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Preliminary Sizing of Large Propeller Driven Aeroplanes

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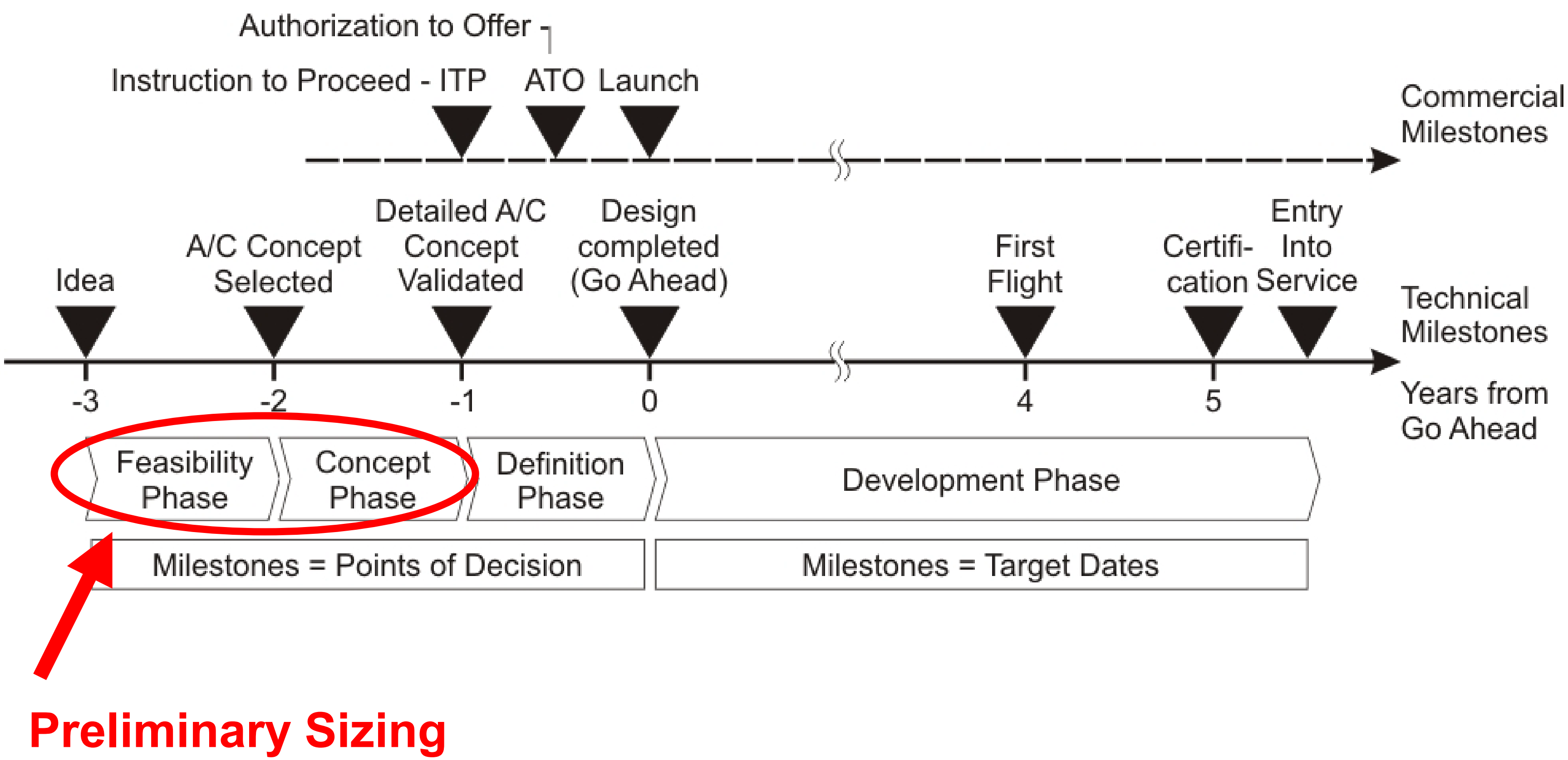
Introduction



Requirements

- Payload, m_{PL}
- Range, R
- Mach number in cruise, M_{CR} or speed, V_{CR}
- Take-off field length, s_{TOFL}
- Landing field length, s_{LFL} or approach speed, V_{APP} or stall speed, V_S
- Climb gradient γ during second segment
- Climb gradient γ during missed approach

Aircraft Parameters

- Take-off mass, m_{MTO}
- Fuel mass, m_F
- Operating empty mass, m_{OE}
- Wing area, S_W
- Take-off thrust, T_{TO} or take-off power, P_{TO}

Aeroplane Categories, Propulsion System and Certification Rules

1. large jet aeroplanes are certified to CS-25 respectively FAR Part 25,
2. very light jets are certified to CS-23 respectively FAR Part 23,
3. large propeller driven aeroplanes are also certified to CS-25 respectively FAR Part 25
4. smaller propeller driven aeroplanes (normal, utility, aerobatic and commuter aeroplanes) are certified to CS-23 respectively FAR Part 23,
5. very light propeller driven aeroplanes (up to a maximum take-off mass of 750 kg) can be certified to CS-VLA,
6. different certification rules exist for ultra light aircraft.

