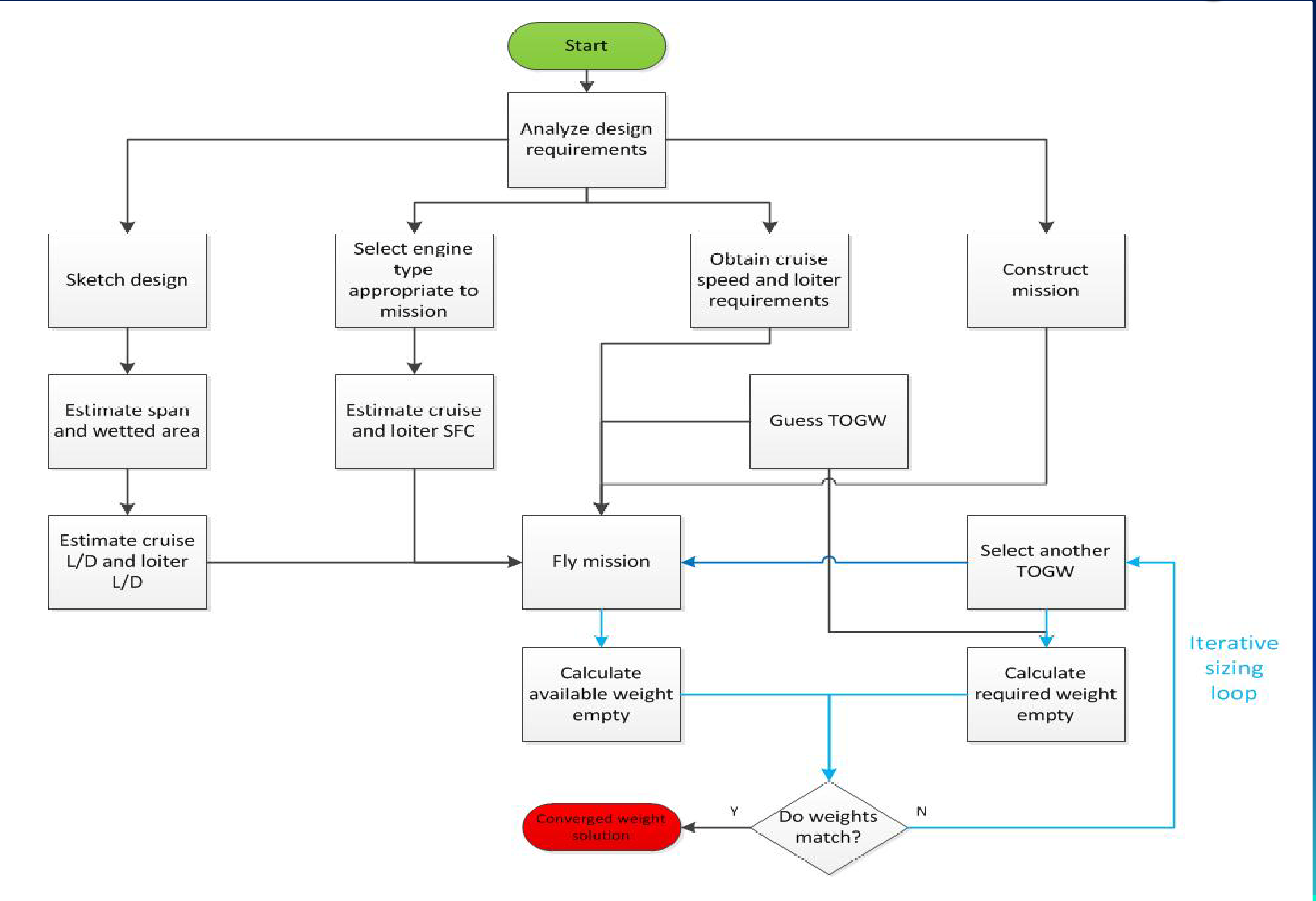
5 First Estimate of Takeoff Gross Weight (TOGW)

Initial Estimate of Take-Off Gross Weight



Initial Estimate of TOGW

- Method for all aircraft sizing programs is "empty weight matching"
- TOGW is defined as

$$W_0 = \underbrace{W_{fuel} + W_{crew} + W_{payload}}_{\text{Useful load}} + W_{empty}$$

Empty weight is

$$W_{empty} = W_0 - \underbrace{\left(W_{fuel} + W_{crew} + W_{payload}\right)}_{\text{Useful load}}$$

Empty Weight Matching

- Match
  - Empty weight available (based on mission analysis)

  To

  - Empty weight required (based on statistical weight analysis of comparable aircraft, or component weight buildup)

