Progettazione di veicoli aerospaziali (AA-LZ)

E1. Conceptual Design of subsonic commercial aircraft

7. Weights

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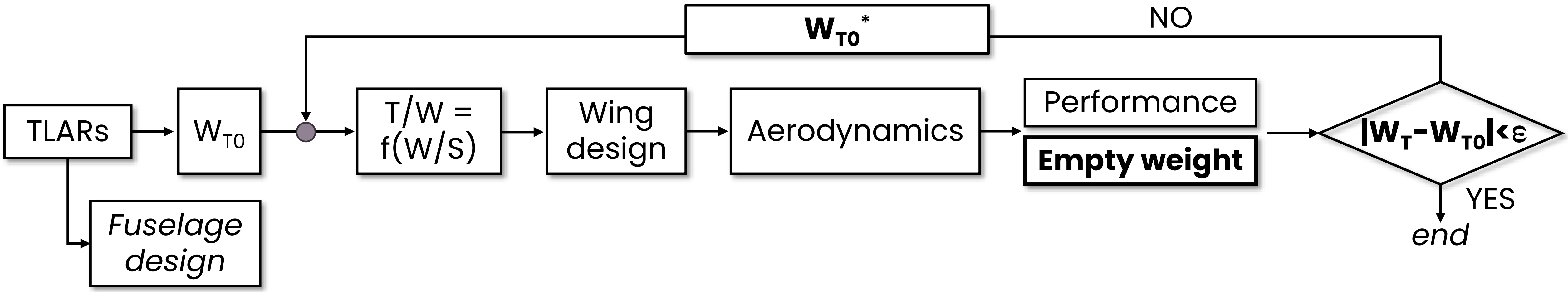
OEW



The **operating empty weight** is the weight of the airplane in a condition **ready to fly**, but with **no fuel or payload** yet taken on board.

OEW

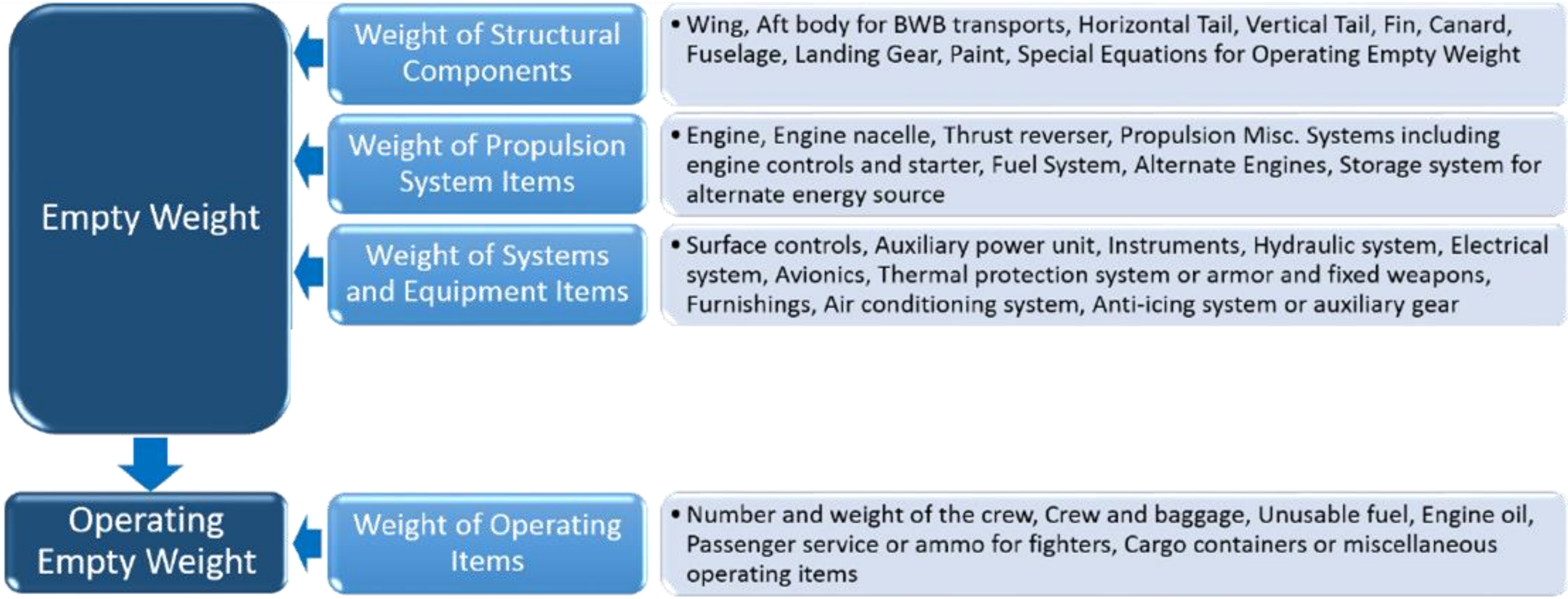
Aircraft operating empty weight

Structural mass
Wing
Tail
Fuselage
Landing gear

Propulsion
Engine and Nacelle

Systems
Fuel, Hydraulic, Electric, Pneumatic, Anti-icing, Instruments, Avionics, Engine

Operating
Furnishing, Services
Crew and attendants



OEW - Wing

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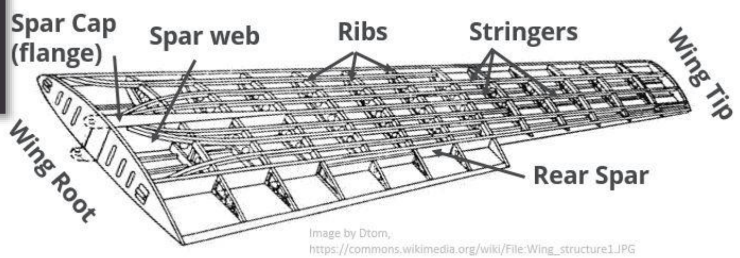
The wing weight (W_{wing}) for a transport aircraft depends on several parameters, such as AR, λ, W/S, t/c. All these parameters are enclosed into a specific parameter named wing geometry index (I_w)

$$I_w = \frac{n_{ult} * AR^{1.5}\left(W_{zf}/W_{to}\right)^{0.5}(1+2\lambda)(W/S)S^{1.5} * 10^{-6}}{(t/c)(\cos\Lambda_{25})^2(1+\lambda)}$$

$$W_{wing} = 0.93 * I_w + 6.44 * S + 390 \quad S > 900\ \text{ft}^2\ (83\ \text{m}^2)$$

$$W_{wing} = 4.24 * I_w + 0.57 * S \quad S < 900\ \text{ft}^2\ (83\ \text{m}^2)$$



W_{zf} = MTOW-m_{fuel} = Zero fuel weight [lb]
λ = taper ratio
n_{ult} = ultimate load factor = 3.75

