing)*.
3. To achieve the desired CG location we move the individual component masses around.
4. First we need to assess the moment arm of all the masses of the empty aircraft about some (arbitrary) datum, typically the nose of the aircraft (or better, a point even further forward and also below the aircraft). We then tabulate all the moment arms (X_i, Z_i) of the component mass CGs.

Note that we will usually need both the longitudinal and vertical location of the CG.



Roskam

Figure 9.1 Definition of Overall C.G. Location and of Component C.G. Location

5. Some of the component CGs will be known (for example, from manufacturer's data in the case of engines). Others can be estimated on the basis of correlations or experience (and ultimately, from parts drawings).

Preliminary balance and CG location — 2

Table 15.2 Approximate empty weight buildup

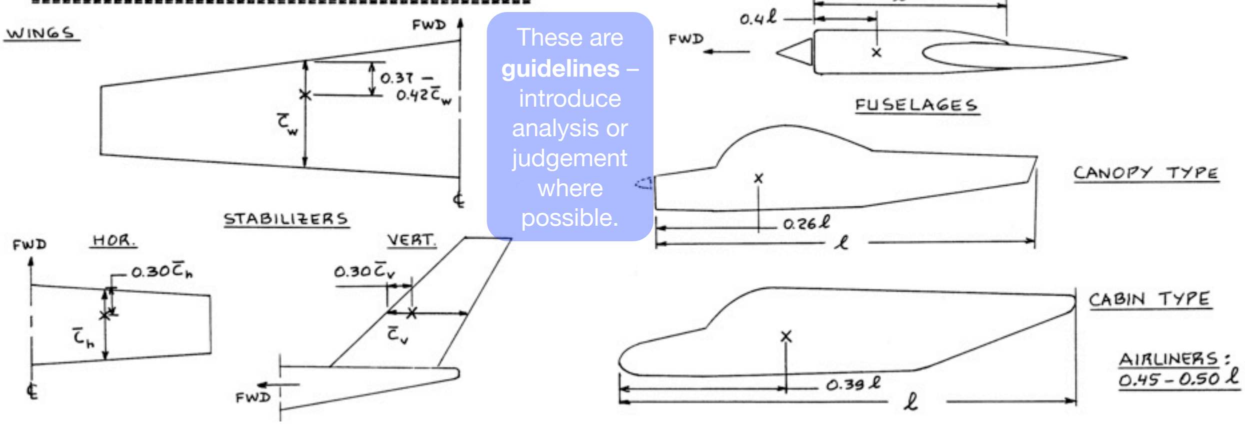
Raymer

Item	Fighters lb/ft²	Fighters {kg/m²}	Transports and bombers lb/ft²	Transports and bombers {kg/m²}	General aviation (metal) lb/ft²	General aviation (metal) {kg/m²}	Multiplier	Approximate location
Wing	9.0	{44}	10.0	{49}	2.5	{12}	$S_{\text{exposed planform}}$	40% MAC
Horizontal tail	4.0	{20}	5.5	{27}	2.0	{10}	$S_{\text{exposed planform}}$	40% MAC
Vertical tail	5.3	{26}	5.5	{27}	2.0	{10}	$S_{\text{exposed planform}}$	40% MAC
Fuselage	4.8	{23}	5.0	{24}	1.4	{7}	$S_{\text{wetted area}}$	40–50% length
Landing gear[a]	0.033	—	0.043	—	0.057	—	TOGW	—
	Navy: 0.045	—						
Installed engine	1.3	—	1.3	—	1.4	—	Engine weight	—
"All-else empty"	0.17	—	0.17	—	0.10	—	TOGW	40–50% length

[a]15% to nose gear; 85% to main gear; reduce gear weight by 0.014 W_0 if fixed gear.

Table 10.2 Location of C.G.'s of Major Components

Roskam



These are **guidelines** – introduce analysis or judgement where possible.

Preliminary balance and CG location — 3

6. Then we form an equilibrium of moments:

$$W_{\text{wing}}X_{\text{wing}} + W_{\text{fuse}}X_{\text{fuse}} + W_{\text{eng}}X_{\text{eng}} + \cdots W_{\text{furn}}X_{\text{furn}} + \cdots = W_{\text{MWE}}X_{\text{CG}}$$

where the manufacturer's empty weight, W_{MWE}, is the sum of the other weights:

$$W_{\text{wing}} + W_{\text{fuse}} + W_{\text{eng}} + \cdots W_{\text{furn}} + \cdots = W_{\text{MWE}}$$

7. Finally we adjust the location of the wing (and perhaps, other masses) so that the aircraft will balance near the $c/4$ point of the wing's MAC, $\bar{c}$. (More generally, the chosen CG location.)

$$W_{\text{wing}}(X_{\text{LE}} + C_1\bar{c}) + (\cdots) = W_{\text{MWE}}(X_{\text{LE}} + C_2\bar{c})$$

$C_1 \approx 0.4$ $\quad$ $C_2 \approx 0.25$

X_{LE} is the LE position of the wing's MAC.

C_1 gives the relative location of the wing's mass in relation to X_{LE}, while C_2 corresponds to where we want to place the overall CG.