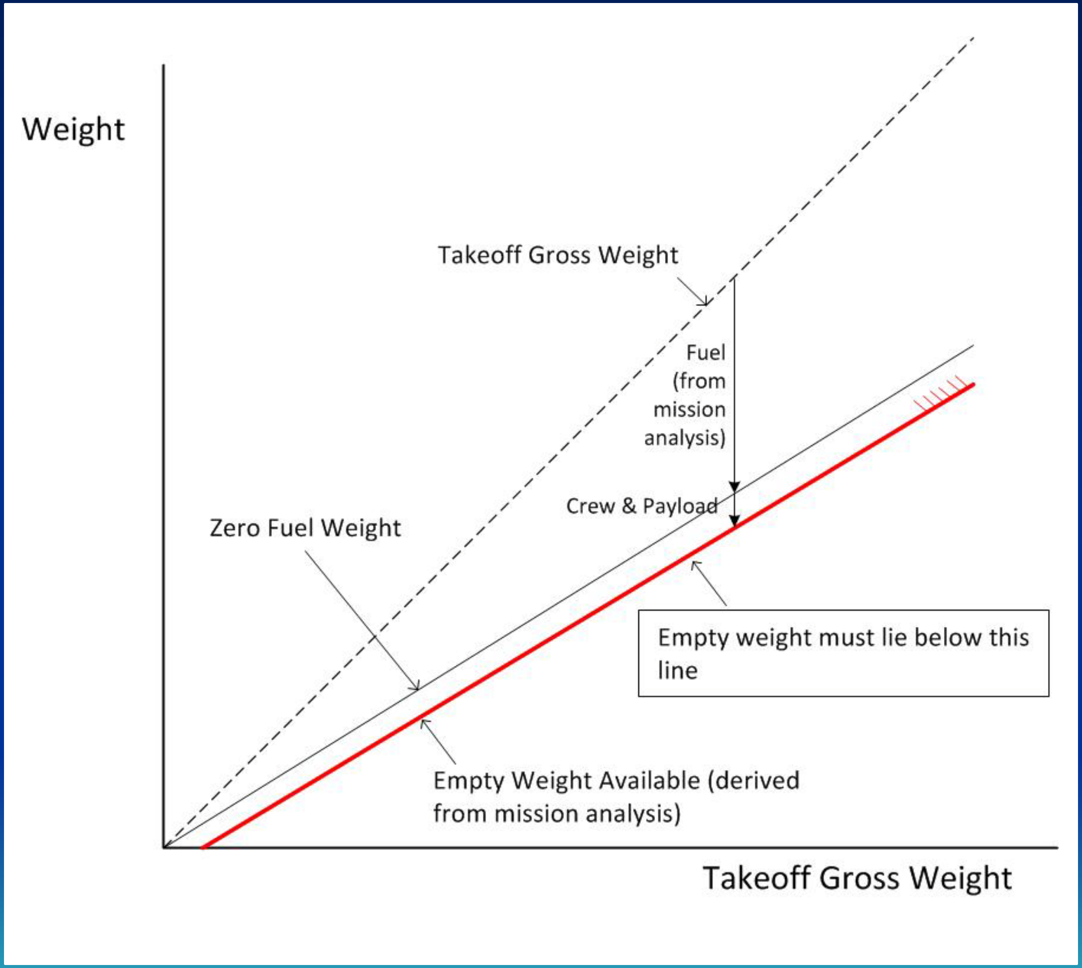
Empty Weight Available

$$W_E = W_{TO} - (W_{FUEL} + W_{CREW} + W_{PL})$$

- Assume value of TOGW
- Fly aircraft on simulated mission
- Calculate fuel consumed plus reserves
- Subtract fuel, crew, and payload weight from assumed TOGW
- Result is “empty weight available”