[S] = ft^2 [W/S] = lb/ft^2 [W_{wing}] = lb

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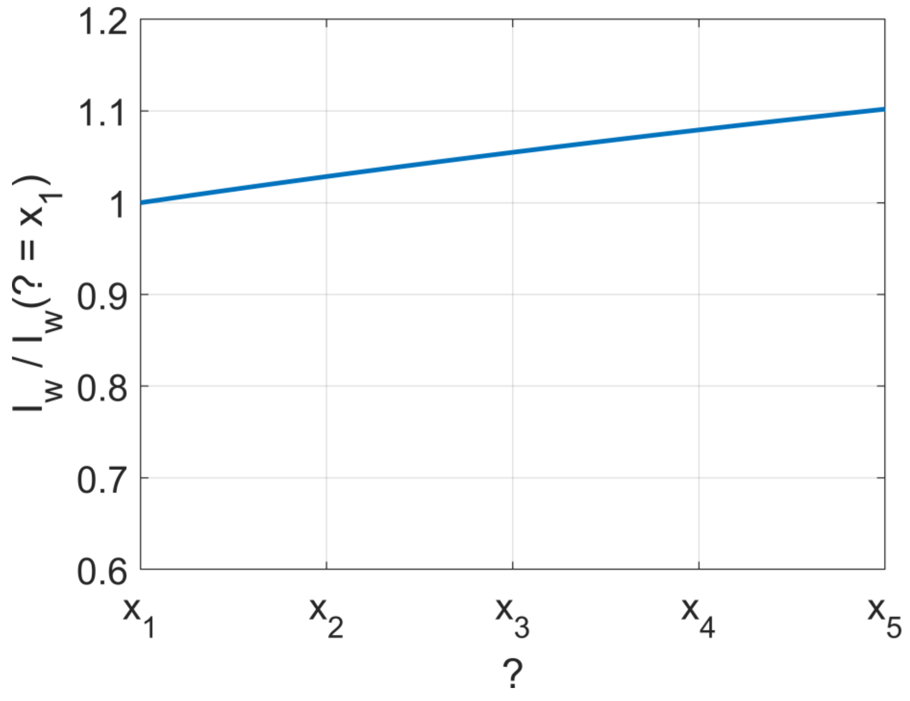

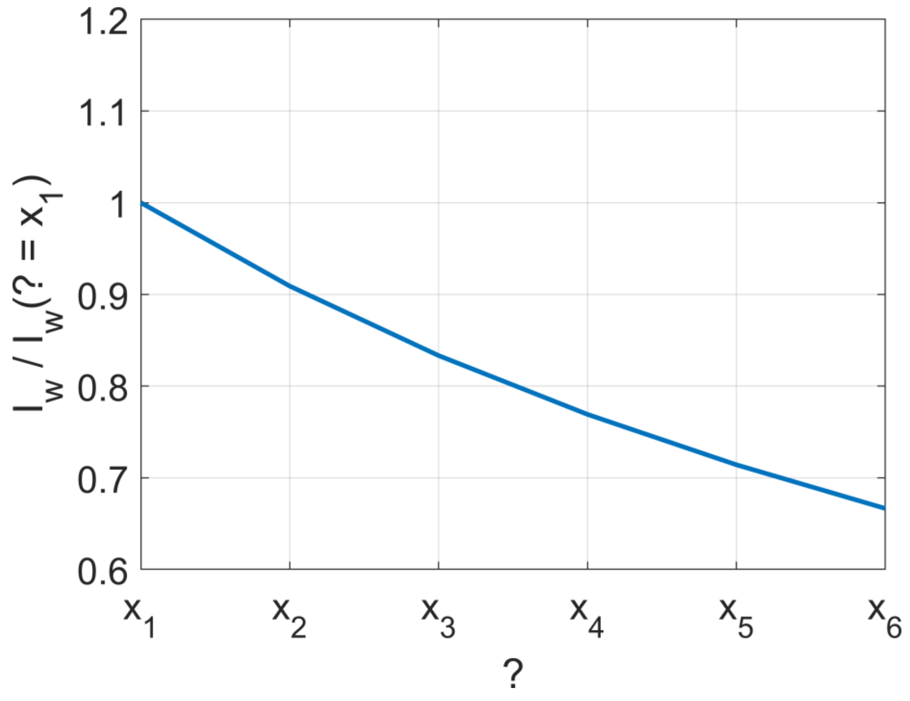

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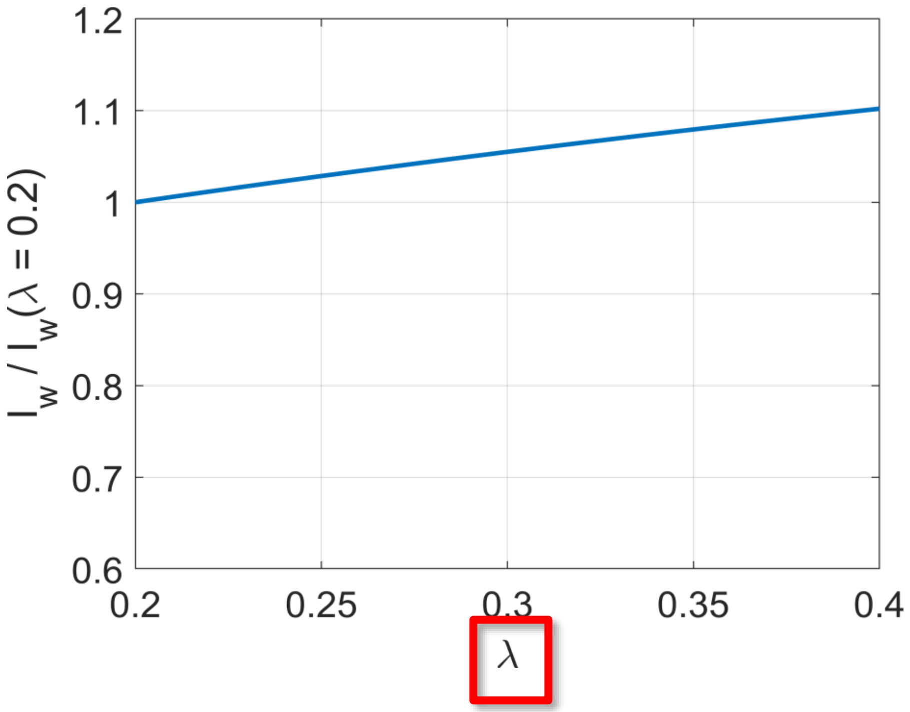