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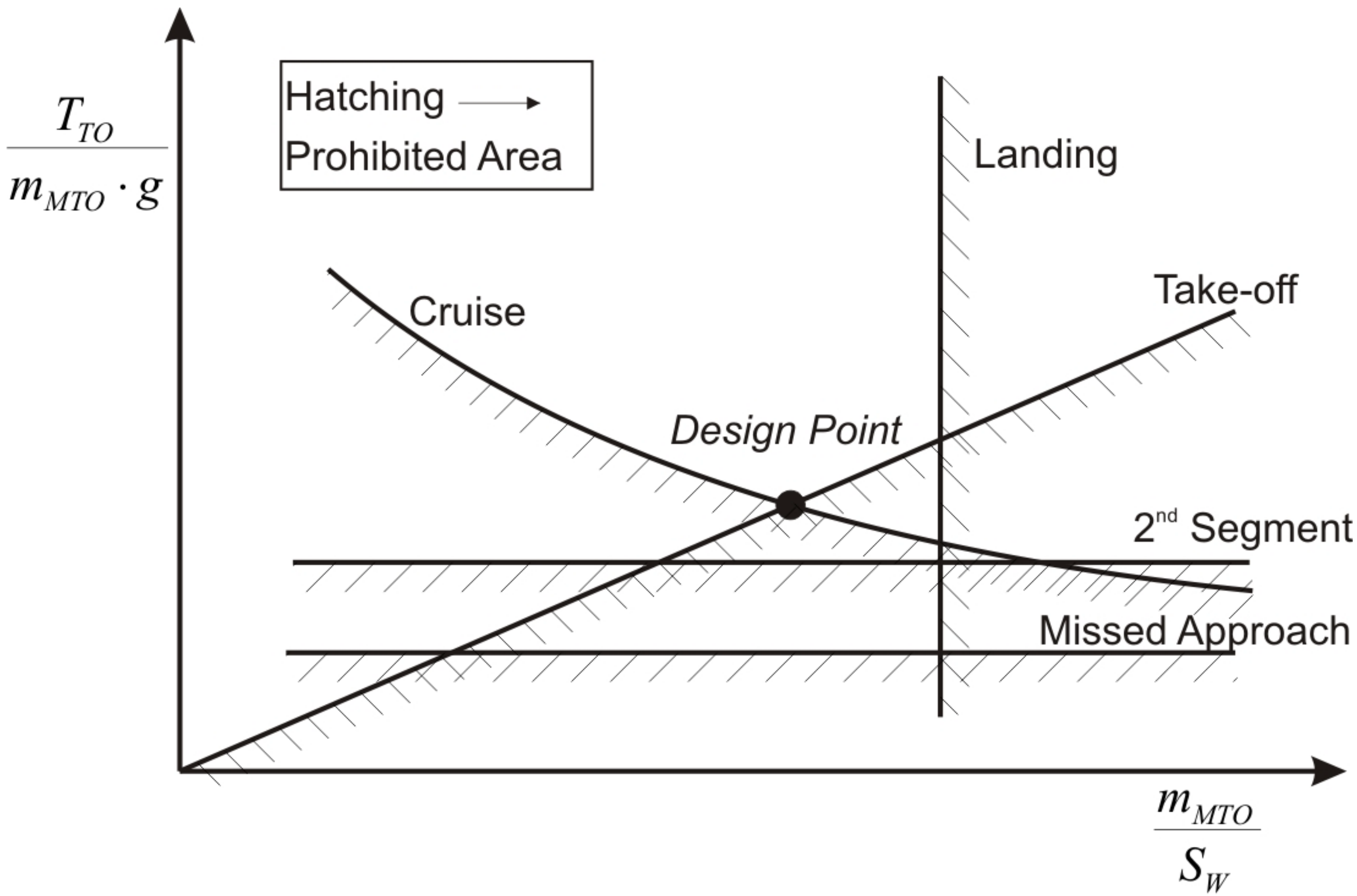
General Approach



