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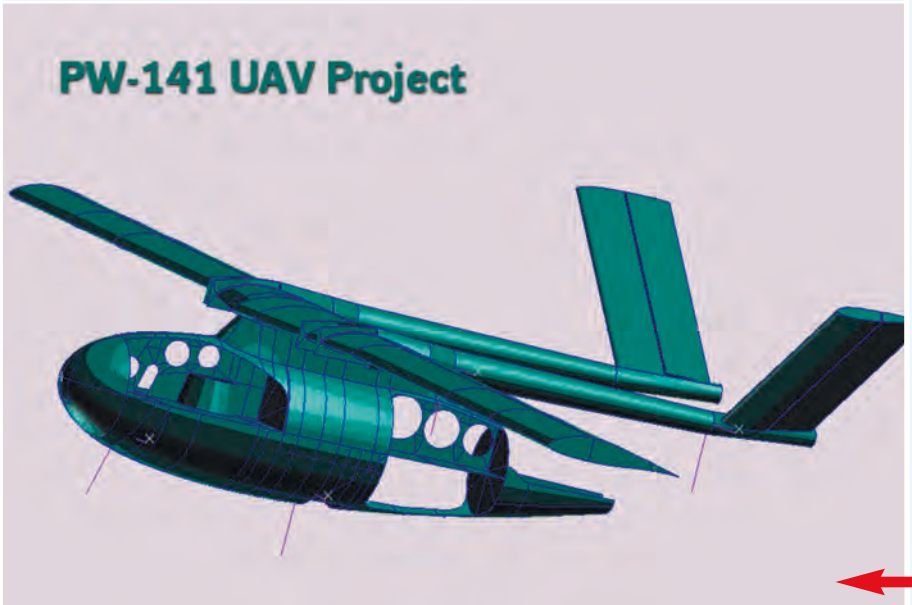

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Preliminary Sizing of Large Propeller Driven Aeroplanes

Předběžný výpočet rozměrů velkého vrtulového letounu

Prof. Dieter Scholz, Mihaela Niță / Hamburg University of Applied Sciences, Hamburg, Germany

Different types of aeroplanes (small / large, propeller / jet) require their own type of preliminary sizing method. One of theses methods differs only in a few but important aspects from the other. For the sake of efficient teaching of students and easy application in practice, the authors ask for the definition of a set of clearly defined step by step preliminary sizing methods. Based on the rather well known sizing method for large jet aeroplanes, the paper derives a preliminary sizing method for large propeller driven aeroplanes. In this way the paper tries to contribute to the definition of the set of methods. The sizing methods are all based on a matching chart that helps to graphically solve a two-dimensional optimization problem. The matching chart draws the optimization variable thrust-to-weight ratio (for jets) respectively power to mass ratio (propeller driven planes) versus wing loading for all basic requirements, which the aeroplane has to fulfill. The sizing method for propeller driven large aeroplanes is explained in detail and applied to a redesign study of the ATR 72. All equations are given in a form readily available for use. This requires in some cases the evaluation of proportionality factors based on aircraft statistics. Given are factors taking into account statistics for landing distance, take-off distance and maximum glide ratio for large propeller driven passenger aircraft. Furthermore, generic equations for the variation of power with altitude and speed of turboprop engines is given as well as a chart to determine the propeller efficiency.

Keywords: aircraft, design, preliminary sizing, matching chart, propeller, ATR 72, redesign.

1 Introduction

1.1 Preliminary Sizing

In literature and in practice, *aircraft development* has been repeatedly broken down into different phases. Various approaches have been followed. **Figure 1** shows one approach of dividing aircraft development into phases and shows key milestones. The development of large civil aircraft has inspired this example. Typical *aircraft design* activities take part primarily in the feasibility, concept and definition phase. *Preliminary sizing* is the first step in aircraft design and as such part of the feasibility phase, which is followed by *conceptual design* in the concept phase.

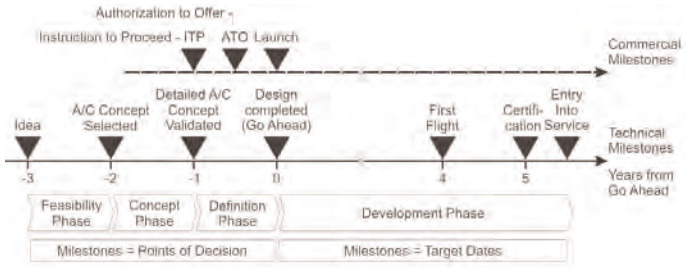


Fig. 1 — Phases of aircraft development

Preliminary sizing of an aircraft is possible without knowledge of the aircraft's geometry. In preliminary sizing the aircraft is more or less reduced to a point mass. However concrete ideas about the aircraft need to exist:

- What type of configuration will be selected?
- What aspect ratio can be expected?
- What cruise Mach number and type of propulsion system will be selected?