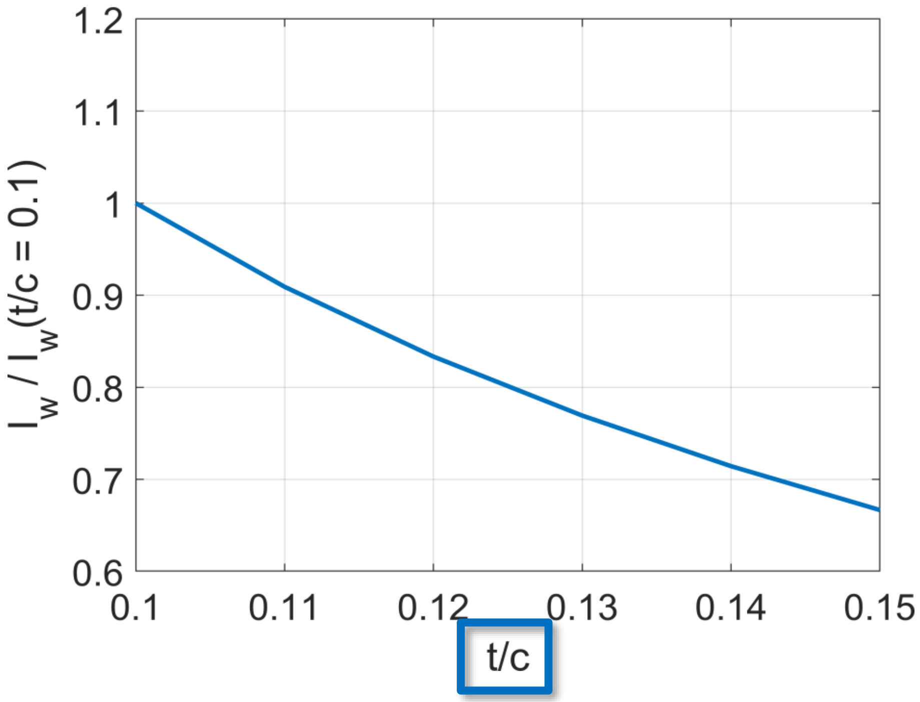

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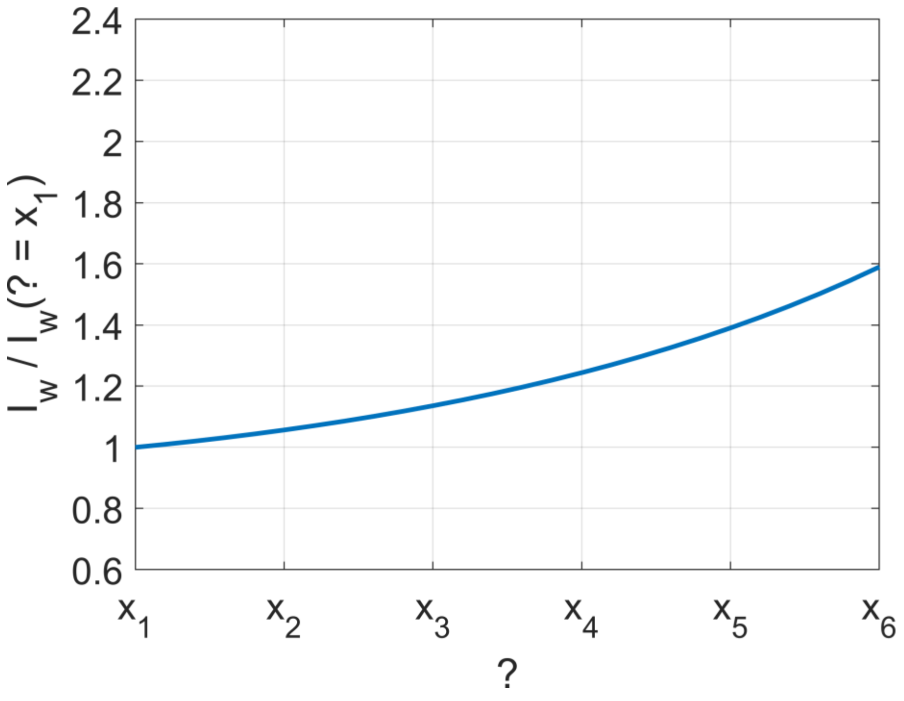

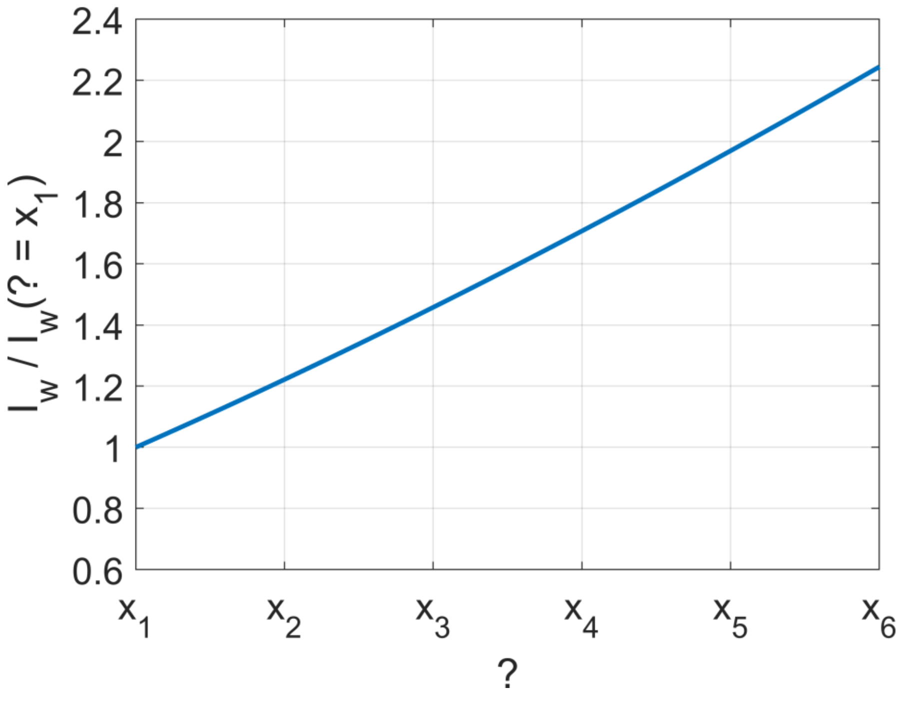

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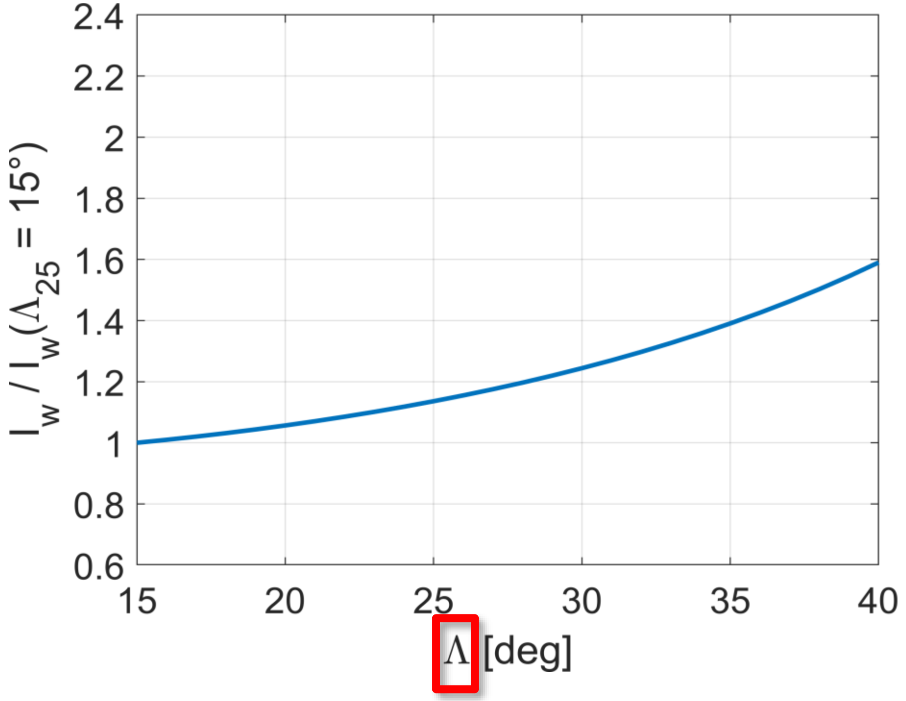