Overview

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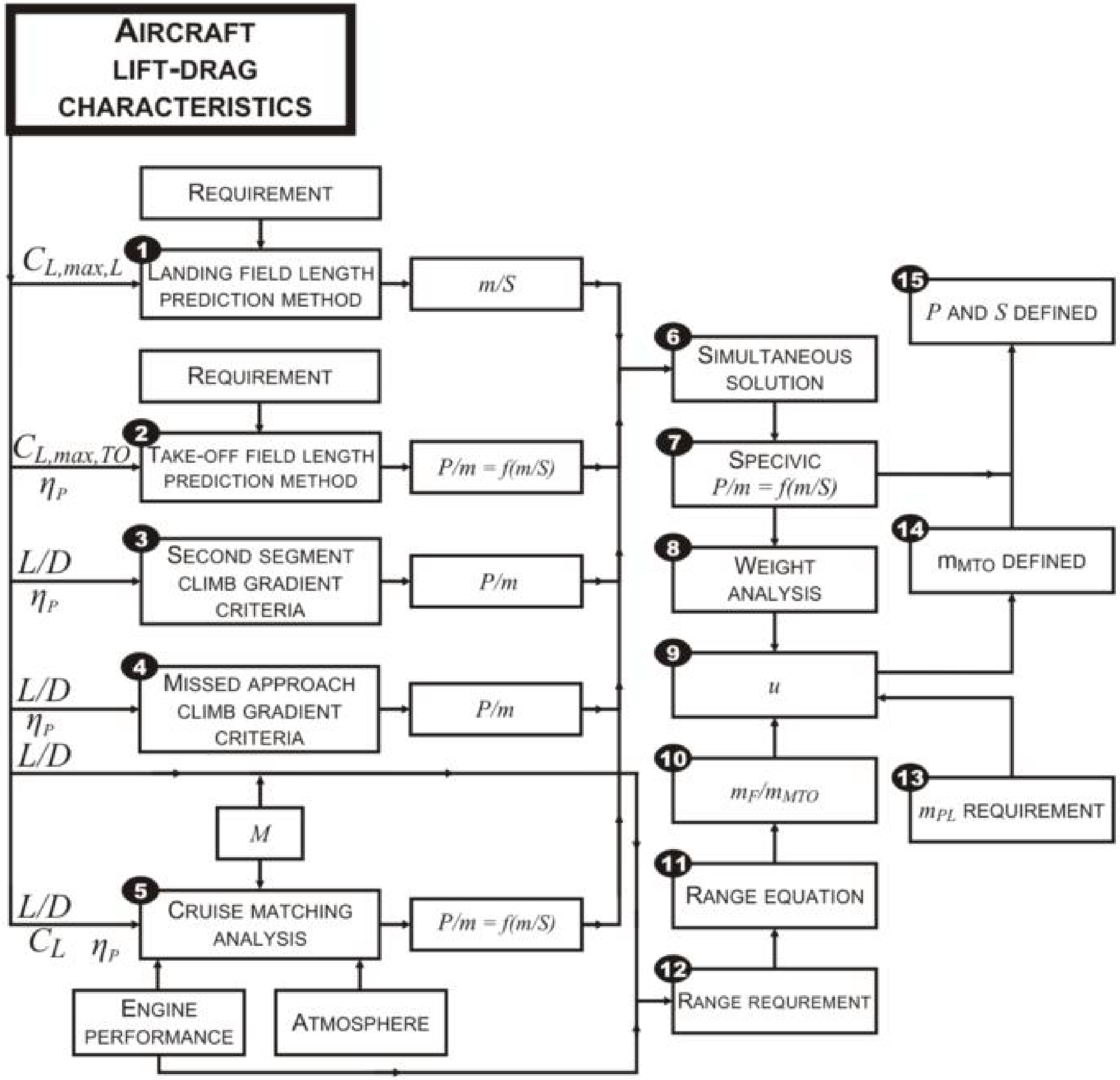

Optimization Parameters from Requirements

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Optimization Parameters

- Power to mass ratio $\frac{P_{TO}}{m_{MTO}}$

- Wing loading $\frac{m_{MTO}}{S_W}$

- The requirements are specified for the various phases of flight ....

Optimization Parameters from Requirements

Approach Speed

The landing requirements can be stated in terms of approach speed or landing field length.

One can be converted into the other: $$s_{LFL} = \left(\frac{V_{APP}}{k_{APP}} \right)^2$$

$$k_{APP} = 1.93 \sqrt{\frac{\text{m}}{\text{s}^2}}$$

Statistical factor for large turboprop aircrafts (calculated from k_L)

or

$$k_{APP} = \sqrt{\frac{2g \cdot 1.3^2}{\rho_0} k_L} = 5.20 \sqrt{k_L}$$

Optimization Parameters from Requirements

Landing Field Length

$$m_{MTO} / S_W \leq \frac{k_L \cdot \sigma \cdot C_{L,max,L} \cdot s_{LFL}}{m_{ML} / m_{MTO}}$$

