Aeronautical Engineering Design I

Weight of an airplane and its first estimate

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Weight components

- Weight components:
  - Crew weight, W_{crew}: people necessary to operate the airplane in flight.
  - Payload weight, $W_{payload}$: is what the airplane is intended or designed to carry.
  - Fuel weight, W_{fuel}: weight of the fuel in the fuel tanks used to complete the mission.
  - Empty weight, W_{empty}: weight of everything else; structure, engines, electrical equipment, avionics, landing gear, fixed equipment.

Design takeoff gross weight, W_o

- Design takeoff gross weight, W_o: the weight of the airplane at the instant it begins its mission.

$$W_o = W_{crew} + W_{payload} + W_{fuel} + W_{empty}$$

$$W_o = W_{crew} + W_{payload} + \frac{W_{fuel}}{W_o} W_o + \frac{W_{empty}}{W_o} W_o$$

$$W_o = \frac{W_{crew} + W_{payload}}{1 - W_{fuel}/W_o - W_{empty}/W_o}$$

Empty weight fraction, W_e/W_o

- Most airplane designs are **evolutionary, not revolutionary** $\Rightarrow$ one can look at existing designs for an initial estimate of the empty weight fraction.

  $$W_e/W_o = AW_o^c K_{vs}$$

  $$K_{vs} = 1.0 \text{ for fixed wing sweep}$$

  $$= 1.04 \text{ for variable sweep}$$

- Empty weight fraction of **composite aircraft** can be estimated by multiplying the statistical empty weight fraction by 0.95.
- Notice: **empty weight fraction decreases with increasing takeoff gross wieght**.

Empty weight fraction, W_e/W_o

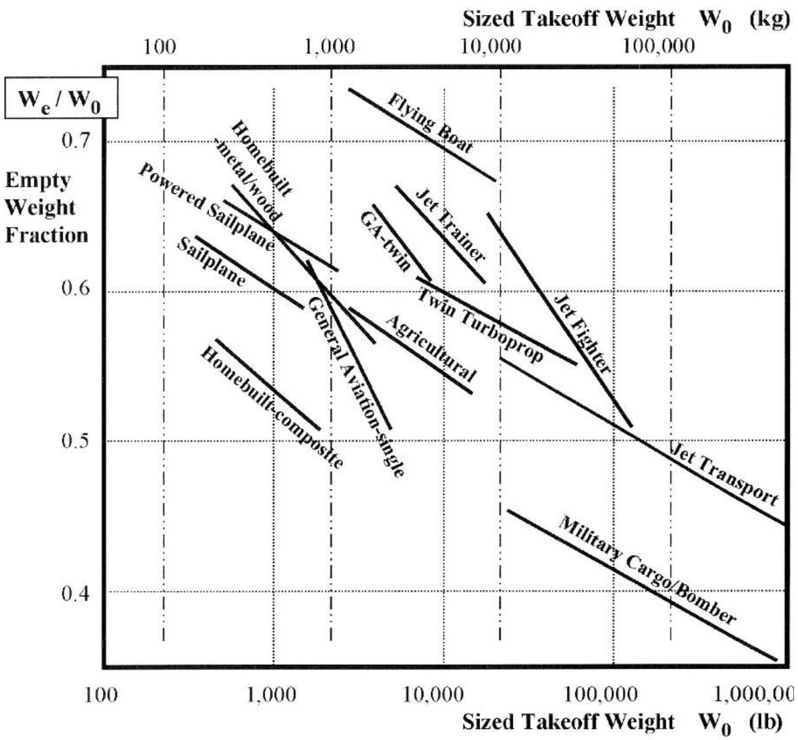


Fig. 3.1 Empty weight fraction trends.

Table 3.1 Empty weight fraction vs W_0

$W_e/W_0 = AW_0^C K_{vs}$	A	{A-metric}	C
Sailplane—unpowered	0.86	{0.83}	−0.05
Sailplane—powered	0.91	{0.88}	−0.05
Homebuilt—metal/wood	1.19	{1.11}	−0.09
Homebuilt—composite	1.15	{1.07}	−0.09
General aviation—single engine	2.36	{2.05}	−0.18
General aviation—twin engine	1.51	{1.4}	−0.10
Agricultural aircraft	0.74	{0.72}	−0.03
Twin turboprop	0.96	{0.92}	−0.05
Flying boat	1.09	{1.05}	−0.05
Jet trainer	1.59	{1.47}	−0.10
Jet fighter	2.34	{2.11}	−0.13
Military cargo/bomber	0.93	{0.88}	−0.07
Jet transport	1.02	{0.97}	−0.06

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

One may also use the average of W_e/W_o of the competitors if the scatter is not too much.