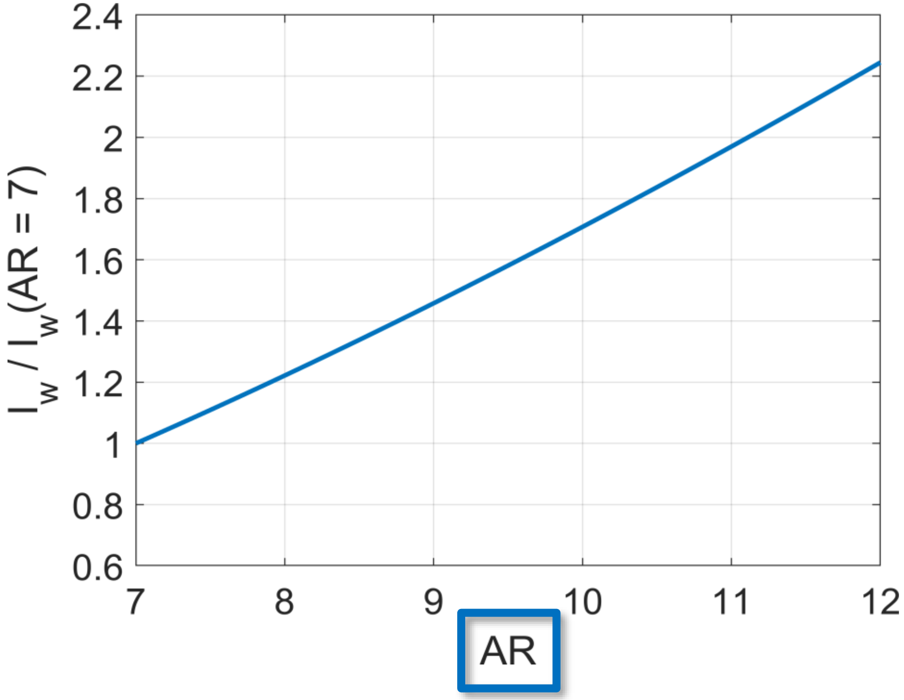

OEW - Tail

Aircraft operating empty weight

Structural mass

Wing

Tail

Fuselage

Landing gear

Propulsion

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Operating

Furnishing, Services

Crew and attendants

T tail

$$W_{tail} = 6.39 * S_{tail}$$

Conventional tail

$$W_{tail} = 5.03 * S_{tail}$$

S_{tail} = Total surface area of horizontal and vertical wing

$[S_{tail}] = ft^2$ $[W_{tail}] =$ lb

OEW - Tail

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Tail surface can be assessed by statistical values of transport aircraft

Table 6.1 Horizontal Tail Properties for a Range of Airliners[a]

Aircraft	Gross Weight W_g (lb)	Wing Area S (sq.ft.)	S_h/S	Horizontal Tail Span b_h (ft)	A_h	Taper λ_h	Sweep Λ_h (deg)
Dash 8 Q100	36,300	585	0.28	26.8	4.43	0.80	6.5
XAC MA60	48,050	810	0.22	31.0	5.49	0.44	20.0
ATR72-500	48,500	657	0.20	24.2	4.37	0.56	8.0
ERJ145LR	46,275	551	0.24	24.8	4.68	0.59	20.0
CRJ200LR	53,000	587	0.19	20.5	3.72	0.50	34.5
CRJ700ER	75,250	739	0.24	28.0	4.36	0.40	33.0
E175	85,517	783	0.32	32.8	4.29	0.50	35.0
B737-700ER	154,500	1341	0.33	47.1	5.04	0.33	36.0
A320-200	169,800	1320	0.26	40.9	4.84	0.31	32.5
A310-300	361,600	2360	0.30	53.2	3.99	0.44	37.0
B767-200ER	395,000	3050	0.28	61.1	4.42	0.30	36.0
B777-200	545,000	4605	0.25	70.6	4.40	0.33	39.5
A340-300	609,580	3890	0.20	63.5	5.12	0.40	32.5
B747-400	875,000	5650	0.26	72.8	3.57	0.24	42.5
A380-800	1,234,600	9104	0.24	99.7	4.45	0.37	37.5

[a] *Manufacturers: Airbus (A320, A310, A340, A380), Avions de Transport Regional (ATR72), Boeing (B737, B747, B767, B777), Bombardier (CRJ200, CRJ700, Dash8), Embraer (ERJ145, E175), Xian Aircraft Industry Co. (XAC MA60).*

Table 6.2 Vertical Tail Properties for a Range of Airliners[a]

Aircraft	Gross Weight W_g (lb)	Wing Area S (sq.ft.)	S_v/S	Vertical Tail Height b_v	A_v	Taper λ_v	Sweep Λ_v (deg)
Dash 8 Q100	36,300	585	0.28	14.0	1.20	0.67	32.0
XAC MA60	48,050	810	0.18	15.2	1.57	0.40	27.0
ATR72-500	48,500	657	0.26	15.8	1.48	0.50	38.5
ERJ145LR	46,275	551	0.18	11.4	1.29	0.64	36.0
CRJ200LR	53,000	587	0.19	11.4	1.16	0.69	44.5
CRJ700ER	75,250	739	0.17	12.0	1.16	0.71	40.0
E175	85,517	783	0.29	20.5	1.84	0.30	40.0
B737-700ER	154,500	1341	0.22	26.8	2.45	0.20	37.0
A320-200	169,800	1320	0.24	23.8	1.77	0.30	39.0
A310-300	361,600	2360	0.26	32.3	1.70	0.34	44.0
B767-200ER	395,000	3050	0.21	33.5	1.77	0.33	45.0
B777-200	545,000	4605	0.18	40.7	2.03	0.25	45.0
A340-300	609,580	3890	0.16	33.6	1.81	0.34	44.0
B747-400	875,000	5650	0.19	38.3	1.39	0.31	49.5
A380-800	1,234,600	9104	0.17	52.6	1.76	0.37	44.0

[a] *Manufacturers: Airbus (A320, A310, A340, A380), Avions de Transport Regional (ATR72), Boeing (B737, B747, B767, B777), Bombardier (CRJ200, CRJ700, Dash8), Embraer (ERJ145, E175), Xian Aircraft Industry Co. (XAC MA60).*

OEW - Fuselage

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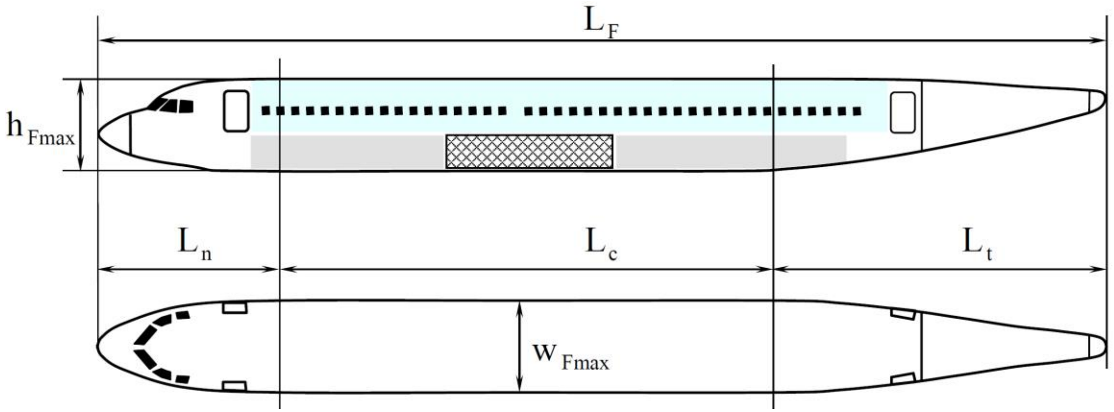
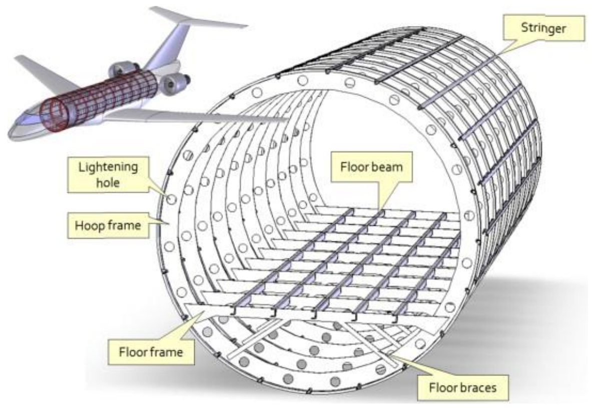
The fuselage weight (W_{Fus}) for a transport aircraft depends on fuselage dimension

$$W_{Fus} = 1.35\left(L_F \bar{D}_F\right)^{1.28}$$
$$\bar{D}_F = \frac{w_{Fmax} + h_{Fmax}}{2}$$