Optimization Parameters from Requirements

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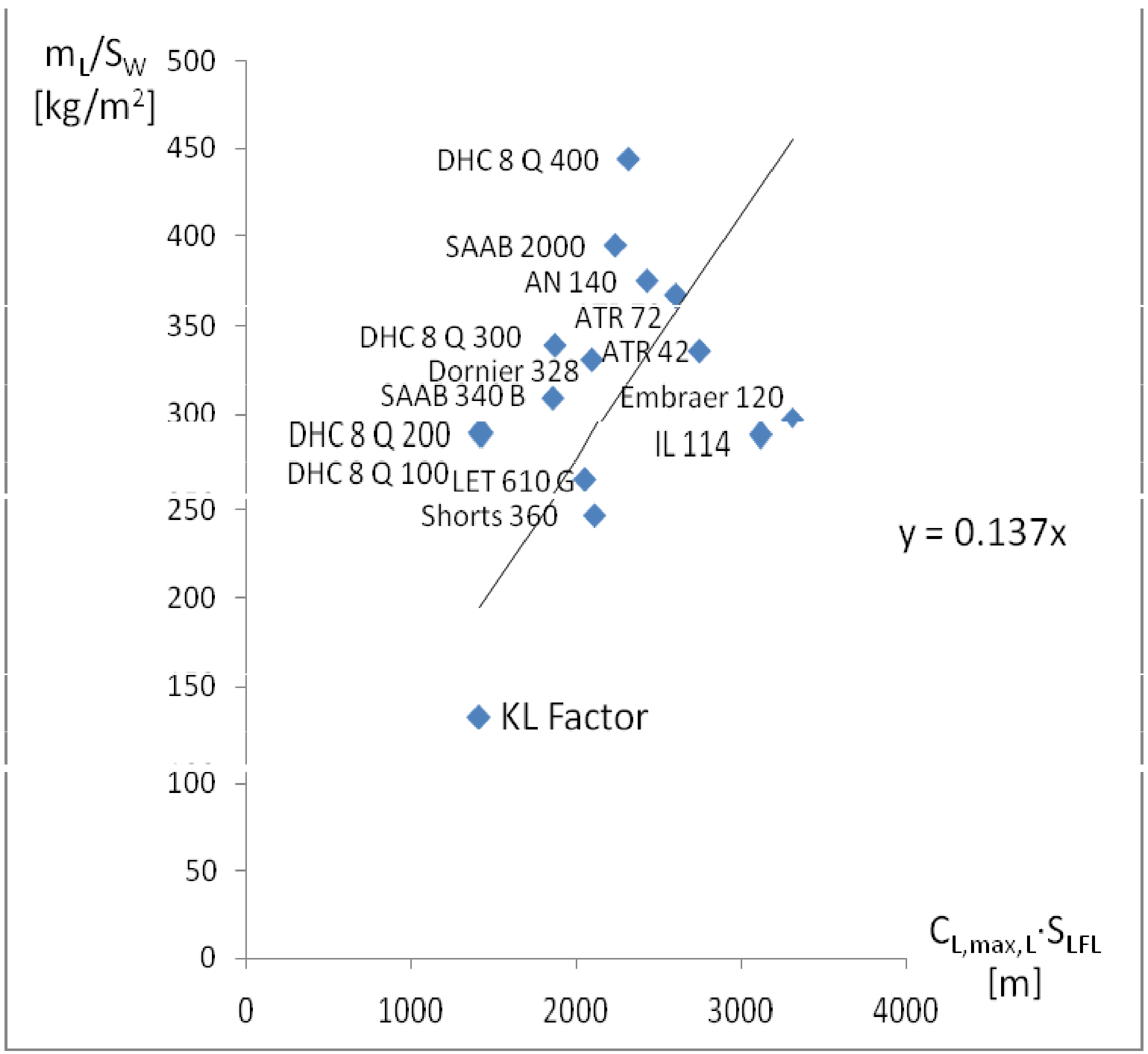
Landing Field Length



$$k_L = 0.137 \frac{\text{kg}}{\text{m}^3}$$

Statistical factor for large turboprop aircrafts

Optimization Parameters from Requirements

Take-Off Field Length

$$\frac{P_{TO} / m_{MTO}}{m_{MTO} / S_W} \geq \frac{k_{TO} \cdot V \cdot g}{s_{TOFL} \cdot \sigma \cdot C_{L,max,TO} \cdot \eta_{P,TO}}$$

