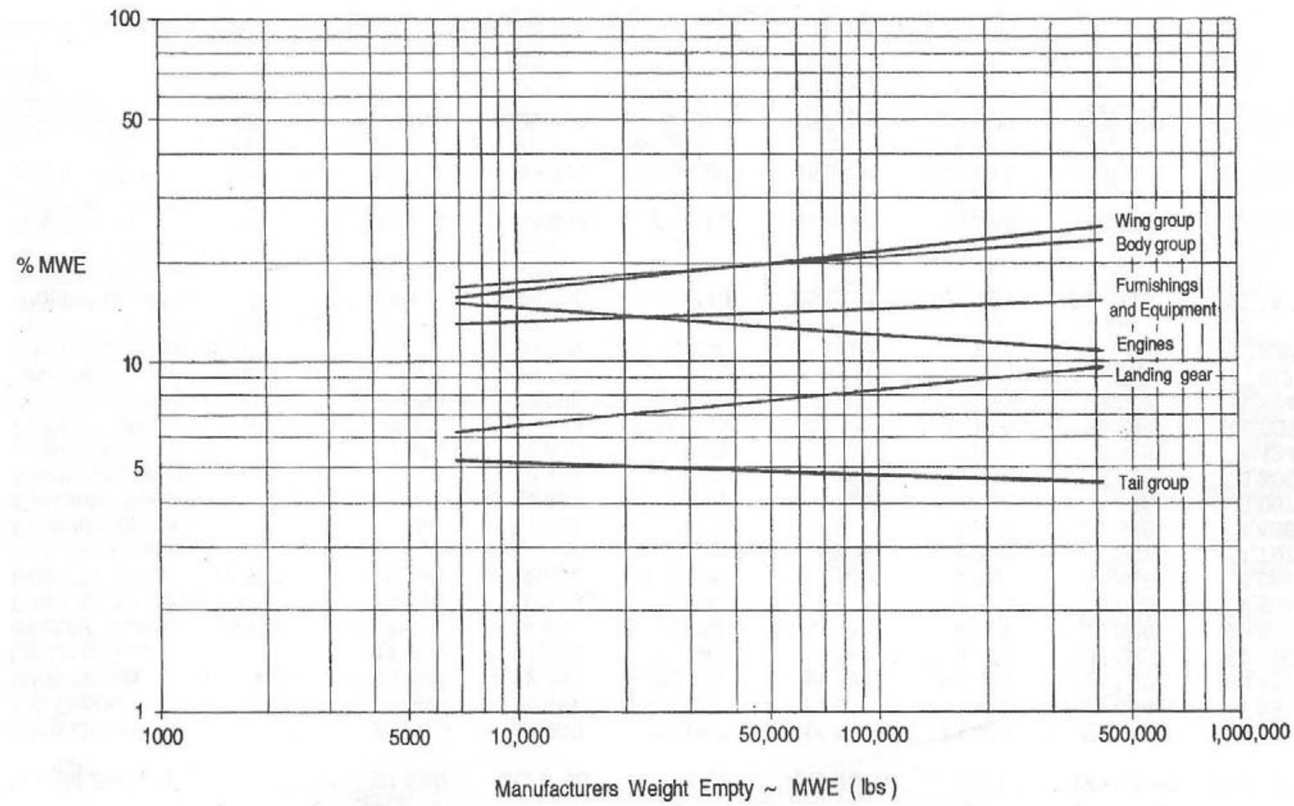
15.2 Approximate Weight Methods

For a commercial aircraft, a first estimation of group weights, for a known value of manufacturer's weight empty (MWE), is shown in Fig. 15.2.1. MWE is the operational weight empty (OWE) less operational items.



Source: Schaufele

Fig. 15.2.1 Manufacturer's Empty Weight Trend Data

Operational items are those required to bring the aircraft up to an operational standard. Examples of operational items are given in Figs. 15.2.2 and 15.2.3. For jet transports, using Raymer Table 3.1 for empty weight fraction, the empty weight calculated earlier was the MWE.