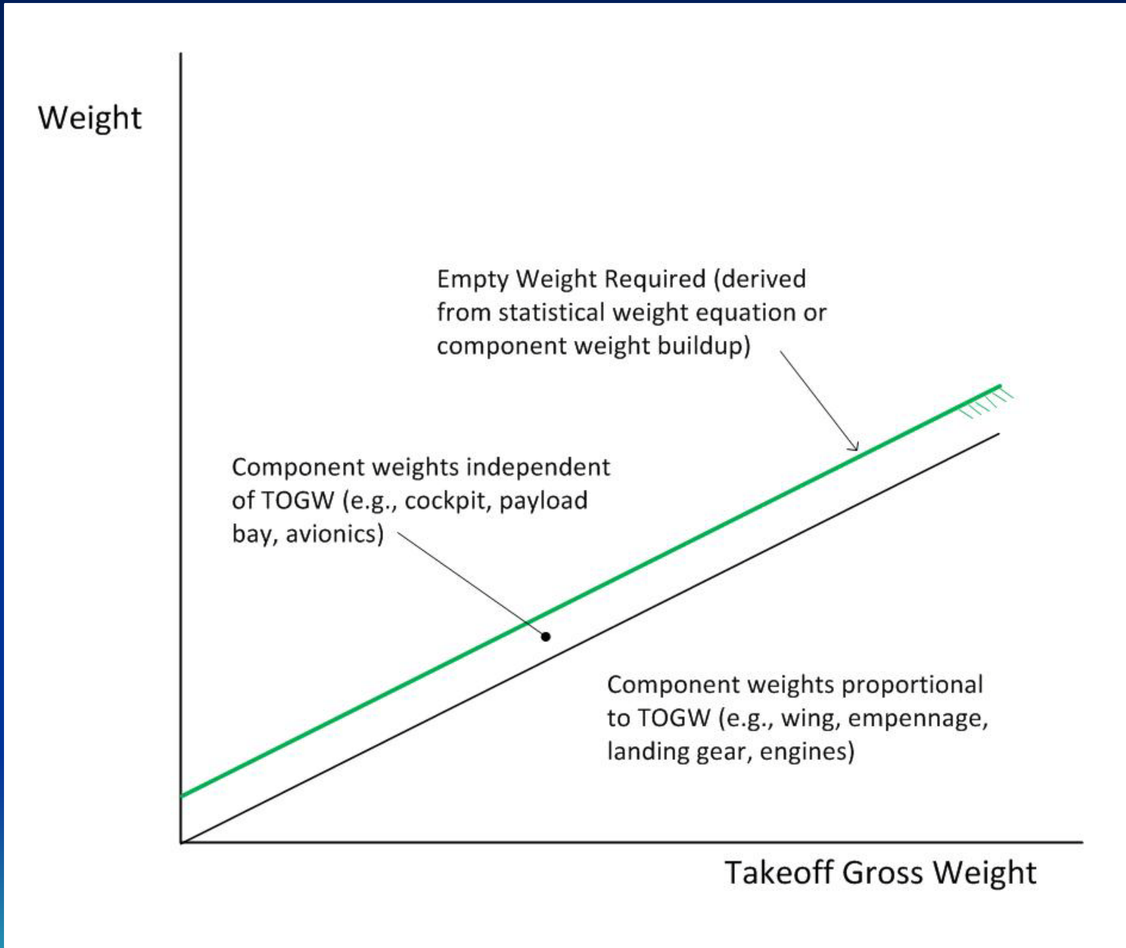
Empty Weight Available

- Empty weight available as a function of assumed TOGW



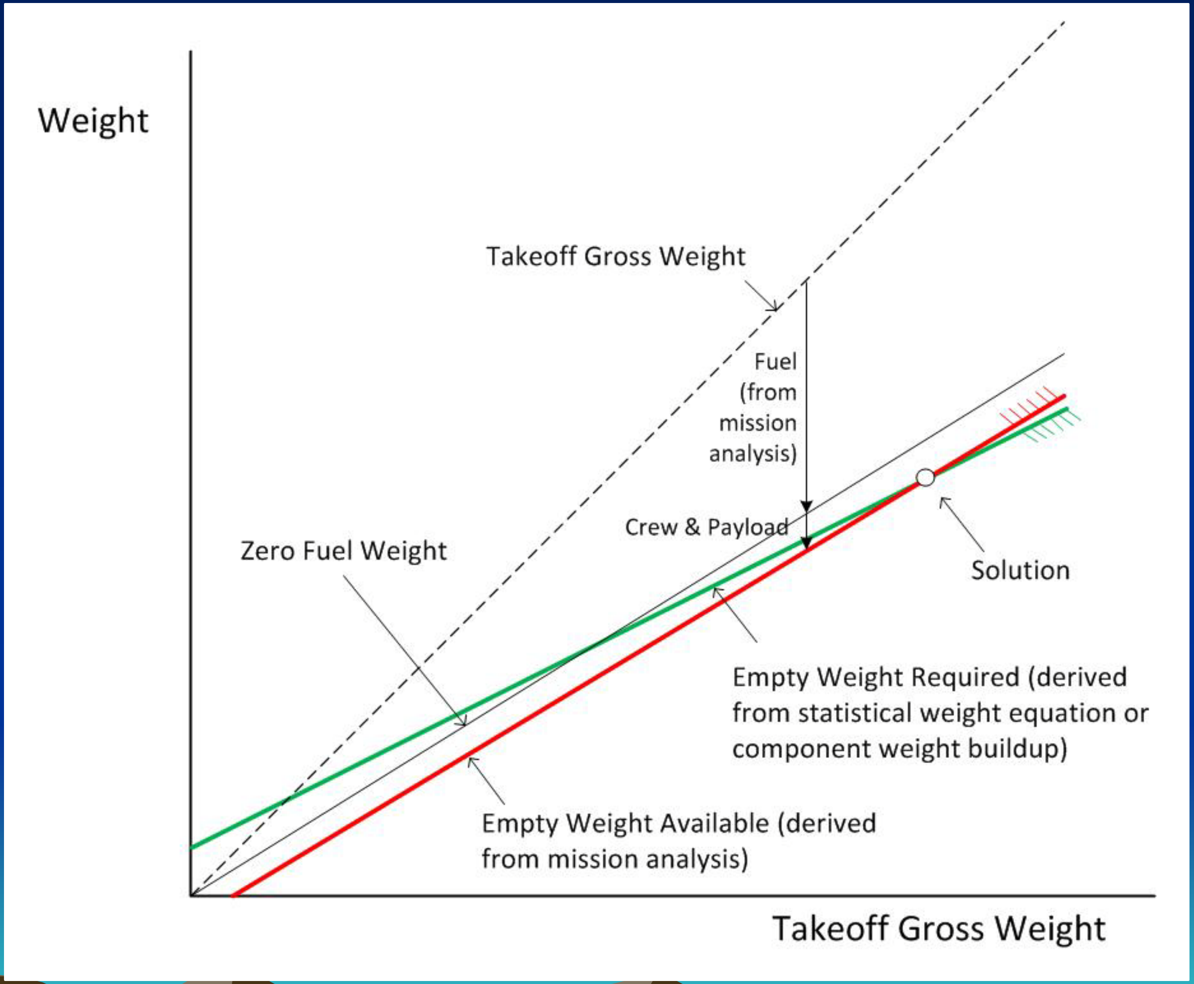
Empty Weight Required

- Empty weight required based on component weight buildup



Empty Weight Solution

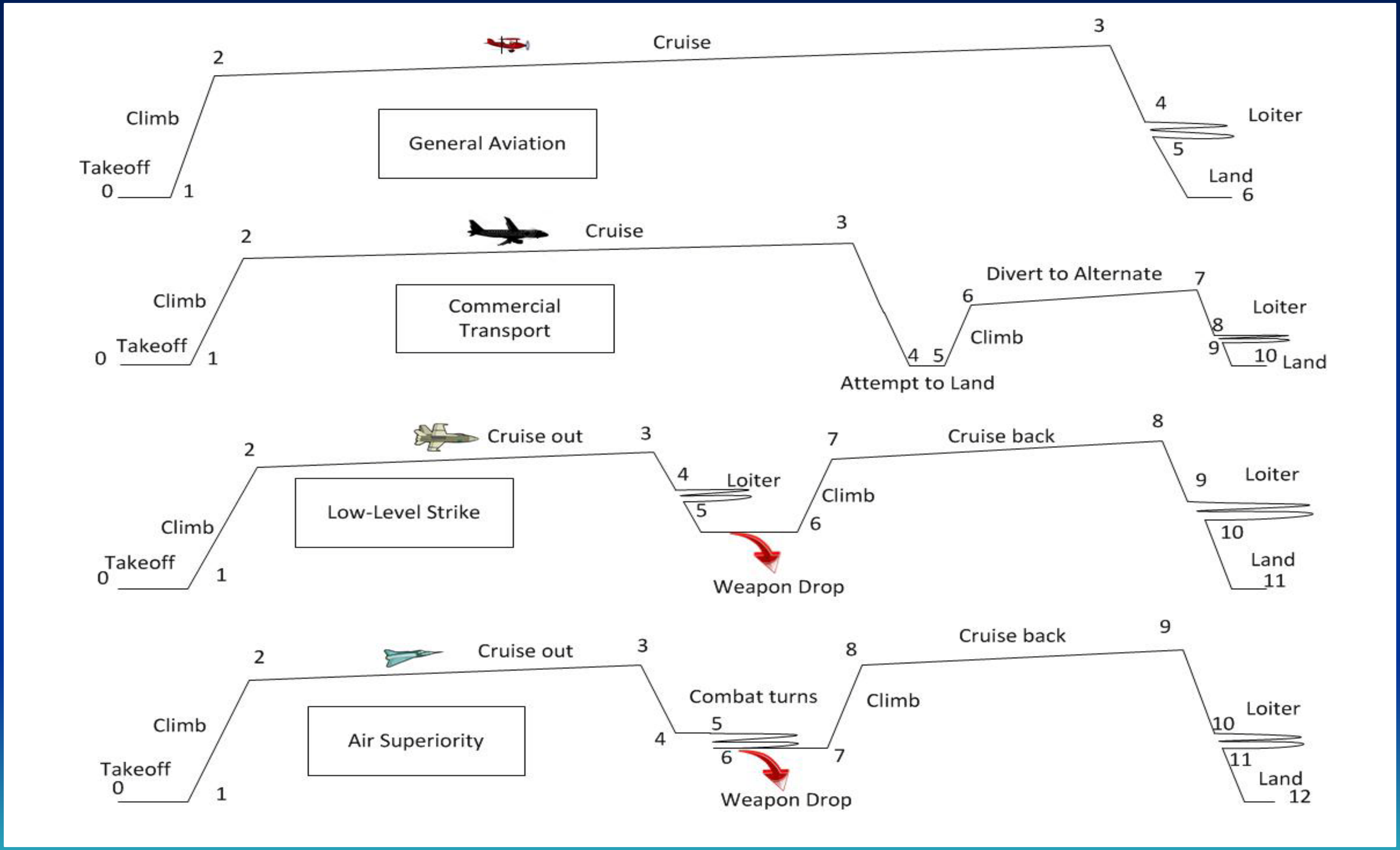
- Minimum empty weight is at intersection of empty weight available and required