Optimization Parameters from Requirements

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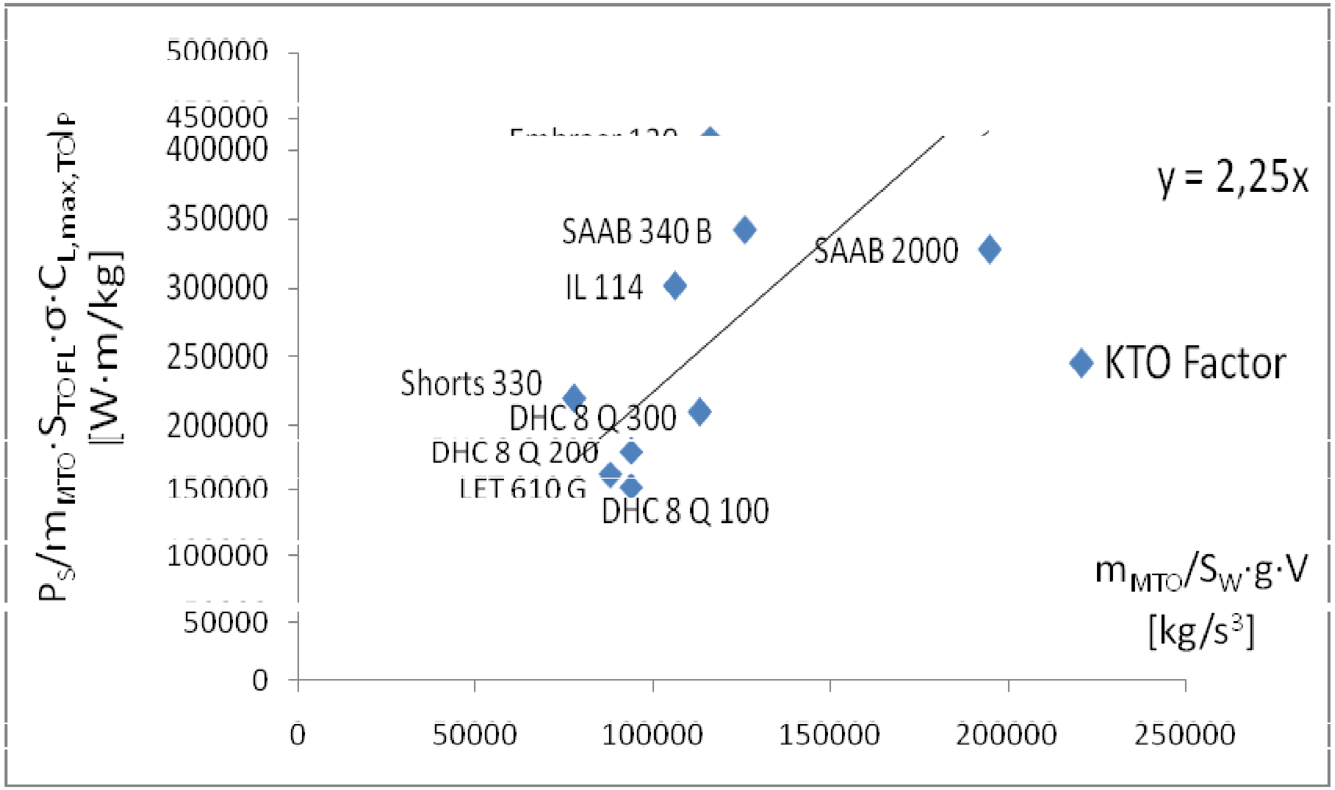
Take-Off Field Length