Rearrange: $$X_{\text{LE}} = \frac{\bar{c}\,(W_{\text{wing}}C_1 - W_{\text{MWE}}C_2) + (\cdots)}{W_{\text{MWE}} - W_{\text{wing}}}$$

8. Rules of thumb for the approximate value of C_2, conventional aircraft layouts, at MWE:
   a. Typically: 0.25

   A more correct way to pick C_2 is to place the CG an appropriate distance ahead of the Neutral Point. These rules of thumb are for very preliminary estimates when the NP location is unknown.

   b. Engines located in nacelles on rear fuselage or layouts where loading pushes CG forward: 0.35
   c. Layouts where loading pushes CG aft: 0.20.
   d. Desirable for supersonic aircraft: 0.50 (note conflict with typical subsonic value).
9. If CG location differs from the above values by more than about 0.02 (2%), consider moving the wing.

Preliminary balance and CG location — 4

10. We should be aware that loading the aircraft will move the CG location. In general, it is best to place fuel and payload as symmetrically as possible in longitude about the chosen CG.
11. A plot of how the CG position varies with lading and with fuel use is called a 'CG loop', a 'weight and balance diagram', or a 'weight excursion diagram':

Schaufele

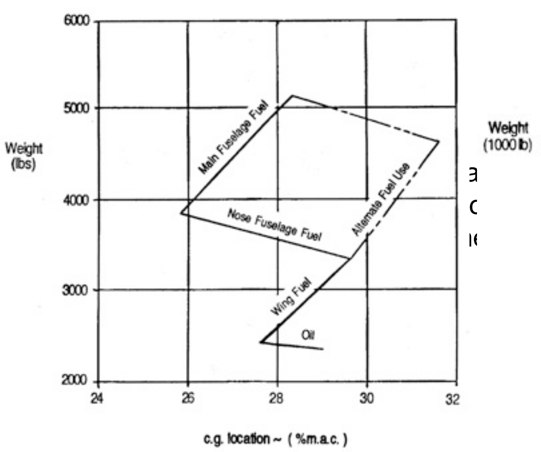


Figure 10-7 Weight and Balance Diagram–Ryan NYP

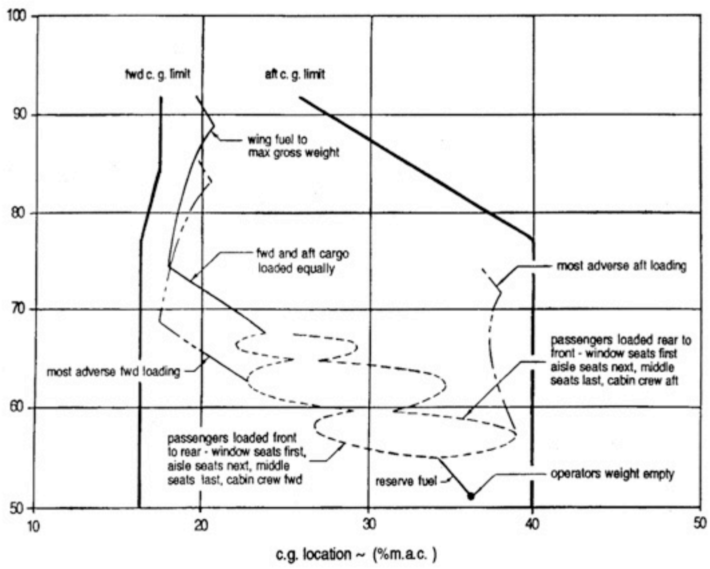


Figure 10-8 Weight and Balance Loading Diagram–Short Range Jet Transport

12. The fore and aft CG limits for the aircraft are related to its static stability (typically the aft limit) and the elevator authority required to trim or manoeuvre the aircraft (typically the forward limit).

Preliminary balance and CG location — 5

13. The layout of the aircraft influences how payload and fuel is distributed, leading to the previous guidelines on the initial target locations of OWE CG location:

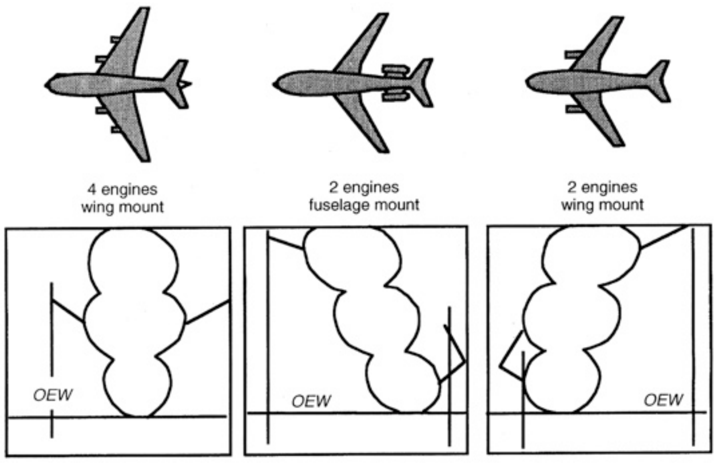


Fig. 7.15 Effect of aircraft configuration on the loading loops. *Jenkinson et al.*

14. Owing to aerodynamic considerations (such as transonic area-ruling) it may be undesirable to shift the wing relative to the fuselage. In this case, other masses must be moved instead in order to achieve the desired initial CG location.

15. Since it is needed for landing gear layout, it is advisable to calculate the vertical as well as horizontal CG location. The methodology is the same as outlined above except that the *Z* locations of all masses are used instead of *X* locations:

$$W_{\text{wing}}Z_{\text{wing}} + W_{\text{fuse}}Z_{\text{fuse}} + W_{\text{eng}}Z_{\text{eng}} + \cdots W_{\text{furn}}Z_{\text{furn}} + \cdots = W_{\text{MWE}}Z_{\text{CG}}$$