Estimating Empty Weight Available

1. Define mission
2. Make a sketch of your airplane, <u>or</u> assume cruise L/D
3. Assume cruise specific fuel consumption (sfc)
4. Assume TOGW (this will change)
5. Calculate fuel consumed on mission, plus reserves
6. Calculate W_e available

Empty Weight Available – Define Mission



Segment Fuel Fractions

Mission segment	W_i / W_{i-1}
Warmup and takeoff	0.970
Climb	0.985
Cruise	Use range equation
Loiter	Use endurance equation
Descent	1
Landing	0.995

Source: Raymer

Assuming 6% allowance for reserves and trapped (unusable) fuel then total fuel for mission W_f is

$$W_f = 1.06\left(W_0 - W_x\right)$$

where W_x is aircraft weight at end of mission (assuming no payload drops)

ADAC Aircraft Design & Consulting

Range Equation

Breguet range equation is

$$R = \left(\frac{V}{C}\right)\left(\frac{L}{D}\right)\ln\left(\frac{W_{i-1}}{W_i}\right)$$

where

$R = \text{range}\ [\text{n mi}]$

$C = \text{specific fuel consumption}\left[\frac{\text{lb}}{\text{lb hr}}\right]$

$V = \text{speed}\ [\text{KTAS}]$

$\frac{L}{D} = \frac{\text{lift}}{\text{drag}}\ \text{ratio}$

Rearrange equation to the form

$$\frac{\text{Weight at end of segment}}{\text{Weight at start of segment}} =$$

$$\frac{W_i}{W_{i-1}} = e^{\frac{-RC}{V\left(\frac{L}{D}\right)}}$$

Breguet range equation will be derived later.

Derivation of Breguet Range Equation

For steady level flight for which $T = D$ and $L = W$,

rate of change of range with aircraft weight can be written as

$$\frac{dR}{dW} = \frac{dR}{dt}\frac{dt}{dW} = \frac{\text{speed}}{-(\text{fuel burn rate})} = \frac{V}{-CT} = \frac{V}{-CD} = V\frac{\frac{L}{D}}{-CW}$$

$$R = \int_{W_{intial}}^{W_{final}} V\frac{\frac{L}{D}}{-CW}\,dW = \frac{V}{C}\frac{L}{D}\int_{W_{initial}}^{W_{final}} -\frac{dW}{W}$$

$$R = \frac{V}{C}\frac{L}{D}\left[-\ln W\right]_{W_{initial}}^{W_{final}}$$

$$\boxed{R = \frac{V}{C}\frac{L}{D}\ln\left(\frac{W_{initial}}{W_{final}}\right)}$$

For mission fuel burn analysis we want in the form

$$\frac{W_{final}}{W_{initial}} = e^{-\frac{R}{\frac{V}{C}\frac{L}{D}}}$$

Louis Charles Breguet pilotant son premier aéroplane (Breguet I) en juin 1909 à La Brayelle près de Douai. (Musée de l'Air).

Endurance Equation

Endurance equation is

$$E = \left(\frac{L}{D}\right)\left(\frac{1}{C}\right)\ln\left(\frac{W_{i-1}}{W_i}\right)$$

where

$E =$ endurance or loiter time $[\text{hours}]$

This may be rearranged to the form

$$\frac{\text{Weight at end of segment}}{\text{Weight at start of segment}} = \frac{W_i}{W_{i-1}} = e^{\frac{-EC}{\frac{L}{D}}}$$

Derivation of Endurance Equation

For steady level flight for which $T = D$ and $L = W$,

rate of change of time with aircraft weight can be written as

$$\frac{dE}{dW} = \frac{1}{-(\text{fuel burn rate})} = \frac{1}{-CT} = \frac{1}{-CD} = \frac{\frac{L}{D}}{-CW}$$

$$E = \int_{W_{intial}}^{W_{final}} \frac{\frac{L}{D}}{-CW} dW = \frac{1}{C}\frac{L}{D} \int_{W_{initial}}^{W_{final}} -\frac{dW}{W}$$

$$E = \frac{1}{C}\frac{L}{D}\left[-\ln W\right]_{W_{initial}}^{W_{final}}$$

$$\boxed{E = \frac{1}{C}\frac{L}{D}\ln\left(\frac{W_{initial}}{W_{final}}\right)}$$

For mission fuel burn analysis we want in the form

$$\frac{W_{final}}{W_{initial}} = e^{-\frac{E}{\frac{1}{C}\frac{L}{D}}} \qquad \text{where } E = \text{required loiter time}$$

Trends in Lift/Drag Ratio

$$\left(\frac{L}{D}\right)_{max} \text{ can be expressed in the form}$$

$$\left(\frac{L}{D}\right)_{max} = K\sqrt{\frac{b^2}{S_{wet}}}$$

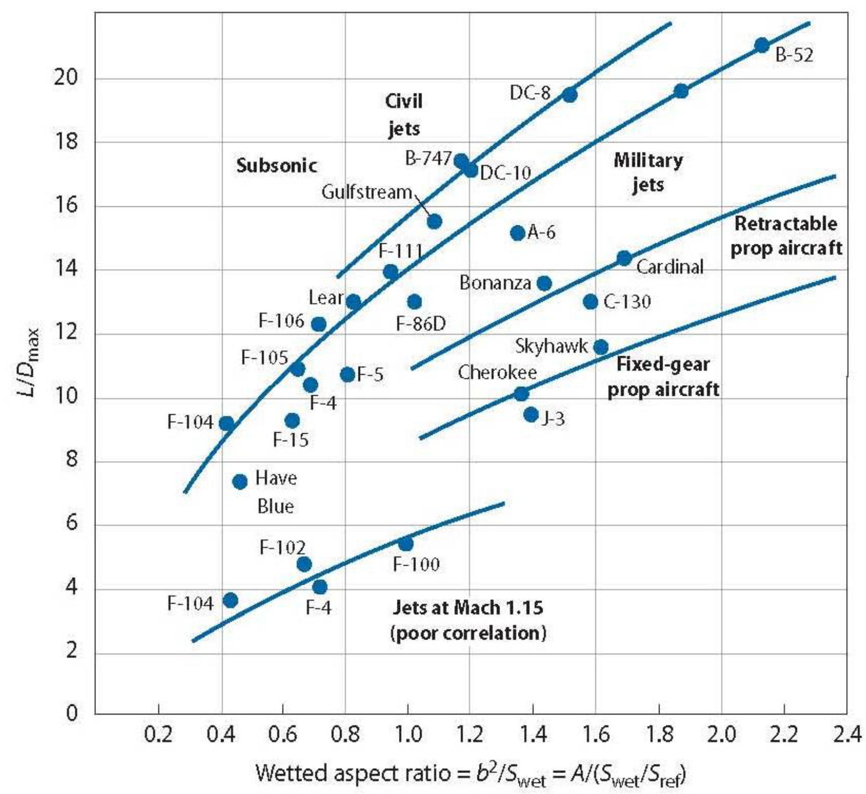
where

$K = 16$ for civil jets

$K = 14$ for military jets

$K = 11$ for propeller aircraft with retractable gear

(Note that these values can be derived analytically.
See Raymer annotations at www.adac.aero)