$$k_{TO} = 2.25 \frac{m^3}{kg}$$

Statistical factor for large turboprop aircrafts



Optimization Parameters from Requirements

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Take-Off Field Length

$$V = V_2 / \sqrt{2}$$

$$V_2 = 1.2 V_{S,TO}$$

$$V_{S,TO} = V_{S,L} \sqrt{\frac{C_{L,\max}}{C_{TO,\max}}}$$

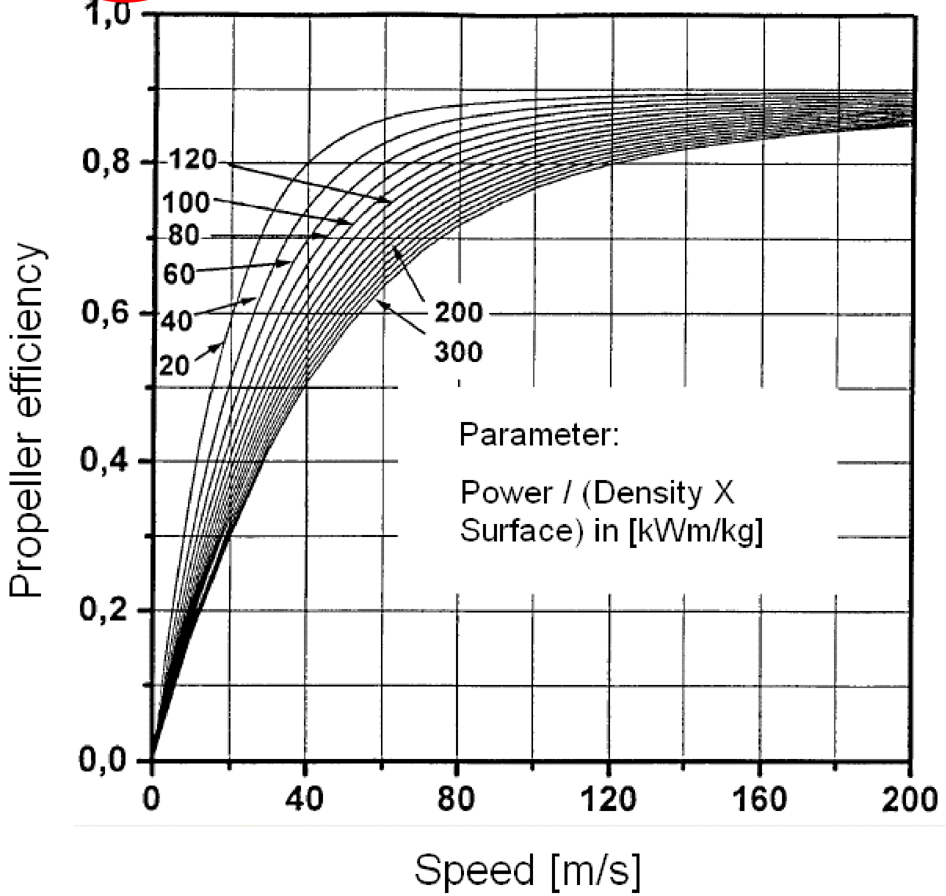
$$V_{S,L} = V_{APP} / 1.3$$

$$\sigma = \frac{\rho}{\rho_0} = \frac{288.15\,\text{K}}{288.15\,\text{K} + \Delta\vartheta_{TO}}$$

disc loading

$$L = \frac{P_{TO}}{\sigma\, \rho_0\, S_D}$$

$$\eta_{P,TO}$$



Optimization Parameters from Requirements

Climb Rate during 2nd Segment

$$\frac{P_{TO}}{m_{MTO}} \geq \frac{n_E}{n_E - 1} \cdot \left(\frac{1}{E} + \sin\gamma \right) \cdot \left(\frac{V_2 \cdot g}{\eta_{P,CL}} \right)$$

$$E = \frac{C_L}{C_D} = \frac{C_L}{C_{D,P} + \frac{C_L{}^2}{\pi \cdot A \cdot e}}$$

$$C_L = \frac{C_{L,\max,TO}}{1.2^2}$$

$$e = 0.7$$

$$C_{D,P} = 0.05 C_L - 0.035$$

$$C_L \geq 1.1$$

C_L depends on flap settings

Optimization Parameters from Requirements

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Climb Rate during Missed Approach

$$\frac{P_{TO}}{m_{MTO}} \geq \frac{n_E}{n_E - 1} \cdot \left(\frac{1}{E} + \sin \gamma \right) \cdot \left(\frac{V_{APP} \cdot g}{\eta_{P,L}} \right) \cdot \left(\frac{m_{ML}}{m_{MTO}} \right)$$

$$E = \frac{C_L}{C_D} = \frac{C_L}{C_{D,P} + \frac{C_L{}^2}{\pi \cdot A \cdot e}}$$

$$\frac{C_{L,max,L}}{1.3^2}$$

$$e = 0.7$$

$$C_{D,P} = 0.05 C_L - 0.035 + \Delta C_{D,gear}$$

$$C_L \geq 1.1$$

C_L depends on flap settings

Optimization Parameters from Requirements

Cruise

Lift = Weight

$$\frac{m_{MTO}}{S_W} = \frac{C_L \cdot M_{CR}{}^2}{g} \cdot \frac{\gamma}{2} \cdot p(H)$$

or

$$\frac{m_{MTO}}{S_W} = \frac{C_L \cdot \rho_0 \cdot V_{CR}{}^2 \cdot \sigma(H)}{2 \cdot g}$$

$$C_L = \frac{C_{L,md}}{(V / V_{md})^2}$$

with

$$C_{L,md} = \frac{\pi A e}{2 E_{\max}}$$

Optimization Parameters from Requirements

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Cruise

Drag = Thrust

$$\frac{P_{TO}}{m_{MTO}} = \frac{M_{CR} \cdot a(H) \cdot g}{P_{CR} / P_{TO} \cdot E \cdot \eta_{P,CR}}$$

or

$$\frac{P_{TO}}{m_{MTO}} = \frac{V_{CR} \cdot g}{P_{CR} / P_{TO} \cdot E \cdot \eta_{P,CR}}$$

$$E = \frac{2E_{\max}}{\frac{1}{\left(\frac{C_L}{C_{L,md}}\right)} + \left(\frac{C_L}{C_{L,md}}\right)}$$