With these first considerations, realistic requirements can be formulated. These *requirements* (some of them depending on the certification rules — see below) will enter the preliminary sizing phase:

- 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} , approach speed V_{APP} or stall speed V_S ,
- Climb gradient γ during second segment,
- Climb gradient γ during missed approach.

Preliminary sizing yields basic *aircraft parameters* like

- 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} .

1.2 Aeroplane Categories, Propulsion System and Certification Rules

When attempting to do the preliminary sizing of a passenger aircraft, it has to be differentiated

a) the type of *propulsion system* (propeller or jet),
b) the *certification rules* for the aircraft.

The certification rules depend as much on the category and size of the aircraft as on the propulsion system. Let's differentiate these categories of aeroplanes:

1 Large jet aeroplanes are certified to CS-25 [CS-25] respectively FAR Part 25 [FAR Part 25],
2 Very light jets are certified to CS-23 [CS-23] respectively FAR Part 23 [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 [CS-VLA],

6 Different certification rules exist for ultra light aircraft.

1.3 Preliminary Sizing Methods

Different preliminary sizing methods are needed for the various categories of aeroplanes given in (1) through (6) above, because equally (a) and (b) have an impact on the underlying flight mechanics of the sizing problem.

Aircraft design text books or lecture notes do not always seem to present a clear step by step method for preliminary sizing. One early text book with a clear step by step method for preliminary sizing was Corning [Corning 1964]. Loftin [Loftin 1980] proposes a preliminary sizing method for large jet aeroplanes (1). Roskam [Roskam 1989], Scholz [Scholz 2008] and others base their preliminary jet sizing method on Loftin. Loftin [Loftin 1980] proposes also another method for smaller propeller driven aeroplanes (4).

What seems to be missing in the literature is a set of clearly defined step by step preliminary sizing methods for each category of aeroplane. This set of methods has to be built in such a way that the user easily understands the similarities and differences of the various methods.

Aim of this paper is to present a sizing method for large propeller driven aeroplanes (3) that follows as closely as possible the better known method for large jet aeroplanes (1) and work in this way towards the goal of a unified and complete set of sizing methods for the most important categories of civil aeroplanes.

1.4 General Approach

A *matching chart* should be at the heart of each sizing method. The matching chart helps to graphically solve a two-dimensional optimization problem. Keeping in mind that flight mechanic calculations for propellers are based on power P, whereas calculations for jets are based on thrust *T*, the two *optimization variables* as proposed here are:

a) thrust-to-weight ratio $T_{TO} / (m_{TO} \cdot g)$ respectively power to mass ratio P_{TO} / S_W

and

b) wing loading m_{MTO} / S_W .

Figure 2 shows a generic matching chart for large jet aeroplanes. From the various requirements, either the wing loading or the thrust-to-weight ratio (or a function of one versus the other) can be calculated. For all calculations it is ensured that wing loading and thrust-to-weight ratio always refer to take-off conditions, which makes it possible to compare the values of different flight phases. The results are plotted on the matching chart. The matching chart for large propeller driven airplanes only differs by putting P_{TO} / m_{TO} on the ordinate and will be explained in the main part of this paper.

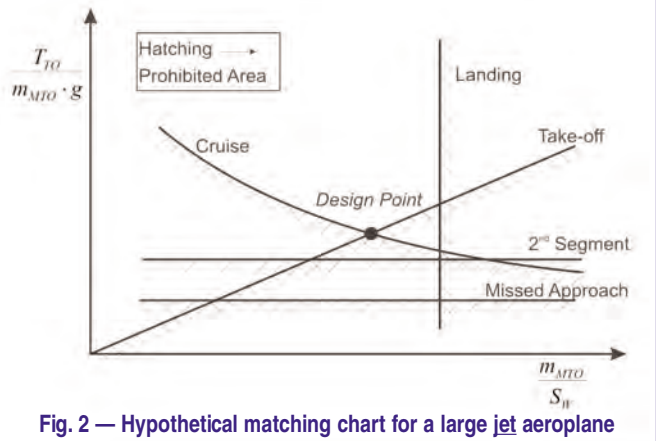


Fig. 2 — Hypothetical matching chart for a large jet aeroplane

The *aim of optimization* is to achieve the following:

- *Priority 1:*
  to achieve the smallest possible thrust-to-weight ratio (respectively power to mass ratio)
- *Priority 2:*
  to achieve the highest possible wing loading (if not other design requirements indicate to decide otherwise).