Fuel weight fraction, W_f/W_o

- Mission fuel depends on mission to be flown, the aerodynamics of the aircraft, and the fuel consumption rate of the engine(s).
- The aircraft weight effects drag so **fuel consumed is a function of aircraft weight**.
- The total fuel consumed during the mission is that consumed from the moment the engine(s) are turned on at the departure location, to the moment they are turned off at the end of the flight at the destination.

Fuel weight fraction, W_f/W_o

- Between these times the flight can be described by a **mission profile**; a conceptual sketch of **altitude vs. time**.

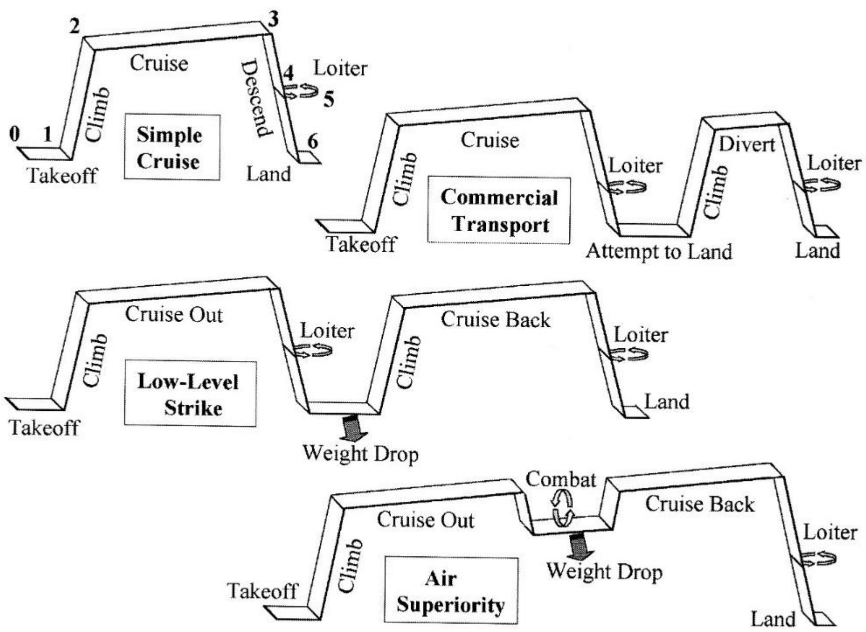
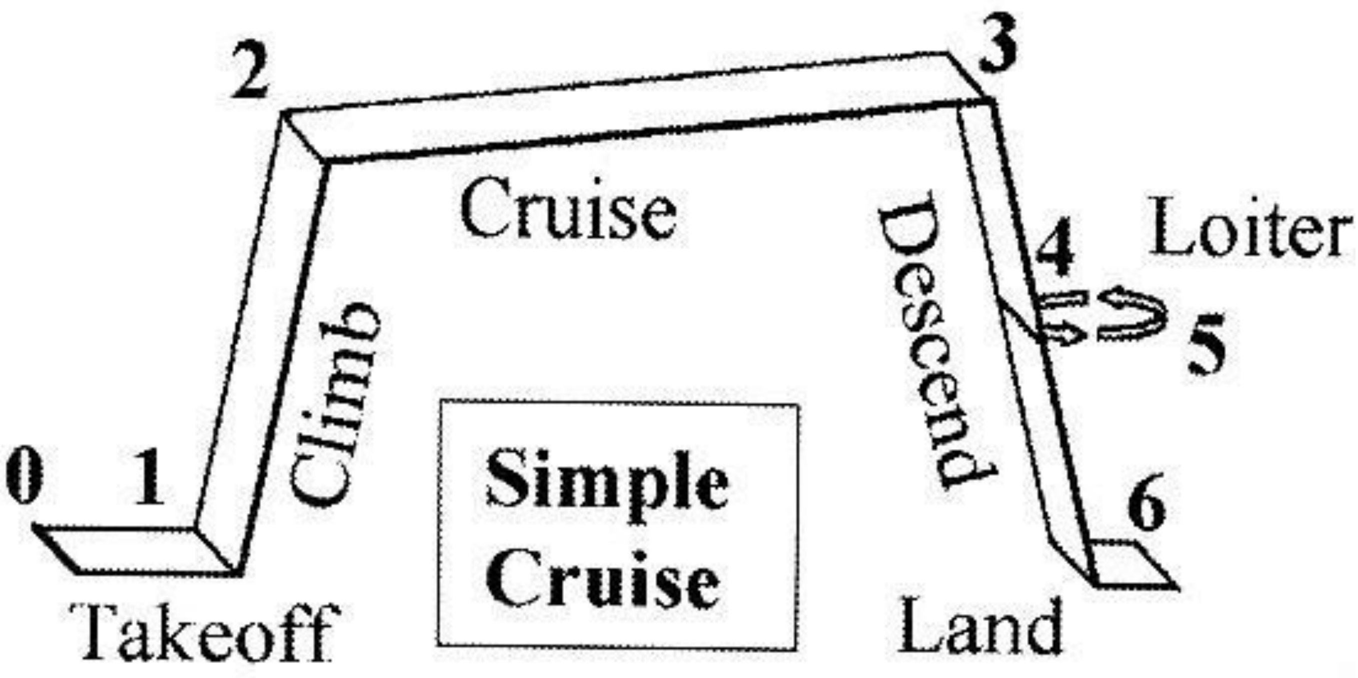