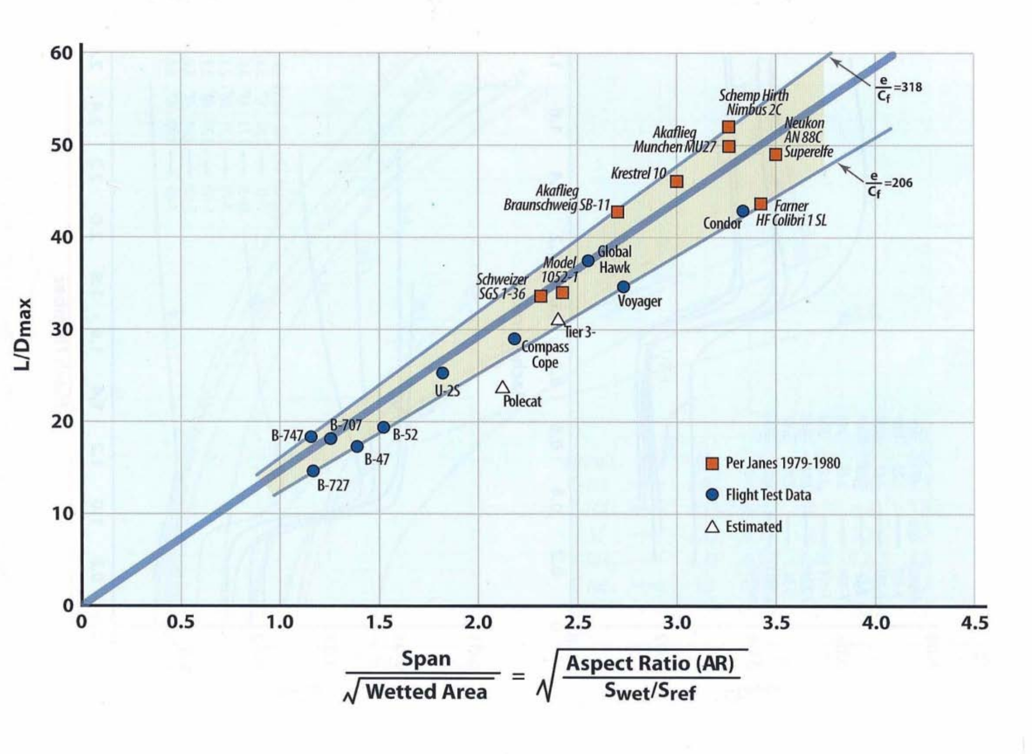


Source: Raymer

Trends in Lift/Drag Ratio

Can also write as

$$\left(\frac{L}{D}\right)_{max} = K\frac{b}{\sqrt{S_{wet}}}$$



Source: Nicolai

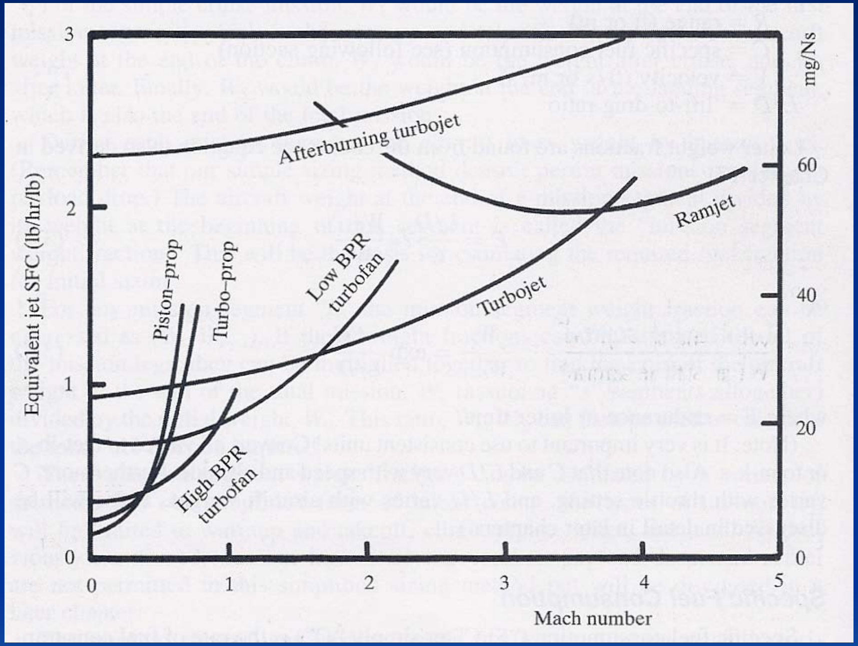
For a high – subsonic cruise aircraft, optimum L/D values are

$$\left(\frac{L}{D}\right)_{cruise} = 0.87\left(\frac{L}{D}\right)_{max}$$

$$\left(\frac{L}{D}\right)_{loiter} = \left(\frac{L}{D}\right)_{max}$$

SFC for Cruise and Loiter

Use this chart for trends in cruise SFC



Source: Raymer

Use these values for loiter sfc

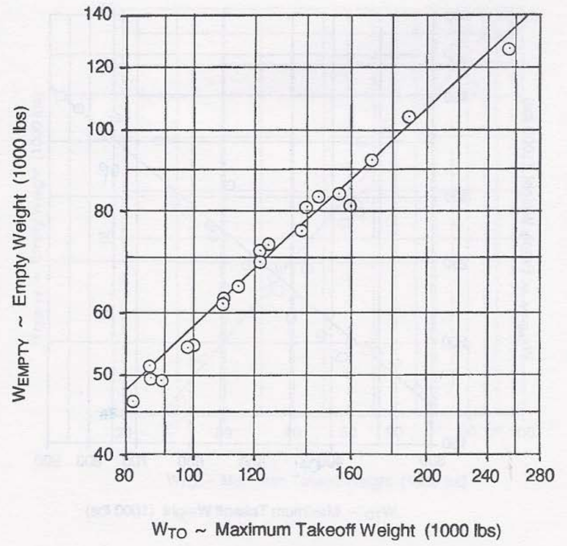
Jet engine cycle	Loiter sfc
Pure turbojet	0.8
Low-bypass turbofan	0.7
High-bypass turbofan	0.4