with

$$C_L / C_{L,md} = 1/(V / V_{md})^2$$

Optimization Parameters from Requirements

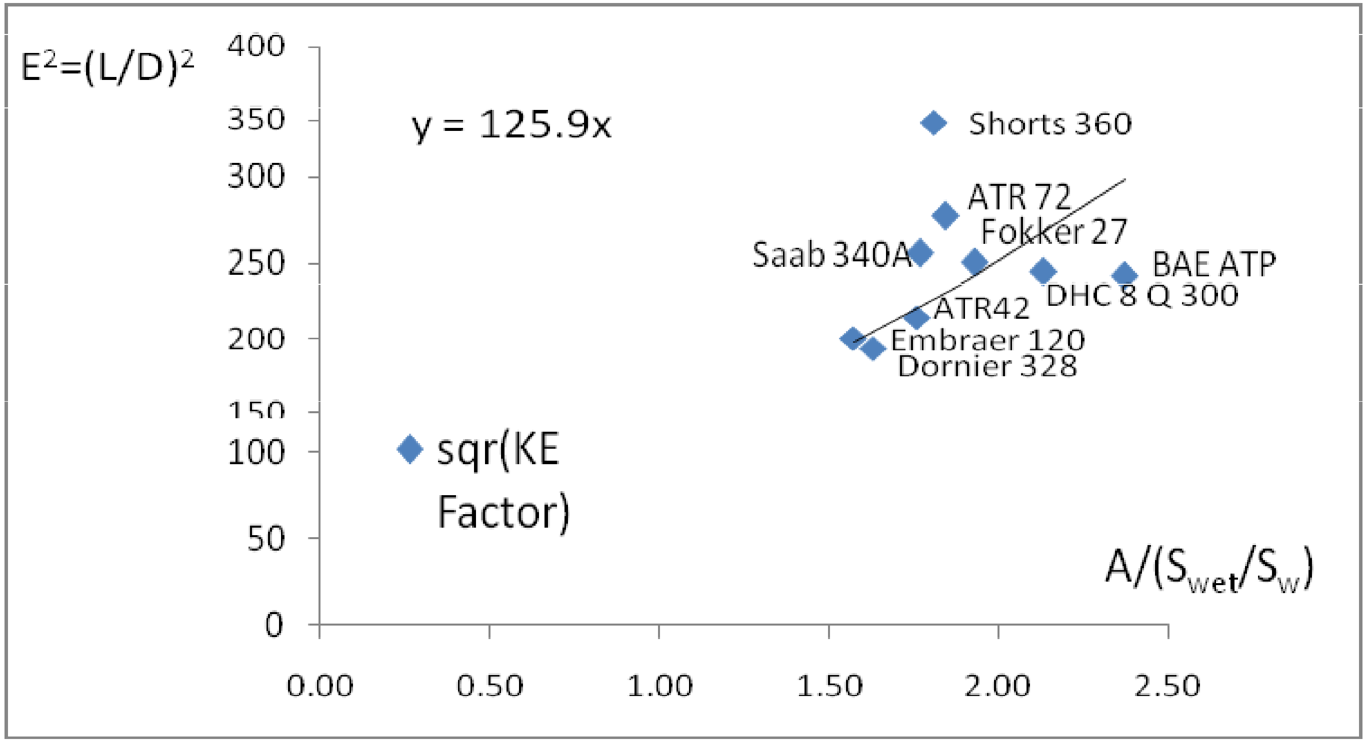
Cruise

Maximum Glide Ration Estimation

$$E_{max} = k_E \cdot \sqrt{\frac{A}{S_{wet} / S_W}}$$

$$k_E = 11.22$$

Statistical factor for large turboprop aircrafts



Optimization Parameters from Requirements

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Cruise

Engine Power Estimation

$$P / P_0 = A M^m \sigma^n$$ for turboprop engines

Author	Ref.Nr.	Page	Engine	A	m	n
Schaufele	[14]	187	generic	1.036	0.101	0.851
Brüning	[15]	58	T 64-GE-7	1.121	0.168	0.755
Russel	[16]	16	Rolls-Royce	1.725	0.267	0.966
Loftin	[7]	375	generic	1.089	0.091	0.924
McCormick & Barnes	[17]	351	PW 120	1.883	0.740	0.929
Average				1.371	0.273	0.885

Combining Results

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1) Generation of matching chart from optimization parameters

$$m_{MTO} = \frac{m_{PL}}{1 - \frac{m_F}{m_{MTO}} - \frac{m_{OE}}{m_{MTO}}}$$

2) Estimation of relative operating empty mass

$$\frac{m_{LOI}}{m_{CR}} = e^{-\frac{s_{CR}}{B_s}}$$

$$B_s = \frac{E \cdot \eta_P}{SFC \cdot g}$$

3) Calculation of relative fuel mass using fuel fractions. Additional distance for flight to an alternate (200 NM) and loiter time 45 min.

Example Calculation: ATR 72

Requirements

Landing:	$S_{LFL} = 1067\ \text{m}$	
Take off:	$S_{TOFL} = 1290\ \text{m}$	
2nd Segment:	$n_E = 2$	$\sin\gamma = 0.024$
Missed Approach:	$n_E = 2$	$\sin\gamma = 0.021$
Cruise:	$M = 0.41$	
Range:	$R = 715\ \text{NM}$	
Payload:	$m_{PL} = 6460\ \text{kg}$	