Fig. 3.2 Typical mission profiles for sizing.

Fuel weight fraction, W_f/W_o

- Consider the simple cruise mission profile:



Fuel weight fraction, W_f/W_o

- Each segment of the mission profile is associated with a weight fraction; airplane weight at the end of the segment divided by the weight at the beginning of the segment.
- Mission segment weight fraction: $\frac{W_i}{W_{i-1}}$
- For the simple cruise mission:

$$\frac{W_6}{W_o} = \frac{W_6}{W_5}\frac{W_5}{W_4}\frac{W_4}{W_3}\frac{W_3}{W_2}\frac{W_2}{W_1}\frac{W_1}{W_o} \qquad (*)$$

Fuel weight fraction, W_f/W_o

$W_f = W_o - W_6$, assuming that the fuel tanks are completely empty at the end of the flight.

$$\frac{W_f}{W_o} = 1 - \frac{W_6}{W_o}$$

$\frac{W_f}{W_o} = 1.06\left(1 - \frac{W_6}{W_o}\right)$, allowing for 6% reserve or trapped fuel. (**)

Fuel weight fraction, W_f/W_o

- W_f/W_o is calculated from:
  - Calculate each mission segment weight fraction,
  - Calculate W_6/W_o from (*),
  - Calculate W_f/W_o from (**).
- This method **does not** allow mission segments involving weight drops, aerial refuelling and combat.

Mission segment weight fractions

- 0-1: Engine start, warmup, taxi and takeoff (historical trend):

$$\frac{W_1}{W_o} = 0.97$$

- 1-2: Climb (historical trend):

$$\frac{W_2}{W_1} = 0.985$$

- 2-3: Cruise (Breguet Range Equation):

$$R = \frac{V_\infty}{C}\frac{L}{D}\ln\frac{W_2}{W_3} \text{ or } \frac{W_3}{W_2} = e^{-\frac{RC}{V_\infty (L/D)}}$$

$C = C(V_\infty, h, \text{throttle setting})$: specific fuel consumption

$L/D = L/D\ (V_\infty, h, \mathrm{W})$: lift-to-drag ratio

Specific fuel consumption

- Specific fuel consumption is the rate of fuel consumption per resulting thrust:

Jet engines: $\frac{fuel\ mass\ flow/hour}{thrust} = \frac{lb/h}{lb} \text{ or } \frac{N/h}{N} = \frac{1}{h} \quad (C)$

Propeller engines: $\frac{fuel\ mass\ flow/hour}{brake\ horsepower} = \frac{lb/h}{bhp} \text{ or } \frac{kg/h}{W} \quad (C_{bhp})$

Propeller efficiency, $\eta_p = \frac{TV_\infty}{P} = \frac{TV_\infty}{550hp}$

$$\Rightarrow C = \frac{W_f/time}{T} = C_p \frac{V_\infty}{\eta_p} = C_{bhp} \frac{V_\infty}{550\eta_p}$$