W_{Fmax} = maximum fuselage width [ft]
D_{Fmax} = maximum fuselage depth [ft]





OEW – Landing gear

Aircraft operating empty weight

Structural mass
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The landing gear mass for a transport aircraft depends on aircraft weight

$$W_{LG_{Group}} = W_{LGstructure} + W_{LGwheelbrakes} + W_{LGtires} + W_{LGcontrols}$$

$$W_{LGstructure} = W_{LG} * \left(0.45 + 23.1 * 10^{-8} * TOGW\right)$$

$$W_{LGwheelbrakes} = W_{LG} * \left(0.268 - 8.12 * 10^{-8} * TOGW\right)$$

$$W_{LGtires} = W_{LG} * \left(0.152 - 8.38 * 10^{-8} * TOGW\right)$$

$$W_{LGcontrols} = W_{LG} * \left(0.130 - 6.56 * 10^{-8} * TOGW\right)$$

W_{LG} is a parameter calculated according to the following equation

$$W_{LG} = 0.044 TOGW - 672 \quad Np > 100$$

$$W_{LG} = 0.0395 * TOGW \quad Np < 100$$

[TOGW] = lb [W_{LG}] = lb

OEW – Engine and Nacelle

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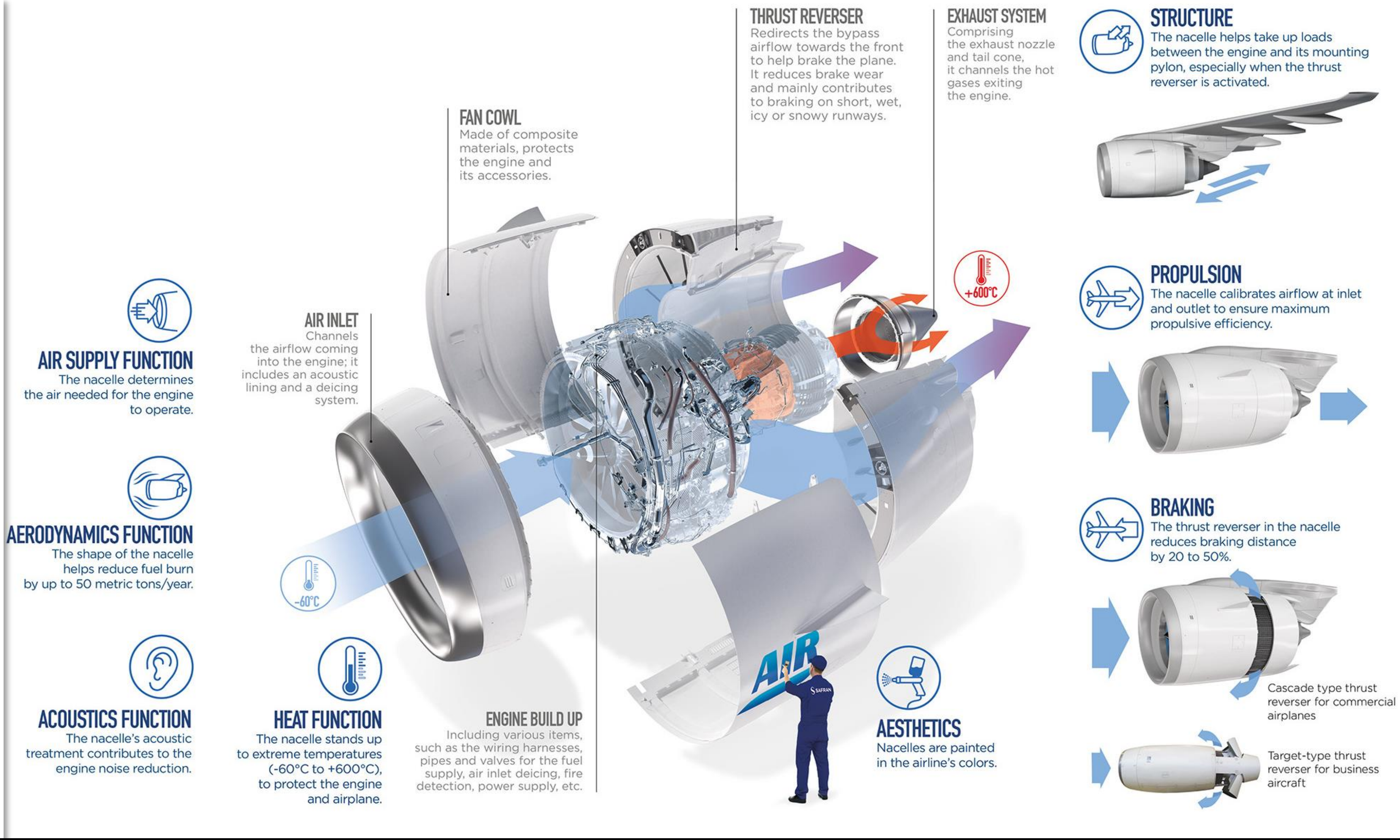

OEW – Engine and Nacelle

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Nacelle

Transport aircraft nacelle weight depends on engine thrust

$$W_{nac} = \frac{1}{4} N_{nac} D_{nac} L_{nac} T_{eng}^{0.36}$$

$$D_{nac} = 0.04 \sqrt{T_{eng}}$$

$$L_{nac} = 0.07 \sqrt{T_{eng}}$$

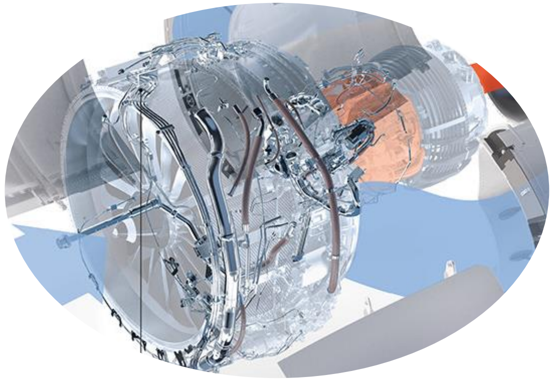
W_{nac} = nacelle mass [lb]
N_{nac} = number of nacelles
D_{nac} = nacelle diameter [ft]
L_{nac} = nacelle length [ft]
T_{eng} = thust if single engine [lb]

Engine

Transport aircraft engine weight depends on engine thrust

$$W_{eng} = \frac{(T/W)MTOW}{5.5}$$

W_{eng} = engine mass [lb]
MTOW = Max TO weight [lb]
T/W = thrust-to-weight ratio



OEW – Systems

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Fuel system

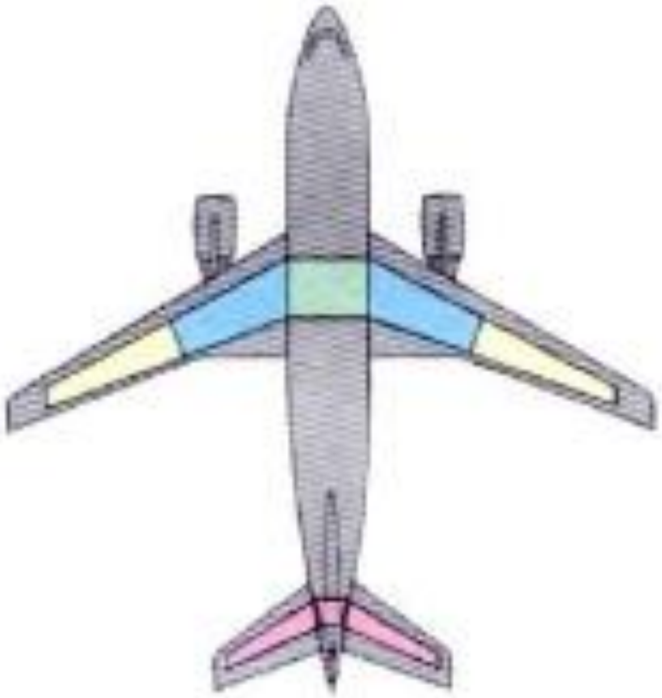
$$W_{fuelsys} = 2.71\left(\frac{b}{\cos\Lambda_{25}}N_t\right)^{0.956}$$