Example Calculation: ATR 72

Results

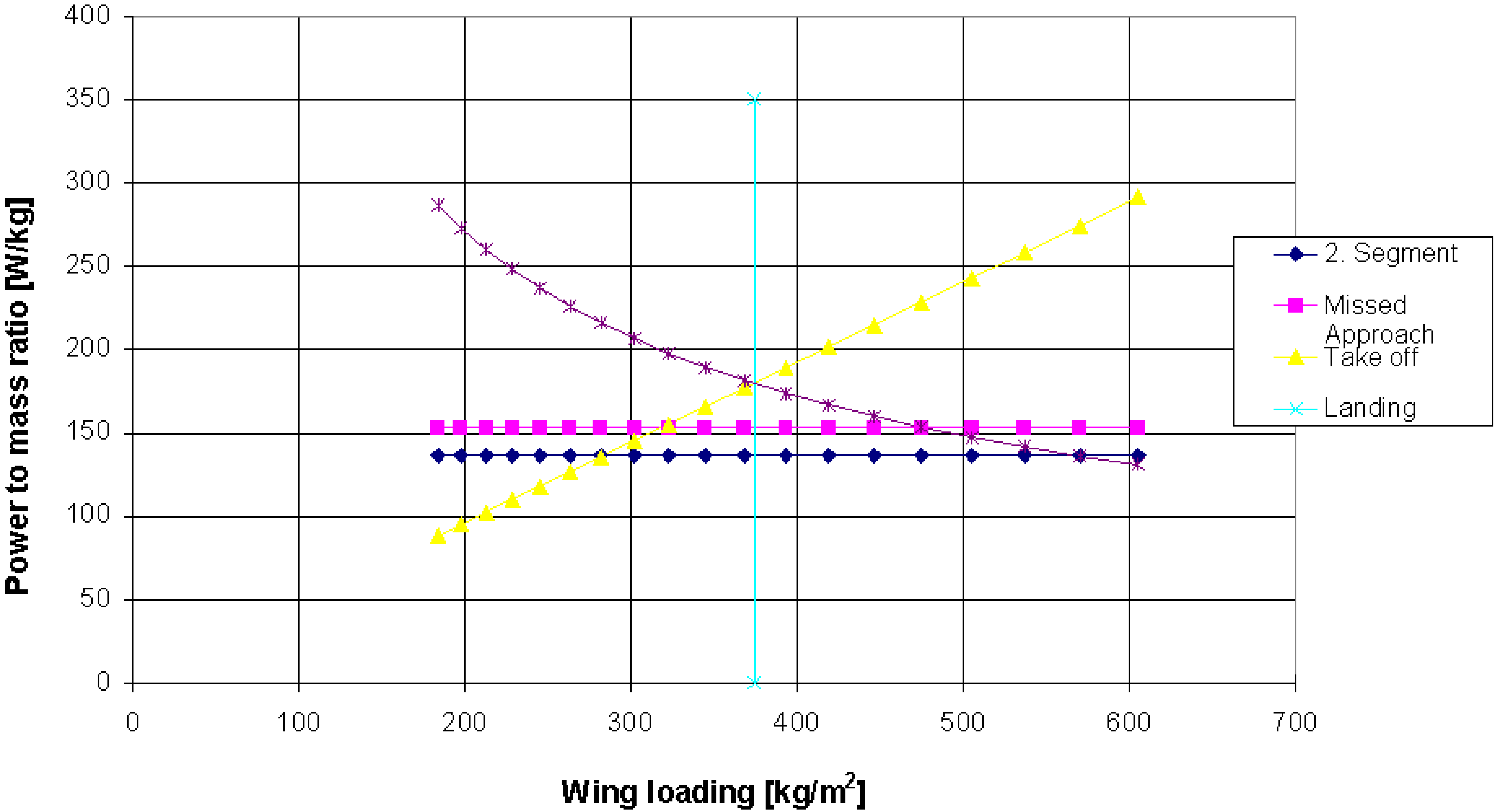
Aerodynamics and Propeller Efficiency

Flight Phase	$C_{L,max}$	C_L	E_{max}	E	η_P
Landing	2.5				
Take-off	2.1				0.64
2nd Segment		1.46		12.28	0.73
Missed Approach		1.48		10.79	0.73
Cruise		0.503	15.74	12.49	0.86

Example Calculation: ATR 72

Results

Matching Chart



Example Calculation: ATR 72

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Results

Aircraft Parameters

Parameter	Original ATR 72	Redesigned ATR 72	Difference
m_{MTO} [kg]	22800	22925	0.5%
m_L [kg]	22350	22466	0.5%
m_{OE} [kg]	12950	13021	0.5%
S_W [m²]	61	61.35	0.6%
b [m]	27.05	27.13	0.3%
P_{TO} (one engine) [kW]	2051	2061	0.5%
m_{MTO}/S_W [kg/m²]	373.8	373.7	0.0%
P_{TO}/m_{MTO} [W/kg]	179.9	179.8	-0.1%

Conclusions

- A preliminary sizing method for turboprop aeroplanes was presented.
- The method includes – where necessary – equations based on aircraft statistics.
- The preliminary sizing method was successfully tested with a redesign task of an ATR 72.

For further information see

http://FE.ProfScholz.de