Specific fuel consumption

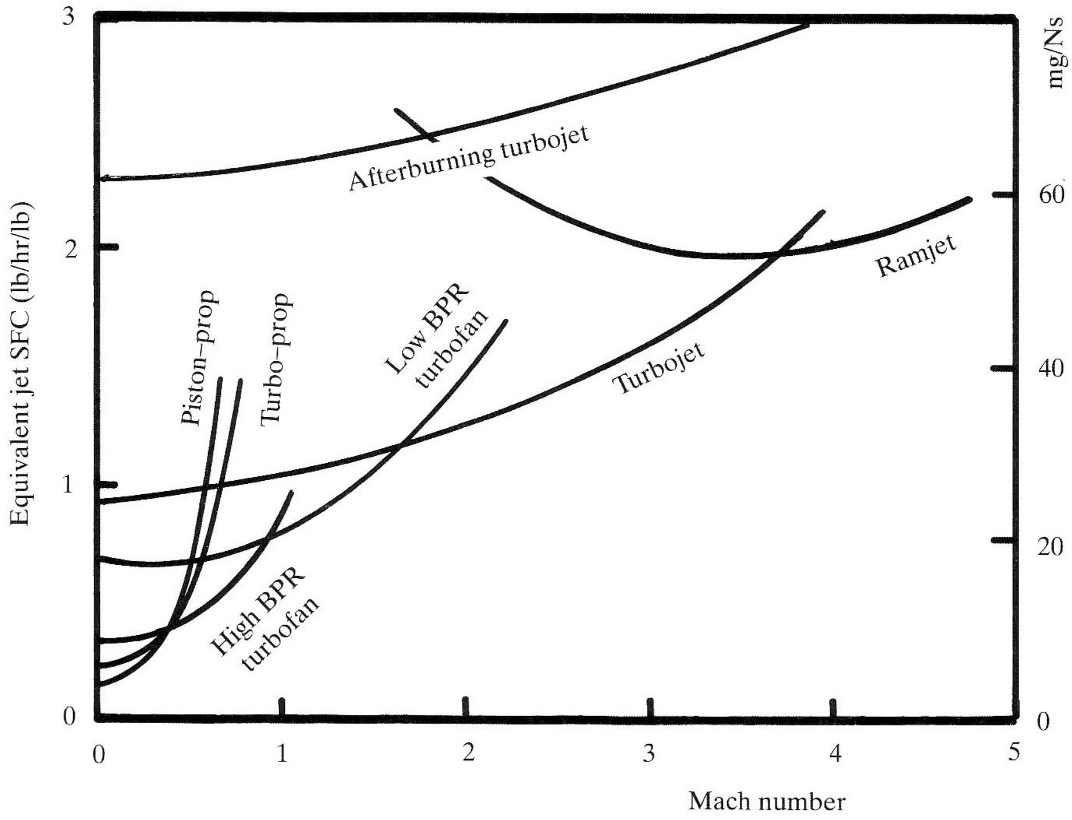


Fig. 3.3 Specific fuel consumption trends (at typical cruise altitudes).

Specific fuel consumption – typical values

Typical jet SFC: 1/h (mg/Ns)	Cruise	Loiter
Pure turbojet	0.9 (25.5)	0.8 (22.7)
Low bypass turbofan	0.8 (22.7)	0.7 (19.8)
High bypass turbofan	0.5 (14.1)	0.4 (11.3)

Typical propeller C_{bhp}: lb/h/bhp (mg/Ws)	Cruise	Loiter
Piston-prop	0.4 (0.068)	0.5 (0.085)
Turboprop	0.5 (0.085)	0.6 (0.101)

Lift-to-drag ratio

- Lift-to-drag ratio (L/D) is a measure of aerodynamic efficiency.
- At subsonic speeds, L/D = L/D(wing span, wetted area).
- Supersonic speeds: L/D=L/D(wing span, wetted area, Mach #).
- In level flight, L=W⇒L/D=L/D(D) only.
- Drag components at subsonic speeds:
  - Induced drag or **drag due-to-lift is a function of wing span**.
  - Parasite drag or zero-lift drag is **skin friction drag and is a function of the total surface area exposed to air (wetted area)**.

⇒**L/D is a function of the wetted aspect ratio**$= \frac{b^2}{S_{wet}}$, use historical trends.