2 Overview

An overview of the proposed preliminary sizing method for large propeller driven aeroplanes is given in **Figure 3**. The blocks in the first column convert the requirements into the optimization parameters, which are power to mass ratio P_{TO} / m_{TO} and wing loading m_{TO} / S_W (shown in Figure 3 in the second column). In detail, we have:

Block 1 "LANDING FIELD LENGTH" provides a maximum value for the wing loading *m/S* (reference value: m_{TO} / S_W). The input values of the calculation are the maximum lift coefficient with flaps in the landing position $C_{L,max,L}$ as well as the landing field length S_{LFL} according to CS/FAR. The maximum lift coefficient $C_{L,max,L}$ depends on the type of high lift system and is selected from data in the literature (see textbooks and lecture notes).

Block 2 "TAKE-OFF FIELD LENGTH" provides a minimum value for the power-to-mass ratio as a function of the wing loading: $P / m = f(m / S)$ with reference value: P_{TO} / m_{MTO} . The functional connection P / m = f (m / S) is dependent on the maximum lift coefficient with flaps in the take-off position $C_{L,max,TO}$, propeller efficiency η_p and the take-off field length s_{TOFL}. The maximum lift coefficient $C_{L,max,TO}$ is selected with the aid of data in the literature. In a first attempt it is often assumed that $C_{L,max,TO}$ is 80% of $C_{L,max,L}$.

Block 3 examines the "SECOND SEGMENT CLIMB GRADIENT" and **Block 4** the "MISSED APPROACH CLIMB GRADIENT". The blocks provide minimum values for the power-to-mass ratio P / m. The input value for the calculations: the lift-to-drag ratio L / D and the propeller efficiency η_p. L / D is estimated on the basis of a simple approximation calculation.

Block 5 "CRUISE MATCHING ANALYSIS" represents the cruise analysis that provides a minimum value for the power-to-mass ratio as a function of the wing loading: $P / m = f(m / S)$. The power-to-mass ratio thus determined is sufficient to facilitate a stationary straight flight with the assumed cruise Mach number M_{CR} or cruise speed V_{CR} for the respective wing loading. The calculation is carried out for the design lift coefficient $C_{L,DESIGN}$. The cruise altitude is also obtained from the cruise analysis. Input values are the lift-to-drag ratio $E = L / D$ during cruise, the assumed cruise Mach number $M = M_{CR}$ or speed $V = V_{CR}$, engine and propeller characteristics and the characteristics of the atmosphere.

The output values of the blocks in the first column of Figure 3 provide a set of relationships between the power-to-mass ratio

and the wing loading. Taken together, these relationships give, in a "SIMULTANEOUS SOLUTION" (**Blocks 6**) a single pair of values: power-to-mass ratio and wing loading (P / m; m / S) (**Block 7**) that meets all requirements and constraints in an economical manner.

Blocks 8 and 9 stand for "WEIGHT ANALYSIS". The relative operating empty mass m_{OE} / m_{MTO} or the relative useful load u are estimated. m_{MTO} is the maximum take-off mass. The relative useful load is defined as

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

Various methods exist in the literature for estimating m_{OE} / m_{MTO} or u. For propeller driven aeroplanes, the power-to-mass ratio (from Block 7) could be used as an input value for a mass estimate according to statistics.

In **Block 11** "RANGE EQUATION" yields the relative fuel mass m_F / m_{MTO} (**Block 10**) which is calculated, using the "Breguet Range Equation" for propeller aircraft, based on the "RANGE REQUIREMENT" (**Block 12**). Other input values are the assumed cruise Mach number M / M_{CR} or cruise speed V / V_{CR}, the lift-to-drag ratio during cruising $E = L / D$, the specific fuel consumption $c = SFC_{CR}$ and the propeller efficiency η_p during cruise.

In **Block 14** maximum take-off mass m_{MTO} is calculated from relative useful load u, relative fuel mass m_F / m_{MTO} and the payload requirement m_{PL} (**Block 13**). With the maximum take-off mass m_{MTO} the necessary *take-off power* $P = P_{TO}$ and the *wing area* $S = S_W$ can then be calculated in **Block 15** from power-to-mass ratio P / m and wing loading m / S.

3 Optimization Parameters from Requirements

Optimization parameters are power to mass ratio P_{TO} / m_{TO} and wing loading m_{TO} / S_W. The requirements are specified for the various phases of flight.