$W_{fuelSys}$= fuel system mass [lb]

b= wingspan [ft]

Λ_{25}= sweep angle [rad]

N_t= number of tanks



TANK CAPACITIES AND LOCATIONS

		Usable fuel				
		Outer	Inner	Centre	Trim	Total
Volume	Litre	3,700	13,950	19,640	6,150	61,090
	USg	978	3,685	5,189	1,625	16,140
Weight kg density 0.8		2,960	11,160	15,712	4,920	48,872
Weight kg density 6.68 lbs/US Gal		6,525	24,605	34,642	10,848	107,750

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Hydraulic and flight control systems

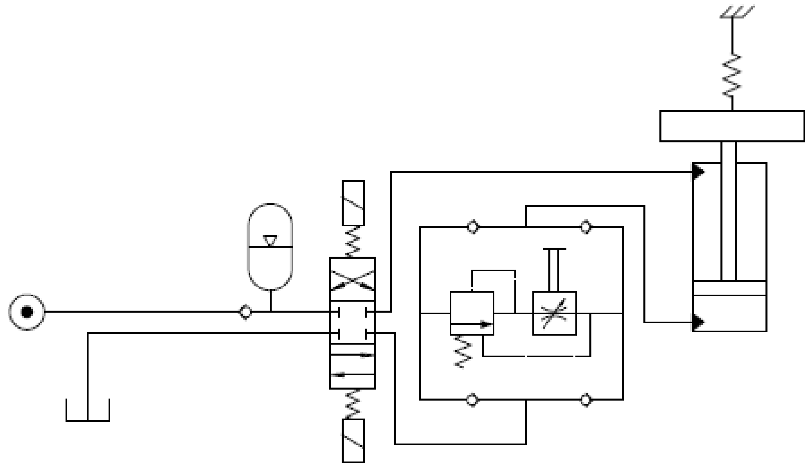
$$W_{hydr\_fc} = 45 + 1.318 * (S + 1.44 S_{tail}) \qquad S + 1.44 S_t \leq 3000\ ft^2$$

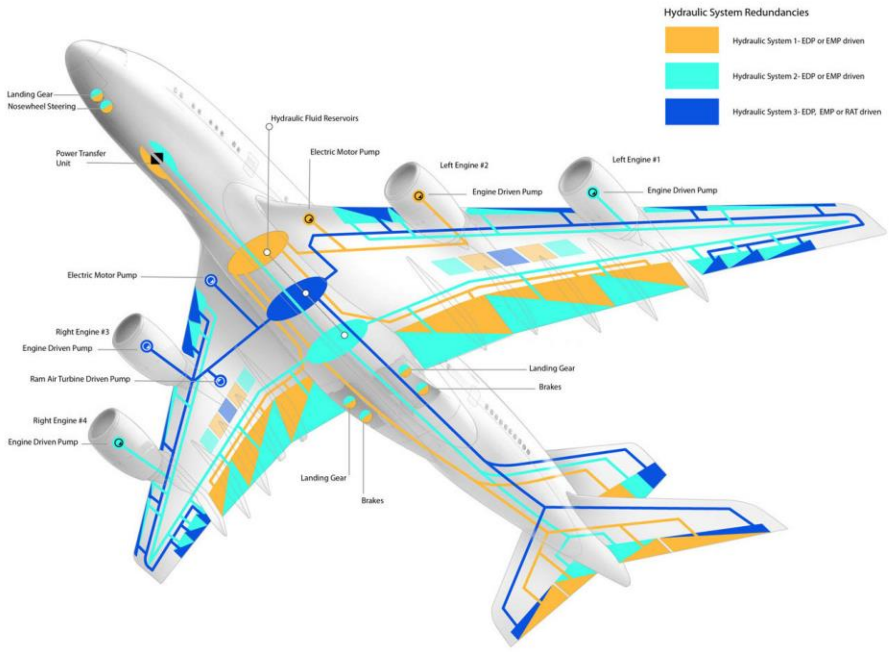
$$W_{hydr\_fc} = 18.7 * (S + 1.44 S_{tail})^{0.712} - 1620 \qquad S + 1.44 S_t > 3000\ ft^2$$

W_{hydr_fc}= hydraulic and fc system mass [lb]

S= wing surface [ft^2]

S_{tail}= total tail surface [ft^2]





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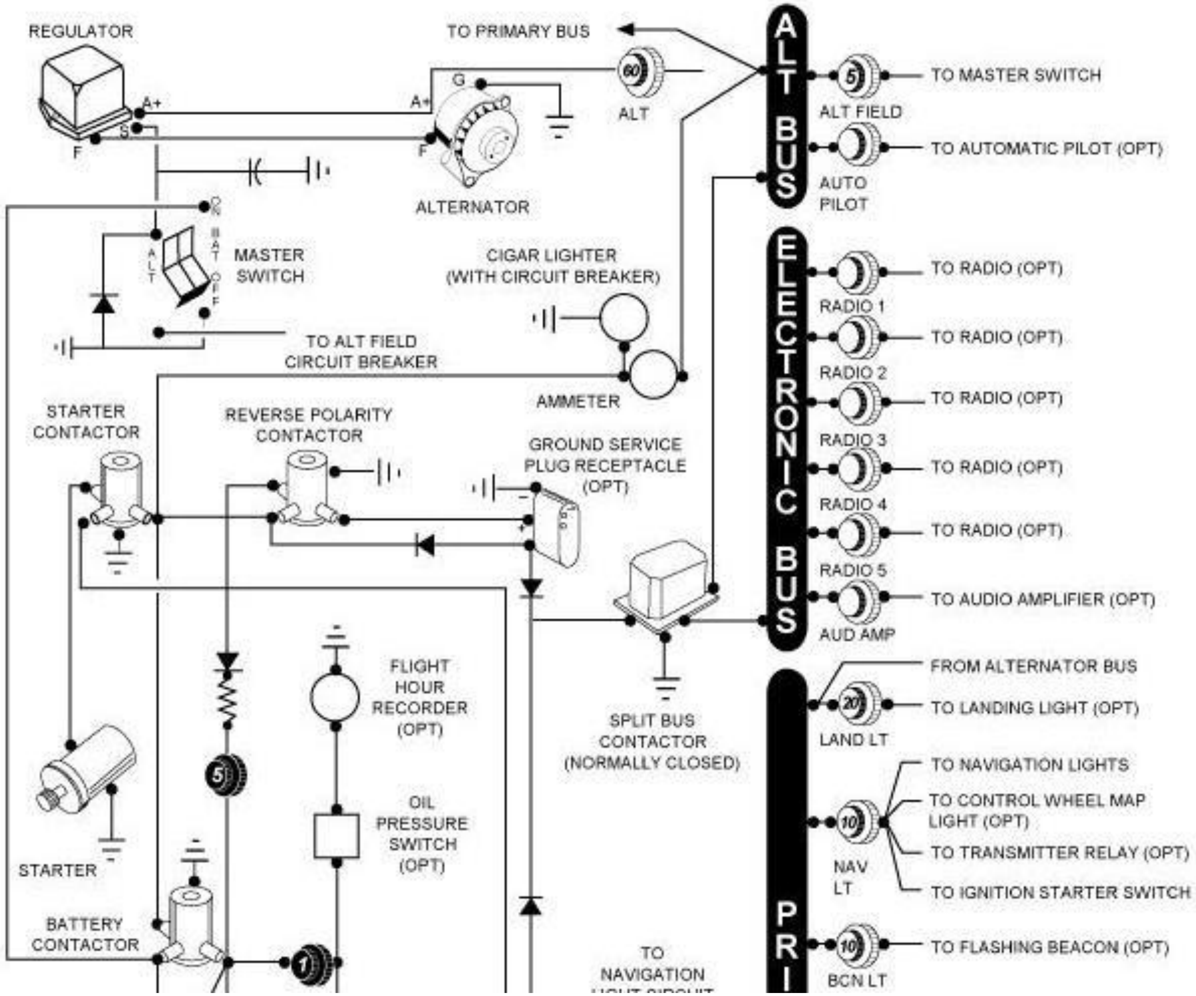
Electric system

$$W_{ele} = 16.2 * N_p + 110$$

W_{ele}= electric system mass [lb]