Source: Raymer

You now have enough information to calculate preliminary TOGW

Empty Weight Required

- For first estimate, empty weight required based on comparable aircraft
- For preliminary design, empty weight based on component weight buildup



Aircraft	W_{TO}	W_{EMPTY}
British Aerospace BAe 146-100	82,250	47,000
Douglas DC-9-10	85,700	51,900
British Aircraft Corporation BAC-111	87,000	49,600
British Aerospace BAe 146-200	89,500	49,300
Fokker F 100	98,000	53,975
British Aerospace BAe 146-300	100,000	54,500
Douglas DC-9-30	108,000	61,400
Boeing 737-200	109,000	63,000
Douglas DC-9-40	114,000	64,600
Douglas DC-9-50	121,000	69,200
Boeing 717-200	121,000	70,790
Boeing 737-300	124,500	72,360
Boeing 737-400	138,500	76,180
McDonnell Douglas MD-81	140,000	80,700
Boeing 737-600	144,500	80,360
Boeing 737-700	154,500	83,790
McDonnell Douglas MD-83	160,000	80,968
Airbus A 320-200	169,800	92,400
Airbus A 321-100	187.400	105,600
Boeing 757-200	255,000	128,730

Estimating Empty Weight Required

Assume empty weight is in the form

$W_e = K_{vs} A W_{TO}^B$

where
K_{vs} = 1.04 for variable sweep
K_{vs} = 1 for fixed sweep
A and B are empirical constants

This does not produce a linear relationship between empty weight and TOGW, but the relationship is almost linear in the region of interest.

Weight Required Coefficients (Raymer)

Airplane Category	A (W in lb)	B
Sailplane - unpowered	0.86	0.95
Sailplane - powered	0.91	0.95
Homebuilt – metal/wood	1.19	0.91
Homebuilt – composite	1.15	0.91
General Aviation – single engine	2.36	0.82
General Aviation – twin-engine	1.51	0.90
Agricultural aircraft	0.74	0.97
Twin turboprop	0.96	0.95
Flying boat	1.09	0.95
Jet trainer	1.59	0.90
Jet fighter	2.34	0.87
Military cargo/bomber/ASW	0.93	0.93
Jet transport	1.02	0.94

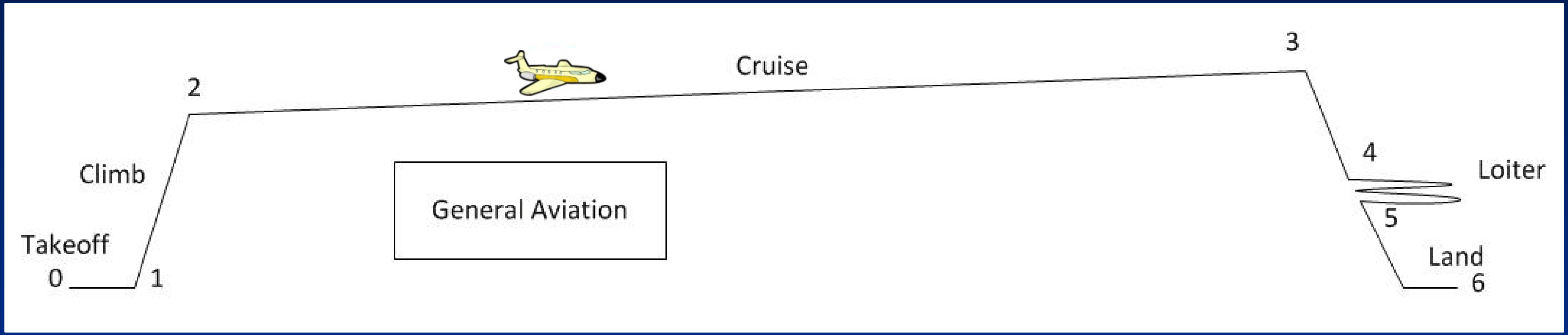
Source: Raymer

Weight Required Coefficients (Schaufele)

Aircraft Category	A (W in lb)	B
Personal/Utilitity	1.26	0.93
Turboprop Commuter	0.39	1.04
Bizjets	1.80	0.89
1-aisle Jet Transports	2.33	0.88
2-aisle Jet Transports	6.94	0.80
Fighter/Attack	0.07	1.18
Mil Turboprop Transports	1.36	0.92
Mil Jet Transports	1.34	0.92

Source: Schaufele

Example – Executive Jet Mission



- Mission
  - Payload: 8 pax + bags at 205 lb (1640 lb)
  - Crew: 2 crew at 195 lb (390 lb)
  - Range: 2500 nmi
  - Cruise Mach: 0.8 @36,000 ft
  - Loiter: 30 min @ 10,000 ft and speed for best L/D

Assumptions

Max L/D = 16
Cruise sfc = 0.8 lb/lb/hr
Loiter sfc = 0.7 lb/lb/hr
Additional reserves = 6% block fuel

Example – Executive Jet Mission

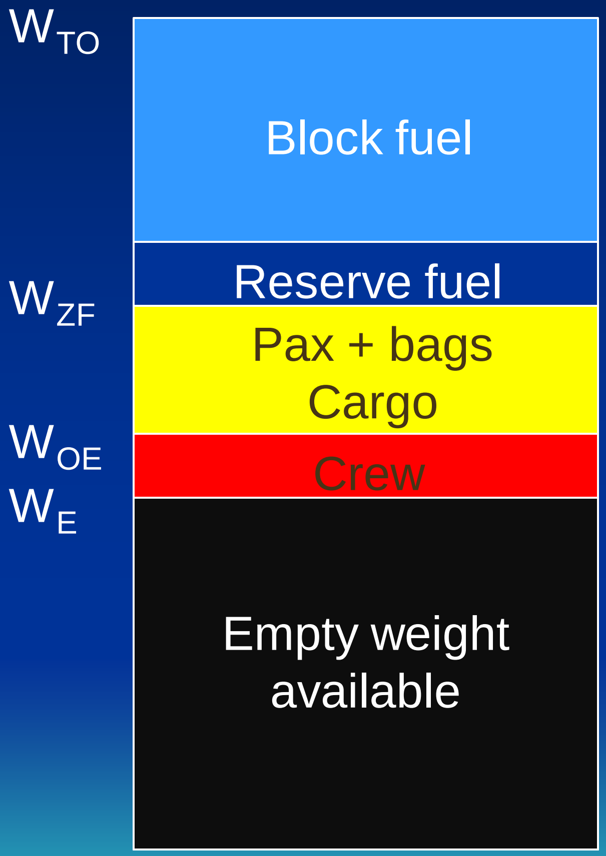
Mission segments	Weight ratio	Wt @ end of segment [lb]
0. Start of mission		28,000
1. Warmup and takeoff	0.970	27,160
2. Climb	0.985	26,753
3. Cruise	0.730	19,529
4. Initial descent	1.000	19,529
5. Loiter	0.978	19,100
6. Descent and land	0.995	19,004
Block fuel (W_{block})	$W_{TO} – W_6$	8,996
Total fuel reqd. (W_{TF})	$1.06\ W_{block}$	9,535
Zero fuel weight (W_{ZF})	W_{TO} - W_{TF}	18,465