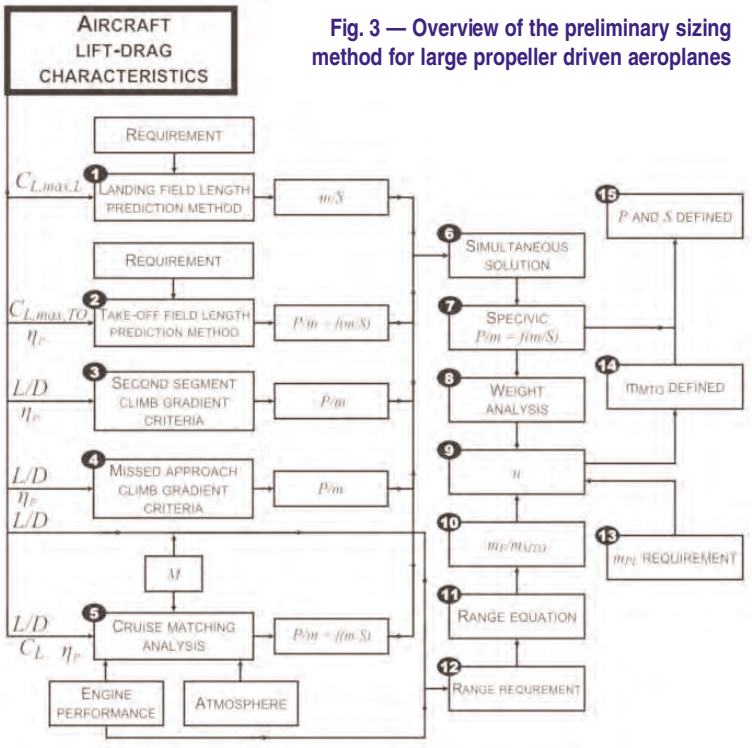


Fig. 3 — Overview of the preliminary sizing method for large propeller driven aeroplanes

3.1 Approach Speed

The landing requirements can be stated in terms of approach speed V_{APP} or landing field length s_{LFL}. Assuming similar braking characteristics of the aircraft of one category, statements of either approach speed or landing field length are equivalent ones. Based on statistics one statement can be transformed in the other:

$$s_{LFL} = \left(\frac{V_{APP}}{k_{APP}} \right)^2$$

The proportionality factor was evaluated (see **Figure 4**) from data selected for this category of large passenger turboprop aircraft:

$$k_{APP} = 1.64 \sqrt{\frac{\mathrm{m}}{\mathrm{s}^2}}$$

It also would have been possible to calculate k_{APP} from k_L (see Subsection 3.2 for k_L)

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

to yield a better value for large passenger turboprop aircraft:

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

The two approaches do not result in exactly the same value because the evaluation was based on different aircraft data. Experience shows that reported values for approach speed are often not given accurately and do not always refer to the $V_{APP} = 1.3\ V_S$ reference speed. For this reason, better results can be obtained when using landing distance data. In comparison, large passenger jets [7], [9]:

$$k_{APP} = 1.70 \sqrt{\frac{\mathrm{m}}{\mathrm{s}^2}} .$$

Based on the latter two values for k_{APP}, turboprop aircraft achieve a shorter landing field length at the same approach speed (by a factor of 1.29). This is due to the their better reverse thrust capabilities, which in turn also resulted in a lower safety factor in the determination of landing field length from landing distance for turboprop aircraft: 1/0.7 = 1.429 for turboprop aircraft versus 1/0.6 = 1.667 for jets [1]. The turboprop advantage comes out as 1.667/1.429 = 1.167 which is about the ratio that resulted from aircraft data.

3.2 Landing Field Length

Landing field length yields the optimization parameter wing loading

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

The proportionality factor was evaluated (see **Figure 5**) from data selected for this category of large passenger turboprop aircraft:

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

In comparison, large passenger jets [7], [9]:

$$k_L = 0.107 \frac{\mathrm{kg}}{\mathrm{m}^3}$$

have a lower value than the 0.137 kg/m³ from above, which means that turboprop aircraft on ave-