Operational Items	3,570 lb
Cockpit Crew (2 x 170 lb)	540
Cabin Crew (4 x 130 lb)	520
Crew Baggage (6 x 25 lb)	150
Flight Kits	25
Oil including Engine, Constant Speed Drive, APU and System Oil	136
Unusable Fuel	300
Food, Galley Service (12 F/C x 7.5 lb/pass + 141 E/C x 3.7 lb/pass)	612
Passenger Service Equipment (147 x 2 lb/pass)	294
Galley Inserts	750
Potable Water	196
Lavatory Fluids	69
Evacuation Slides	127
Life Vests	11

Source: Schaufele

Fig. 15.2.2 Operational Item List – Typical Short Range Jet Transport

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

Source: Schaufele

Fig. 15.2.3 Operational Item List – Typical Long Range Jet Transport

Estimation of C.G. Location – Passenger Transports

This exercise is best done using a spreadsheet with a format similar to Figure 15.2.4 shown here. This is similar to Raymer Table 15.1, but with local c.g. values (that is, the location of the c.g. with respect to the group itself) added. The locations of the c.g. for the weight groups are taken from Ref. 15.2.1. The spreadsheet will contain many more rows which will include combinations of passenger loading, cargo, and fuel. You may want to use additional columns for c.g. locations (forward location and aft location) and moment arms for determining forward and aft c.g. limits.

The c.g. of the airplane at the MWE condition can be calculated by summing the moments of each group as illustrated in the table shown here. Use Fig. 15.2.1 to determine the group weights as a function of MWE. For your design, establish a reference point (use the nose of the airplane, or preferably some arbitrary location forward of the nose) and find the location of the c.g. of each group with respect to the reference point.

	C.g. location		Group weight	Moment
	Local c.g. location	c.g. location (wrt ref.)		
Wing	0.37 - 0.42 MAC_{wing}			
Horizontal tail	0.30 MAC_{ht}			
Vertical tail	0.30 MAC_{vt}			
Nacelle	0.40 l_{nac}			
Fuselage - canopy type	0.26 l_{fuse}			
Fuselage - cabin type	0.39 l_{fuse}			
Fuselage - airliner	0.45 - 0.5 l_{fuse}			
Landing gear	0.95 l_{gear}			
Furnishings and Equipment	Same as fuselage			
MWE		$\frac{\Sigma \text{(moments)}}{\Sigma \text{(weights)}}$	Σ (weights)	Σ (moments)
Additional rows for pax. & cargo				

Note: l_{gear} is the distance between the nose gear and main landing gear.

Fig 15.2.4 Calculation of Aircraft Center of Gravity at MWE

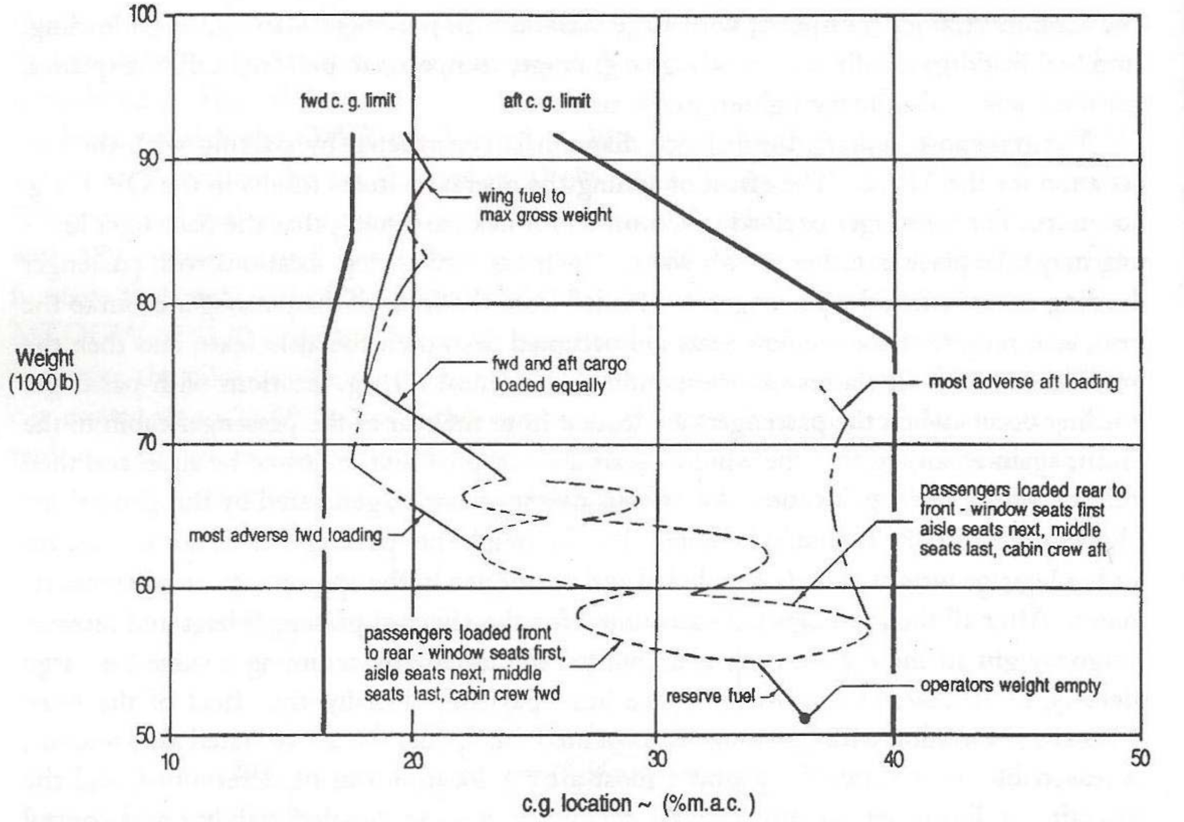
From this table you can calculate moments and c.g. location. If necessary move the wing so that the c.g. meets the following requirements:

- For engines located on the wing 25% MAC
- For engines located on the aft fuselage 35% MAC

This is an approximate method of wing location. You may have to move the wing more than you expect, and it may be better to think in terms of moving the fuselage with respect to the wing. Wing and engines may constitute half the MWE of the airplane, so if the engines are on the wing, the fuselage has to be moved a long way to change the location of the c.g.

If you move the location of the wing, then you <u>should</u>, but you won't have time to do it here, readjust the tail areas to reflect the change in length of the tail arm.

For a passenger-carrying transport aircraft, the next step is to add passengers. Inspect Fig. 15.2.5, and note that this applies to the DC-9-20 with engines at the rear. This plot is also known as a "potato plot". Assume operational items are 5% MWE for single aisle jet transports and 6% MWE for twin aisle jet transports. Add the operational weights in to get to OWE. If engines are mounted on the wing the c.g. travel from MWE to OWE will be small, so you may assume that the OWE is located at the same % MAC as MWE. If the engines are at the rear, the OWE will be forward of the MWE by 3 - 4% MAC.



Source: Schaufele

Fig. 15.2.5 Weight and Balance Loading Diagram – DC-9-20

Now add reserve fuel (which you know from your mission calculations). If the engines are on the wing, you can assume reserve fuel is in the outer wing tanks, which may move the c.g. aft about 3 - 4% MAC. If the engines are at the rear you will want reserve fuel to move the c.g. as far forward as possible, so assume that reserve fuel is in the inboard tanks. This will take you to the bottom of the first "potato" of the potato plot.

The following steps apply only to Fig. 15.2.5. Your schedule will probably be different. The DC-9 has five seats per row, with two seats on the left side (looking forward) of the aisle and three on the right. Fig. 15.2.5 refers to adding cabin crew in addition to passengers. This is not correct. Cabin crew are a component of the operational items (see Fig. 15.2.3 or 15.2.4) and were therefore added when adding weight to MWE to reach OWE.

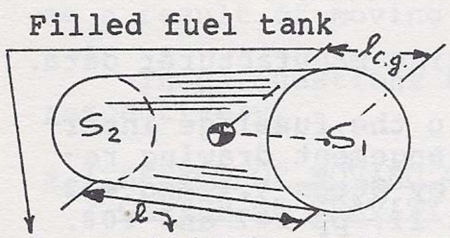
1. Fill all the window seats on both side of the airplane for the aft half of the airplane only, starting at the rear seats. This will take you to the right hand side (RHS) of the bottom potato.
2. Now fill the remainder (the forward half) of the window seats. This will now take you to the top of the bottom potato.
3. Take out all the passengers, and repeat steps 1 and 2, this time starting with the front seats, and filling toward the rear. This will provide the shape of the forward half of the bottom potato.
4. With the window seats now filled, repeat steps 1 through 3 again, this time for the aisle seats. This will take you to the top of the second potato.
5. With the window and aisle seats filled, repeat steps 1 through 3 again for the middle seats. Since there is only one middle seat per row on the DC-9, the potato is only half the size of the other two potatoes.