Wetted aspect ratio

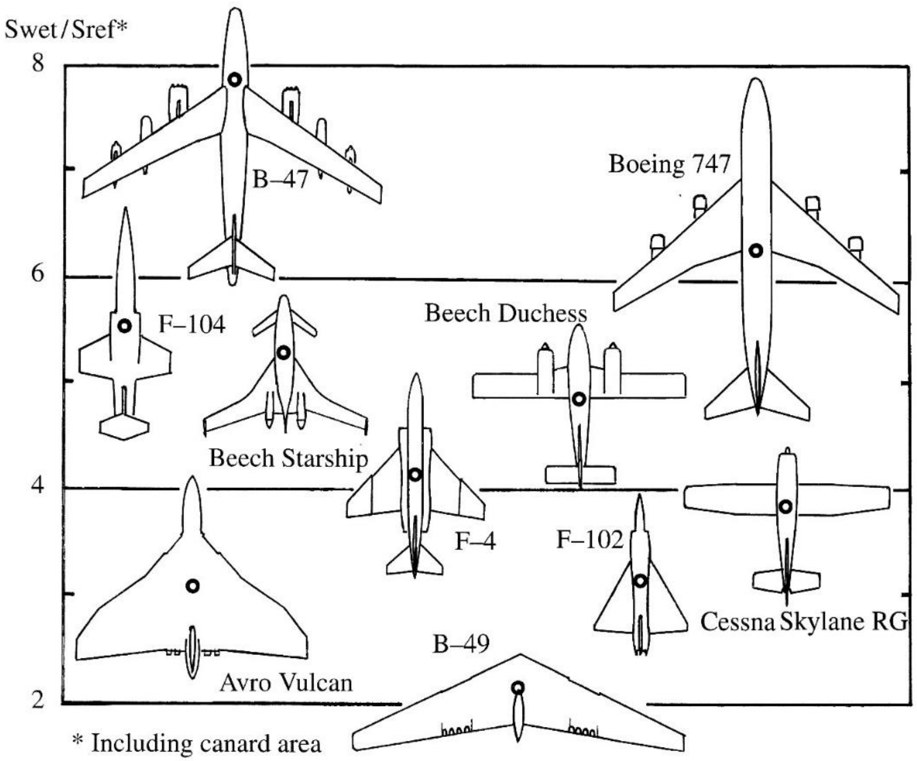


Fig. 3.5 Wetted area ratios.

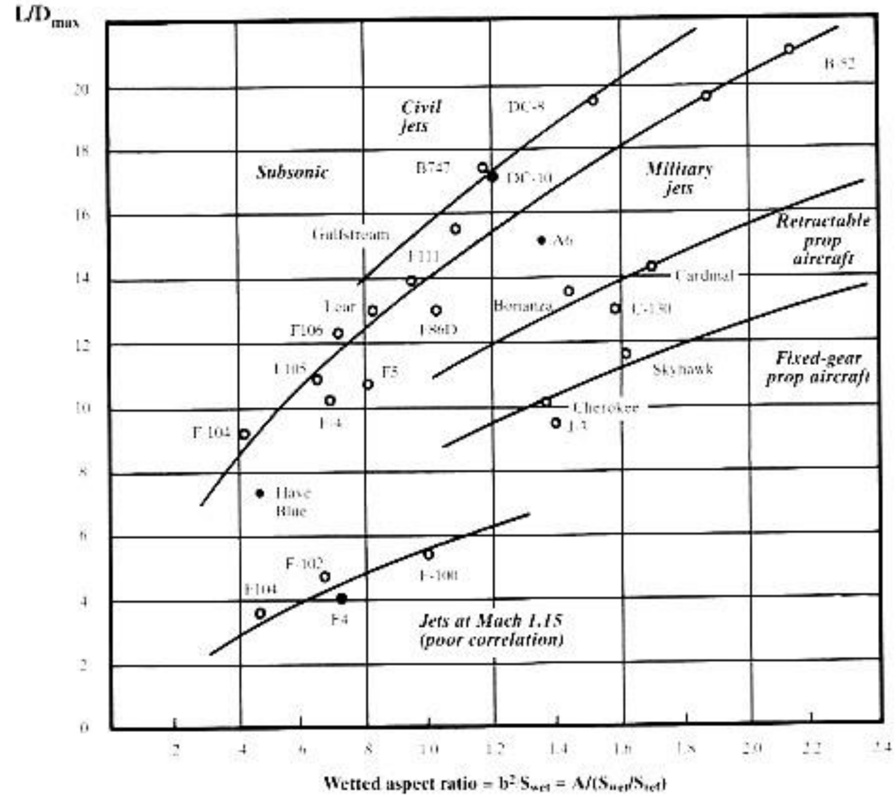


Fig. 3.6 Maximum lift-to-drag ratio trends.