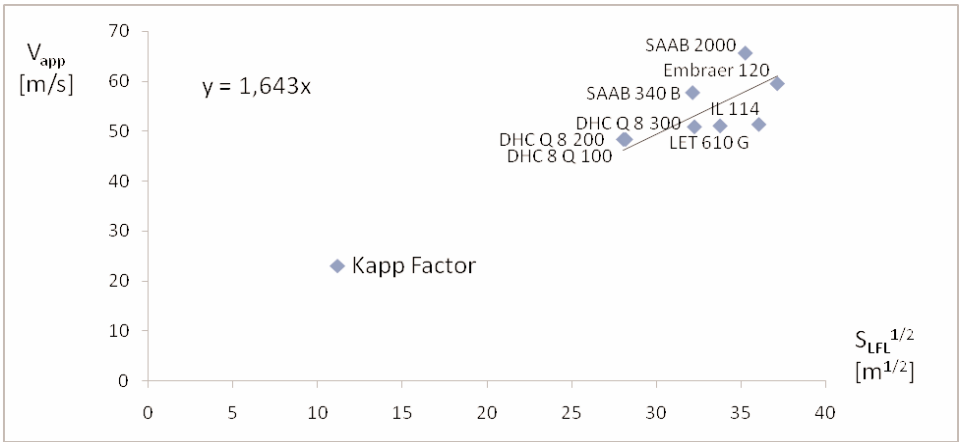


Fig. 4 — Statistical factor k_{APP} for approach speed calculation from landing field length for turboprop aircraft

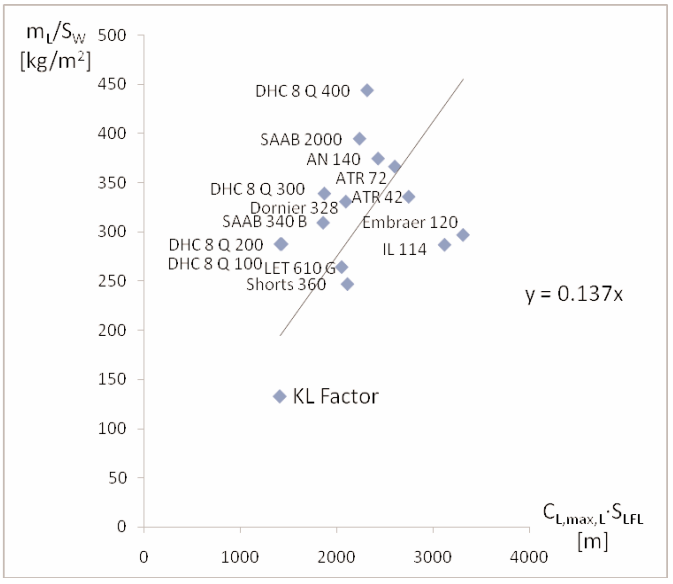


Fig. 5 — Statistical factor k_L for calculating wing loading from landing field length and maximum lift coefficient upon landing for turboprop aircraft

rage achieve a shorter landing field length with the same wing loading.

$$\sigma = \frac{\rho}{\rho_0} = \frac{288.15\,\mathrm{K}}{288.15\,\mathrm{K} + \Delta T_L}$$

is the density ratio. σ differs from unity, if landing requirements have to be met at a high (or lower) temperature than following from International Standard Atmosphere (ISA) at Mean Sea Level (MSL).

m_{ML} / m_{MTO} has to be selected. It may not be too low, otherwise fuel reserves or remaining fuel upon landing due to favorable flight conditions could result in a landing mass greater than maximum landing mass $m_L > m_{ML}$ that is clearly not permissible. Typical values for large propeller driven aeroplanes are in the range between 0.95 and 1.00. On average a value of 0.97 may be selected. These aircraft are short range aircraft. For this reason the value is always very close to 1.0.

3.3 Take-Off Field Length

Take-off field length yields a fixed ratio between the optimization parameters power to mass and wing loading. In the matching chart this forms a straight line through the origin.

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

The proportionality factor was evaluated (see **Figure 6**) from data selected for this category of large passenger turboprop aircraft:

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

In comparison, large passenger jets [7], [9]:

$$k_{TO} = 2.34\,\frac{\mathrm{m}^3}{\mathrm{kg}}$$

have practically the same value.

The speed V is the average speed during take-off. Averaging is done with respect to dynamic pressure which yields

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

V_2 is the take-off safety speed that has to be reached at the end of the take-off distance. It is usually taken as

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

New amendments of CS-25 [1] also indicate the possibility to set V_2 as low as

$$V_2 = 1.13\,V_{S,TO} .$$

Take-off stall speed depends on flap setting and hence selected lift coefficient. Making a connection to high lift capabilities during landing, we get

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

Older aircraft were designed to

$$V_{APP} = 1.3\,V_{S,L} .$$

New amendments of CS-25 [1] also indicate the possibility to set V_{APP} as low as

$$V_{APP} = 1.23\,V_{S,L} .$$

So

$$V_{S,L} = \frac{V_{APP}}{1.3} \text{ or } V_{S,L} = \frac{V_{APP}}{1.23}$$

$$V_{APP} = k_{APP} \cdot \sqrt{S_{LFL}}$$

$$\sigma = \frac{\rho}{\rho_0} = \frac{288.15\,\mathrm{K}}{288.15\,\mathrm{K} + \Delta T_{TO}}$$

The propeller efficiency $\eta_{P,TO}$ for take-off is obtained from **Figure 7** for the average speed V (see above) and a disc loading

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

calculated from take-off power, density and disc area. During the first run of the sizing program the take-off power is not known. Instead a propeller efficiency is merely estimated from Figure 7. In a second iteration applying the sizing method, the take-off power from Block 15 can be used for a better estimate of the propeller efficiency with the help of Figure 7. At this point we should also be more specific about was is meant here with engine power: The power indicated is always the shaft power $P = P_S$ and $P_{TO} = P_{S,TO}$.