N_p= n. of pax



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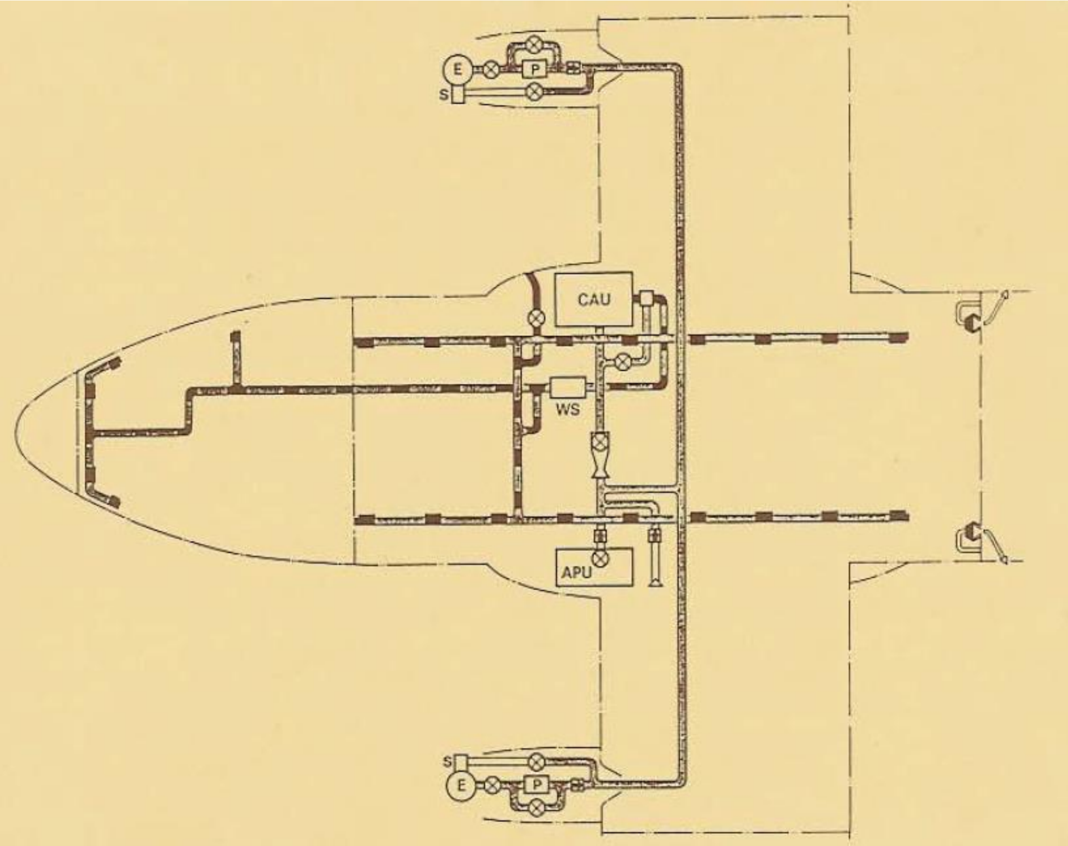
Pneumatic and air conditioning systems, APU

$$W_{aircnd\_pneum\_APU} = 26.2 * N_p^{0.944}$$

$W_{aircnd\_pneum\_APU}$ = pneumatic and air conditioning systems and APU mass [lb]

N_p = n. of pax



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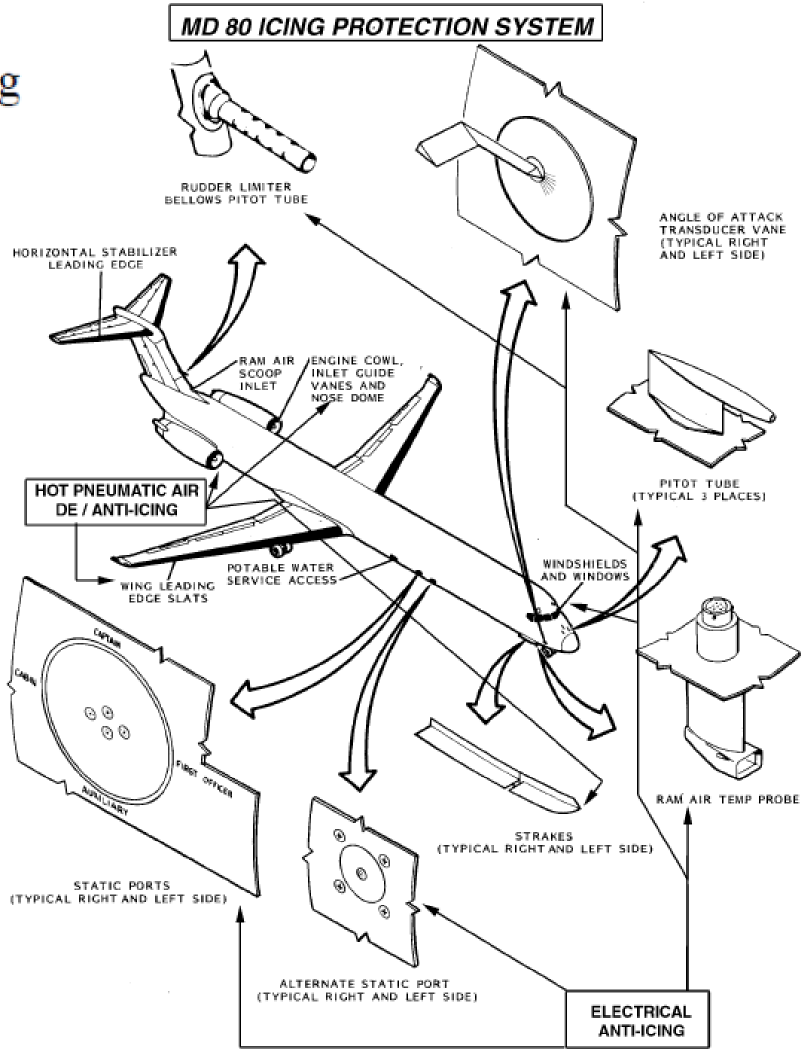
Anti-icing system

$$W_{anti-ice} = 0.120 * S$$ without tail anti icing

$$W_{anti-ice} = 0.238 * S$$ with tail anti ice

$W_{anti-ice}$= anti-icing system mass [lb]

S= wing surface [ft^2]



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Instruments

$$W_{thrustinstr} = (0.00145T + 30)N_{eng}$$

$$W_{fuelinstr} = 0.00714 * G + 34$$

$$W_{otherinstr} = 1.872 * N_p + 128$$

$W_{thrustinstr}$ = thrust instrument mass [lb]

$W_{fuelinstr}$ = fuel instrument mass [lb]

$W_{otherinstr}$ = other instrument mass [lb]

T = thrust [lb]

N_{eng} = number of engines

G = fuel volume [gal]

N_p = number of passengers

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Avionics

Avionics is a category of electronic systems and equipment specifically designed for use in aviation.

$$W_{av} = 2.8 * N_p + 2320$$ → Category III Overwater

W_{av} = avionics system mass[lb]

N_p = number of passengers

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Engine system

$$W_{engsys} = 133 * N_{eng}$$

W_{engsys} = engyne system mass[lb]

N_{eng} = number of engines

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Furnishings

Furnishings are the **physical elements** and items within the cabin that passengers interact with (e.g., seats, tray tables, entertainment screens, blankets). They form part of the aircraft's infrastructure.