Most efficient L/D values for cruise and loiter

Type of airplane	Cruise	Loiter
Jet	$0.866\ L/D)_{max}$	$L/D)_{max}$
Propeller	$L/D)_{max}$	$0.866\ L/D)_{max}$

Mission segment weight fractions

- 3-4: Descent:

$$\frac{W_4}{W_3} = 1.0$$

- 4-5: Loiter (endurance equation):

$$E = \frac{L/D}{C} \ln \frac{W_4}{W_5} \text{ or } \frac{W_5}{W_4} = e^{-\frac{EC}{(L/D)}}$$

- 5-6: Descent and landing (historical trend):

$$\frac{W_6}{W_5} = 0.995$$

First order design method

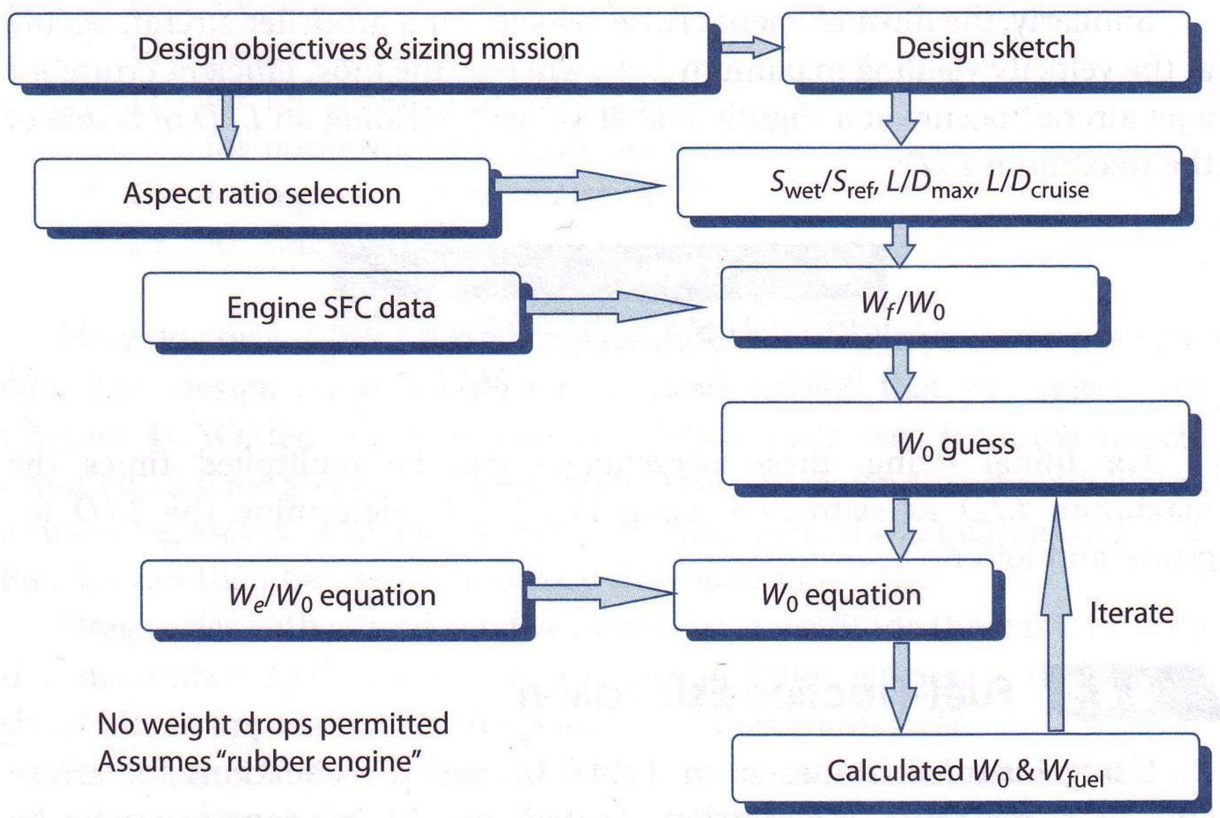


Fig. 3.7 First-order design method.

Trade (sensitivity) studies

- An important part of conceptual design is the evaluation and **refinement of the design requirements**.
- This is done by:
  - Calculating total weight by changing the weight fractions using arbitrarily selected range, endurance, etc.
  - Changing payload weights.
- By this, the **variation in the design takeoff gross weight** can be determined.