3.4 Climb Rate during 2nd Segment

2nd segment climb rate yields the optimization parameter power to mass

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

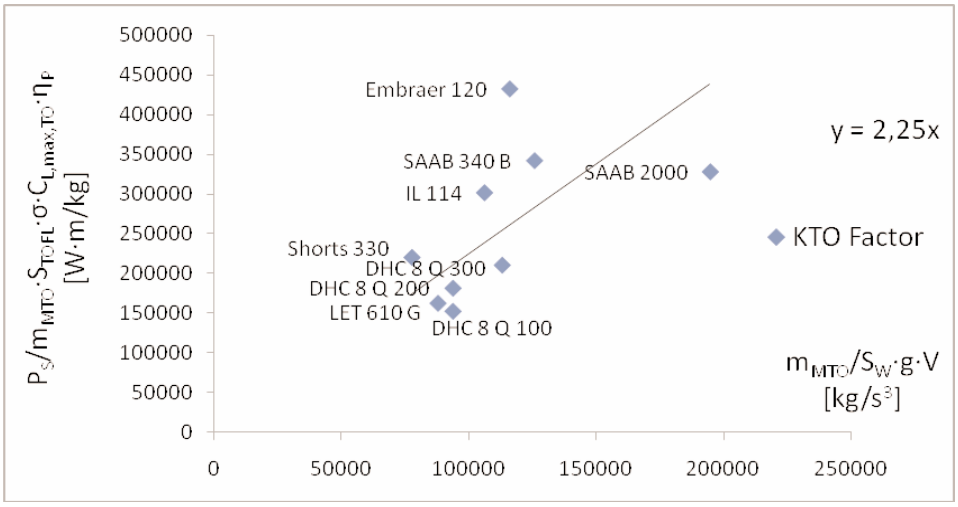


Fig. 6 — Statistical factor k_{TO} for calculating the take-off optimization parameter from take-off field length and maximum lift coefficient upon take-off for turboprop aircraft

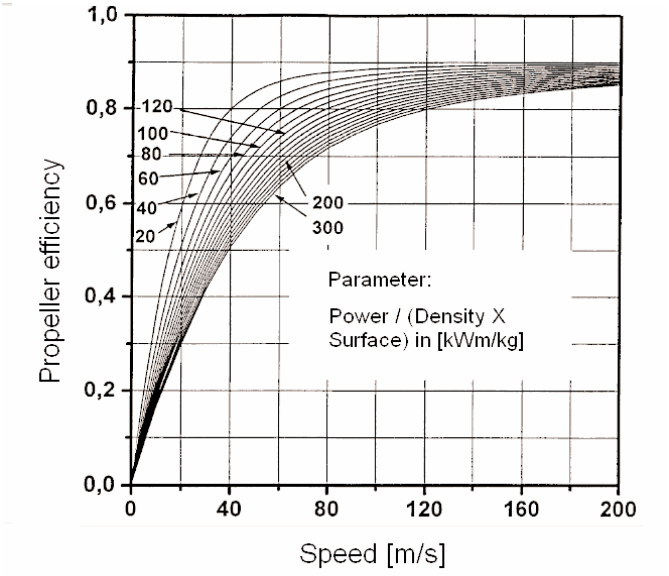


Fig. 7 — Propeller efficiency for variable pitch propellers as a function of aircraft speed and disc loading (the reference surface area is the propeller disc area). Adapted from [10]

n_E stands for the number of engines. $E = L/D$ is the glide ratio during take-off estimated from aspect ratio A, Oswald factor e:

$$E = \frac{C_L}{C_D} = \frac{C_L}{C_{D,P} + \frac{C_L^2}{\pi \cdot A \cdot e}}, \quad C_{D,P} = 0.05 C_L - 0.035 \text{ (for } C_L \geq 1.1), \quad e = 0.7, \quad C_L = \frac{C_{L,\max,TO}}{1.2^2}.$$

The climb rate (sin γ) is given in [1]: "The steady gradient of climb may not be less than 2.4% for two-engined aeroplanes, 2.7% for three-engined aeroplanes and 3.0% for four-engined aeroplanes."