Weight ratio equation in exponential form

Calculating Empty Weight Available

$$W_{empty} = W_{TO} - W_{fuel} - W_{payload} - W_{crew}$$

W_{ZF}	18,465
$- \; W_{payload}$	- 1,640
W_{OE}	16,825
$- \; W_{crew}$	- 390
W_{empty}	16,435



Calculating Empty Weight Required

From Schaufele's table of coefficients, for bizjet

A = 1.80

B = 0.89

$$W_{empty} = A\, W_{TO}{}^{B} = 1.8 \times 28{,}000^{0.89}$$
$$= 16{,}340 \text{ lb}$$

This is close enough to available W_{empty}, so TOGW = 28,000 lb is correct value for this mission

Spreadsheet Solution

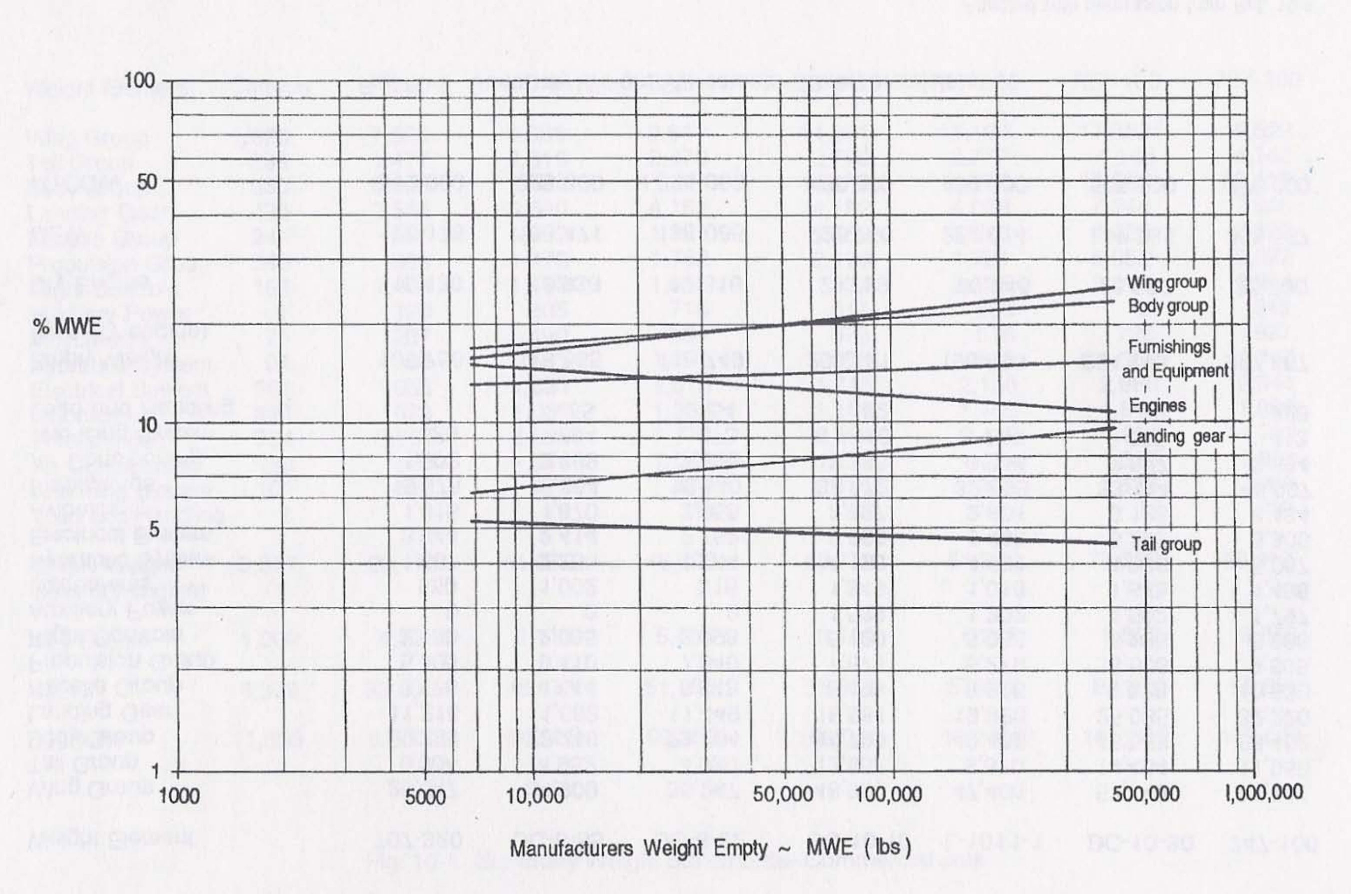
Assumptions								
Range [nmi]	2500			Loiter time [hr]	0.5		Weight coeffs (Schaufele)	
Cruise Mach	0.8			Loiter sfc [lb/lb/hr]	0.7		A	1.8
Max L/D	16			Addn. reserves	6%		B	0.89
Cruise sfc [lb/lb/hr]	0.8			Payload [lb]	1640			
Speed of sound @ 36Kft [Kt]	573.8			Crew wt [lb]	390			
Mission								
	Ratio	Wt ratio	Wt [lb]					
0. TOGW (assumed)			28000					
1. Warmup and taxi	W_1/W_0	0.970	27160					
2. Climb	W_2/W_1	0.985	26753					
3. Cruise	W_3/W_2	0.730	19535					
4. Initial descent	W_4/W_3	1.000	19535					
5. Loiter	W_5/W_4	0.978	19112					
6. Descent and land	W_6/W_5	0.995	19016					
Block fuel [lb]	$W_{TO} - W_6$		8984					
Total fuel required [lb]	$1.06\ W_{BLOCK}$		9523					
Zero fuel weight [lb]	$W_{TO} - W_{TF}$		18477					
Weight empty (avail) [lb]	$W_{ZF} - W_{PL} - W_{CREW}$		16447				Weight empty (reqd) [lb]	16340
				We(avail) - We(reqd) [lb]	108			