For a 747 with ten seats per row (ABC/DEFG/HJK), fill seats AK first, then HC, then DG, then BJ, then EF (there is no seat "I" so that passengers will not be confused with Row 1 and try to sit in first class). For other airplane configurations, use a similar loading logic. If the engines are located on the wing, the potatoes will stack almost vertically.

All airliners, but not business jets, will have the capability of carrying cargo in the hold under the passenger floor in addition to the passengers' checked bags. Cargo capacity will typically be of the order of 50% of the passenger capacity but may be almost 100% of the passenger capacity, as for example the 767-300ER or 767-400ER. When the airplane is operated at less than the design range, cargo revenue is a significant source of income to the airline. Cargo capacity is a function of how many containers (Raymer Fig. 9.4) can be fitted into the cargo hold and average container payload density, and is beyond the scope of this exercise. Assume therefore that another 50% of the payload (pax plus baggage) can be carried as cargo.

- From the most adverse passenger aft c.g. loading condition, add cargo from the aft end going forward. This will give you the most adverse aft loading.
- From the most adverse passenger forward c.g. loading condition, add cargo from the forward end going aft. This will give you the most adverse forward loading.
- The addition of cargo weights will bring the weight on the loading diagram up to the end of mission weight (pax plus cargo plus reserve fuel) for a mission operating at the space-limited payload. The space-limited range is less than the design range.

In practice, the airplane will have loading combinations of fuel and cargo for a constant MTOGW. However, we will assume that no cargo is on board when mission fuel is added. Assume two tanks per side of equal volume. Estimate the total wing fuel tank volume by calculating the volume between the front and rear spars from the side of body to 85% of the span, and then assume fuel occupies 92% of the gross volume. Each side normally has two tanks, inboard and outboard. Assume they are of equal volume. Jet A has a density of about 50.4 lb/ft^3. If the mission fuel does not fit into the wing tanks, the remainder will have to have to go into the center wing box. The c.g. of each tank may be estimated using the following equation taken from Ref 15.2.2:



Assuming a prismoidal shape (See figure left), the c.g. is located relative to plane S_1 at:

$$l_{cg} = (1/4)\{S_1 + 3S_2 + 2(S_1S_2)^{1/2}\}/\{S_1 + S_2 + (S_1S_2)^{1/2}\}$$

Figure 15.2.6 Estimate of Fuel Tank Center of Gravity

A more accurate method of estimation of fuel tank volume is given in the annotation to section 17.2.4.

- From the top of the top potato, add mission fuel, first to the outer (most aft tanks), then the inner tanks.
- This will bring you up to MTOGW for a configuration operating at the design range.
- Draw an envelope around the c.g. travel that is vertical up to the end of mission weight, then merges to have about a 10% c.g. travel limit at MTOGW.

In practice, airplane loading may be limited to avoid extreme c.g. travel. For example a business jet with aft-mounted engines may have to have bags loaded in the forward baggage compartment first. The pilot is responsible for checking weight and balance (Ref. 15.2.3).

In addition, aircraft may have slightly different c.g. limits for flight and ground operations. The ground operation aft c.g. limit may be determined by tip-up or by having sufficient load on the nose gear for adequate steering control.

Estimation of C.G. Location – Military and General Aviation

For aircraft apart from passenger transports, Raymer Table 15.2 may be used to estimate the group weights, and thus the empty weight location.

The location of the c.g. is critically important for two reasons:

1) the wing must be located in the correct position on the body to give the appropriate static margin, and
2) the landing gear must be located with the correct position for the appropriate tip-back margin, otherwise the aircraft will either unable to rotate on takeoff, or it may tip back on to its tail.

References

15.2.1 Roskam, J., "Airplane Design Part II: Configuration Design", Roskam Aviation and Engineering Corp, 1985

15.2.2 Roskam, J., "Airplane Design Part V: Component Weight Estimation", Roskam Aviation and Engineering Corp, 1985

15.2.3 Anon, "Pilot's Weight and Balance Handbook", Federal Aviation Administration, US Department of Transportation, AC 91-23A, 1977