V_2 and $\eta_{P,CL}$ from Section 3.3. $\eta_{P,CL}$ is calculated with a speed V_2 . Note correct propeller efficiency calculation requires iteration.

3.5 Climb Rate during Missed Approach

Missed approach climb rate puts once again a boundary condition on the optimization parameter power to mass

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

This time the estimate for $E = L/D$ is done with

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

$C_{D,P} = 0.05 C_L - 0.035$ (for $C_L \geq 1.1$),
$e = 0.7$, $C_L = \frac{C_{L,\max,L}}{1.3^2}$
$\Delta C_{D,gear} = 0$ for [1] and
$\Delta C_{D,gear} = 0.015...0.020$ for [2].

The climb rate (sin γ) is given in [1]: "The steady gradient of climb may not be less than 2.1% for two-engined aeroplanes, 2.4% for three-engined aeroplanes and 2.7% for four-engined aeroplanes."

V_{APP} is taken from Section 3.3. m_{ML}/m_{MTO} is taken from Section 3.2. $\eta_{P,L}$ from Section 3.3, calculated with a speed V_{APP}. Note correct propeller efficiency calculation requires iteration.

3.6 Cruise

Cruise matching is based on the assumption of steady state straight flight. From the requirement of a certain cruise speed V_{CR} or cruise Mach number M_{CR}, the power to mass ratio and the wing loading are determined. In order to achieve this, two equations can be used: *Lift = Weight* and *Drag = Thrust*. Thrust will be replaced by power in the last equation. Both equations include atmospheric and/or engine parameters that are a function of cruise altitude. Since cruise altitude is not known when starting the sizing method, the power to mass ratio and the wing loading are calculated for a range of possible cruise altitudes. Data from this table is later drawn into the matching chart and stays for the cruise requirement.

3.6.1 Lift = Weight

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

or

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

It is $C_L / C_{L,md} = 1/(V/V_{md})^2$, so the lift coefficient in cruise follows from $C_L = \frac{C_{L,md}}{(V/V_{md})^2}$,
with $C_{L,md} = \frac{\pi A e}{2E_{\max}}$.

V / V_{md} is an input parameter to the sizing method to help match the cruise performance. Maxim glide ratio E_{max} from Section 3.6.3. $\sigma(H)$ is the relative density from the ISA, $\rho_0 = 1.225$ kg/m³ is the density of the air at MSL from ISA. $\gamma = 1.4$ is the ratio of specific heats.

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

V / V_{md} is an input parameter to the sizing method to help match the cruise performance. η_{PCR} from Section 3.3, E from Section 3.6.3, P_{CR} / P_{TO} from Section 3.6.4. $a(H)$ is the speed of sound from the ISA.

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

Tab. 1: Parameters A, m and n to calculate the relative amount of engine shaft power P_{CR} / P_{TO} as a function of altitude (expressed by σ) and Mach number M

3.6.3 Maximum Glide Ratio Estimation

Maximum glide ratio $E_{max} = (L / D)_{max}$ is estimated from aspect ratio A and wetted area S_{wet}. The ratio S_{wet} / S_{wet} for large turboprop aeroplanes is between 5 and 7 with an average at about 6.2.

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

The proportionality factor was evaluated (see **Figure 8**) based on data from [11] for this category of

large passenger turboprop aircraft: $k_E = 11.22$.

In comparison [9],

large passenger jets, long range: $k_E = 17.25$,
large passenger jets, medium range: $k_E = 16.19$,
large passenger jets, short range: $k_E = 15.15$.

It can be determined that statistically, the maximum lift coefficient (at the same aspect ratio and wetted area ratio) is smaller for aircraft with smaller range. Since the turboprop aircraft offer usually a smaller range than jets their maximum glide ratio is smaller (does not need to be that high).