OEW – Operating

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Wing
Tail
Fuselage
Landing gear

Propulsion
Engine and Nacelle

Systems
Fuel, Hydraulic,
Electric, Pneumatic,
Anti-icing, Instruments,
Avionics, Engine

Operating
Furnishing, Services
Crew and attendants

Furnishings

$$W_{furn} = 62.3 * N_p + 290 \qquad N_p \leq 80$$

$$W_{furn} = 118.4 * N_p - 4190 \qquad N_p > 80$$

W_{furn} = furnishing mass [lb]

N_p = number of passengers

OEW – Operating

Aircraft operating empty weight

Structural mass
Wing
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Fuselage
Landing gear

Propulsion
Engine and Nacelle

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Operating
Furnishing, Services, Crew and attendants

Services

Services are actions and provisions provided by the airline to ensure a smooth, comfortable, and safe journey. They are more about **interaction** and **support** (e.g., **catering**, safety demonstrations, customer assistance).

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Services

$$W_{srv} = \left(5.164\, N_{p,f} + 3.846 N_{p,b} + 2.529 N_{p,t}\right)\left(\frac{R}{M}\right)^{0.225}$$

W_{srv} = passenger service mass[lb]

$N_{p,f}$ = number of first class passengers

$N_{p,b}$ = number of business class passengers

$N_{p,t}$ = number of tourist class passengers

R = design range [nm]

M = cruise mach number

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Crew and attendants

The number of components of flight crew, i.e. pilot and flight attendants, is regulated by FAA

$$n_{fa} = \left\lceil \frac{N_p}{50} \right\rceil \qquad W_{fa} = n_{fa} \times 155$$

W_{fa} = flight attendant mass [lb]
n_{fa} = number of flight attendants

For short-medium range

$$n_{pc} = 2 \qquad W_{pc} = n_{pc} \times 225$$

W_{pc} = pilot mass [lb]
n_{pc} = number of pilots

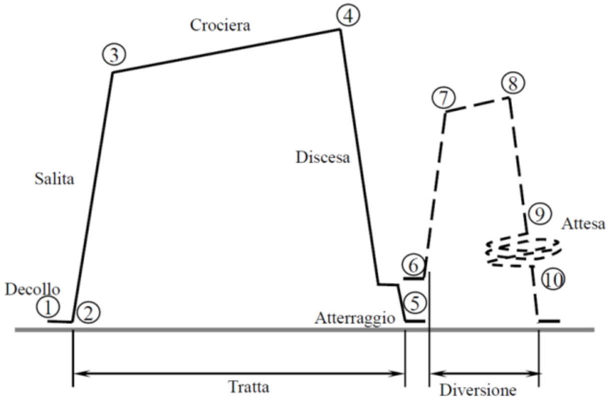
Performance

TLARs → W_{T0} → T/W = f(W/S) → Wing design → Aerodynamics → **Performance** / Empty weight → $|W_T - W_{T0}| < \varepsilon$

TLARs → *Fuselage design*

NO → W_{T0}^*

YES → *end*



$$\left(\frac{W_2^{(i)}}{W_{TO}^{(i)}}\right) = 0.970 \qquad \left(\frac{W_7^{(i)}}{W_6^{(i)}}\right) \cong 1$$

$$\left(\frac{W_3^{(i)}}{W_2^{(i)}}\right) = 0.985 \qquad \left(\frac{W_8^{(i)}}{W_7^{(i)}}\right) = ?$$

$$\left(\frac{W_4^{(i)}}{W_3^{(i)}}\right) = ? \qquad \left(\frac{W_9^{(i)}}{W_8^{(i)}}\right) \cong 1$$

$$\left(\frac{W_5^{(i)}}{W_4^{(i)}}\right) = 0.995 \qquad \left(\frac{W_{10}^{(i)}}{W_9^{(i)}}\right) = ?$$

$W_{TO}^{(i)}$ →

$$\left(\frac{W_F^{(i)}}{W_{TO}^{(i)}}\right) = \left(\frac{W_{F-MIS}^{(i)}}{W_{TO}^{(i)}}\right) + \left(\frac{W_{F-RIS}^{(i)}}{W_{TO}^{(i)}}\right)$$

$$\left(\frac{W_{F-MIS}^{(i)}}{W_{TO}^{(i)}}\right) = 1 - \left(\frac{W_2^{(i)}}{W_{TO}^{(i)}}\right)\left(\frac{W_3^{(i)}}{W_2^{(i)}}\right)\left(\frac{W_4^{(i)}}{W_3^{(i)}}\right)\left(\frac{W_5^{(i)}}{W_4^{(i)}}\right)$$

$$\left(\frac{W_{F-RIS}^{(i)}}{W_{TO}^{(i)}}\right) = 0.05\frac{W_{F-MIS}^{(i)}}{W_{TO}^{(i)}} + \left(1 - \frac{W_{F-MIS}^{(i)}}{W_{TO}^{(i)}}\right)\left[1 - \left(\frac{W_7^{(i)}}{W_6^{(i)}}\right)\left(\frac{W_8^{(i)}}{W_7^{(i)}}\right)\left(\frac{W_9^{(i)}}{W_8^{(i)}}\right)\left(\frac{W_{10}^{(i)}}{W_9^{(i)}}\right)\right]$$

→ $\left(\frac{W_F^{(i)}}{W_{TO}^{(i)}}\right)$

$$\frac{dx}{dW} = -\frac{V}{c \cdot T} \xrightarrow{T = D \quad L = W} \frac{dx}{dW} = -\frac{V \cdot L}{c \cdot D \cdot L} = -\frac{V \cdot E}{c \cdot W}$$

$$\boxed{\frac{dW}{W} = -\frac{c \cdot dx}{V \cdot E}}$$

Ipotesi:

$V =$ Costante

Assetto Costante $\Rightarrow$ $E =$ Costante

$$\boxed{\frac{W_{i+1}}{W_i} = e^{-\frac{c \cdot \Delta x_i}{V \cdot E}}}$$

Configurations Matrix

Summary of the set of configurations designed

Main configuration features should be inserted in the configuration matrix, e.g.:

Geo: S_{ref}, b, c_r, c_t, Λ, λ, AR, t/c, W/S, $S_{wet\ wing}$, Vol_{tank}, *and others*

Perfo: E_{cruise}, M, m_{fuel}, C_{D0}, C_{Dw}, C_{Di}, C_{dtot}, e, C_{Ltrim}, C_{Lmax}, T/W, T_{max}, *and others*

Weights: MTOW, W_{eo}, W_{wing}, *and others*

Geometry						Weights						Performance						FoMs					
x_1	x_2	x_3	…	…	x_n	w_1	w_2	w_3	…	…	w_n	y_1	y_2	y_3	…	…	y_n	f_1	f_2	f_3	…	…	f_n
x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx
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x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx	x.xx

Task 6.1

Task: Generate the configuration matrix

Be focused on: build the design convergence loop and <u>TEST</u> the sub-parts of the code