Use Excel Solver Add-In

Assumptions					
Range [nmi]	2500			Loiter time [hr]	0.5
Cruise Mach	0.8			Loiter sfc [lb/lb/hr]	0.7
Max L/D	16			Addn. reserves	6%
Cruise sfc [lb/lb/hr]	0.8			Payload [lb]	1640
Speed of sound @ 36Kft [Kt]	573.8			Crew wt [lb]	390
Mission					
	Ratio	Wt ratio	Wt [lb]		
0. TOGW (assumed)			28000		
1. Warmup and taxi	W_1/W_0	0.970	27160		
2. Climb	W_2/W_1	0.985	26753		
3. Cruise	W_3/W_2	0.730	19535		
4. Initial descent	W_4/W_3	1.000	19535		
5. Loiter	W_5/W_4	0.978	19112		
6. Descent and land	W_6/W_5	0.995	19016		
Block fuel [lb]	$W_{TO} - W_6$		8984		
Total fuel required [lb]	$1.06\ W_{BLOCK}$		9523		
Zero fuel weight [lb]	$W_{TO} - W_{TF}$		18477		

- Select Data Tab
- If Solver doesn't appear on taskbar, then:
  - Click on Office button > Excel Options > Add-Ins > Manage [Disabled Items]
- Using Solver: Set target cell [F22] equal to [0] by changing [D10]

Adjusting for Composites



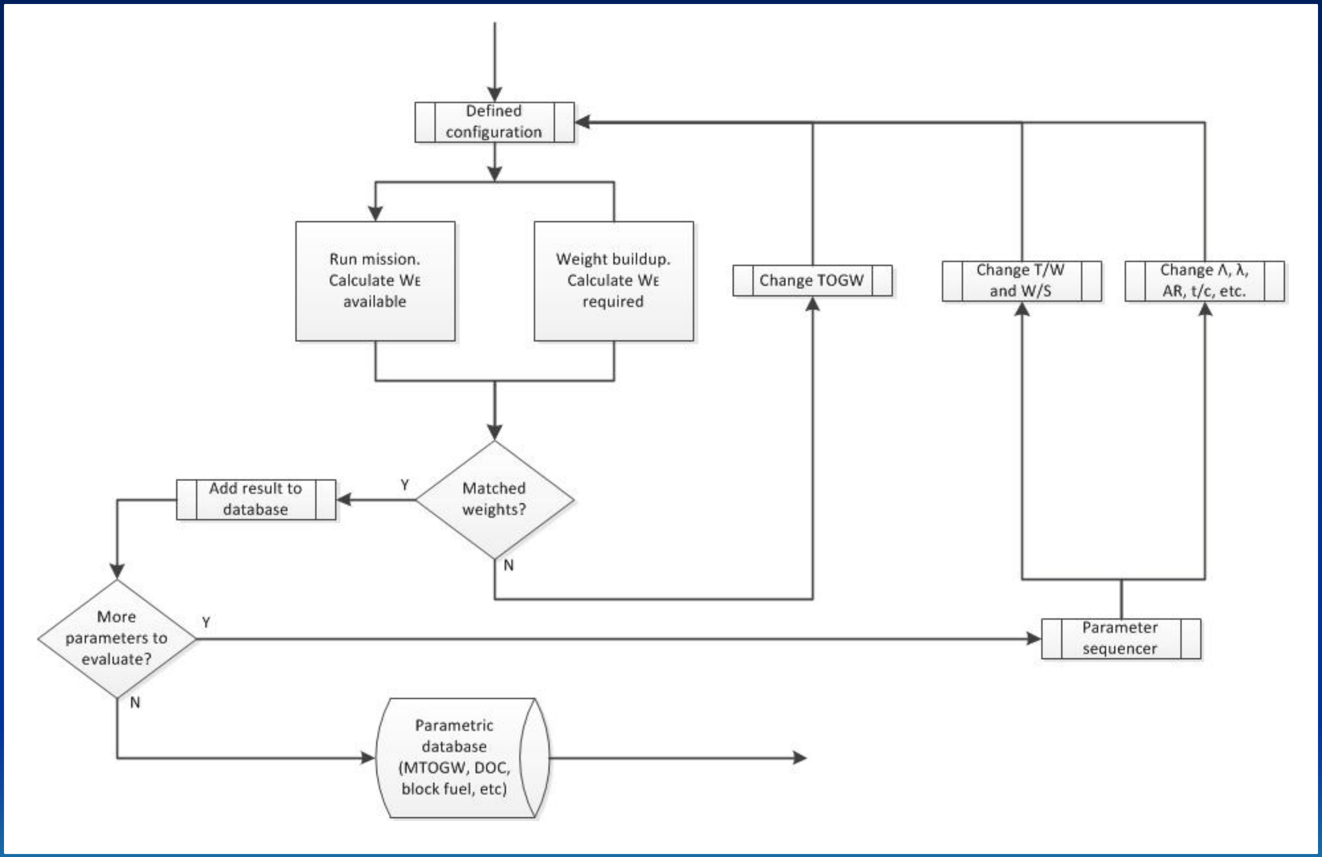
- Estimate group weight breakdown

Adjusting for Composites Example

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			16.0	16.0
Systems			(7.5)	(7.5)
Total			100	95.6

- Multiply coefficient “A” (in eq’n $W_E = A*W_{TO}^B$) by Reduced Group %MWE Total

Inner Loop in Mission Sizing Program



Limitations of this Method

- Initial sketch is a rough estimate of geometry, so L/D is approximate
- SFC is also approximate
- So empty weight available is approximate
- Empty weight required applies not to your sketch, but to the class of airplane you are designing
- Lines representing empty weight available and empty weight required meet at an acute angle, so small changes make a large difference in TOGW. This applies particularly if the payload and other weights independent of TOGW are small
- If a similar design, with a similar mission is available, it may be easier to assume the TOGW of that airplane.

Where are we now?

- Defined aircraft requirements
- Made a guess as to cruise L/D
- Made a guess as to cruise sfc
- Calculated estimate of MTOGW (W_{TO}) and W_E