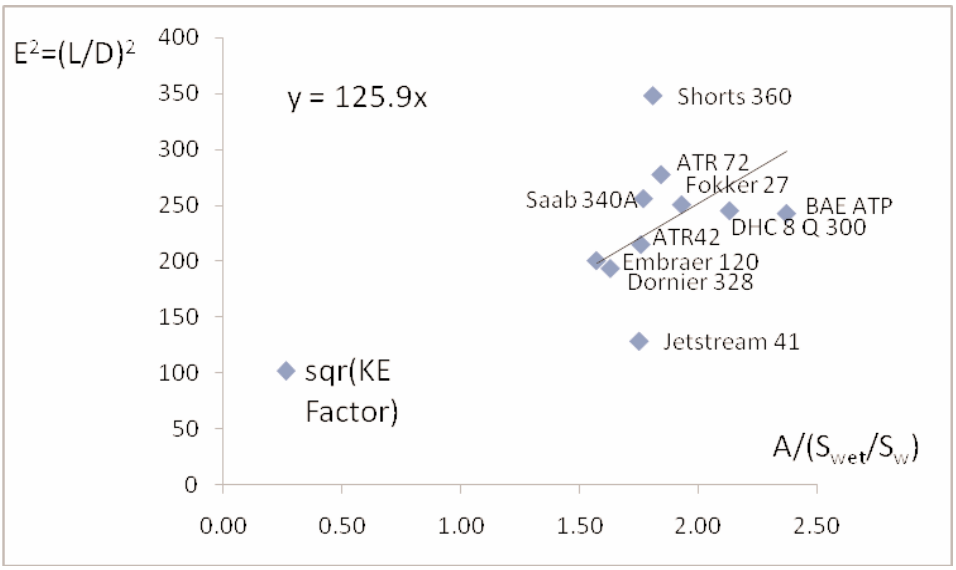


Fig. 8 — Statistical factor k_E for calculating the maximum glide ratio E_{max}, for turboprop aircraft based on data from [11]

3.6.4 Engine Power Estimation

In Section 3.6.2 the ratio P_{CR} / P_{TO} is used. This is the relative amount of engine shaft power left at altitude and at a certain aircraft speed. Since the sizing method should be a generic one, a data sheet that applies only for one specific engine may not be so helpful. For this reason, different sources with specific and generic engine performance data where studied in [13]. Furthermore, published equations to calculate P_{CR} / P_{TO} were investigated and fitted to the available data. As a result of the investigation an equation was recommended for use:

$P / P_0 = AM^m\sigma^n$ with parameters A, m and n from **Table 1**.

4 Combining Results

Values of optimization parameters are drawn in the matching chart. An example is given in Section 5. The design point is found as explained in Section 2. The rest of the sizing process is straight forward and does not differ much from that process for large jet aeroplanes (see [9]).

The required fuel mass is calculated using fuel fractions. Fuel reserves have to be included. Domestic and international flights are distinguished. For turboprop aeroplanes usually domestic reserves apply. The additional distance for the flight to an alternate, which is normally assumed to be 200 NM for larger jets, may also be selected as a shorter distance for turboprops that are not so big. Reserve loiter time is 45 minutes.

As in all other sizing processes, it is important to make a clear statement about the payload range requirements. Payload and range must from a pair of values in the payload range diagram (not any payload combined with any range). The fuel reserves and the cruise speed must be clearly stated together with the payload range requirements.

The fuel fractions for cruise flight, flight to the alternate and for loiter has in this sizing process to be based on the range equations for propeller aircraft. The Breguet factor for propeller aircraft

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

is used to calculate the segment fuel fraction for the cruise flight phase

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

s_{CR} is the distance flown in cruise. If the distance to the alternate and the distance covered during loiter is added, no other equation is needed. Other segment fuel fractions (e.g. for take-off and landing) may be taken from tables [8]. All segment fuel fractions combined yield relative fuel mass m_F / m_{MTO}. Maximum take-off mass is finally calculated from

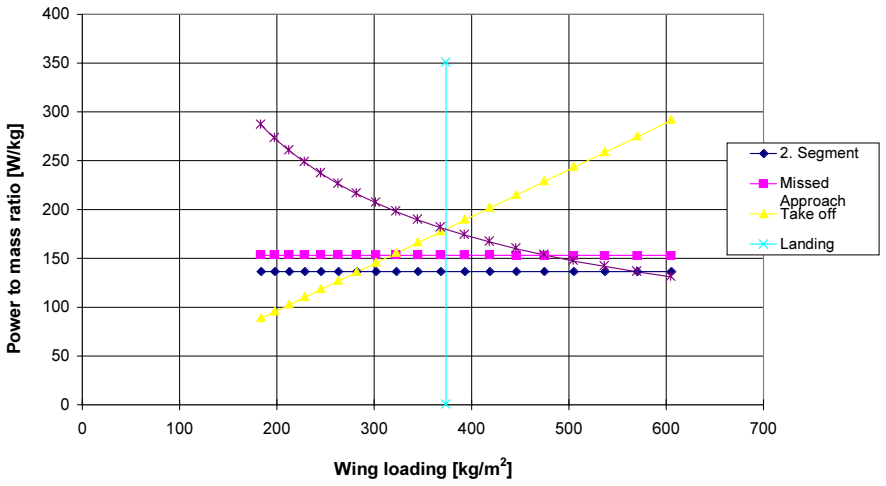
$$m_{MTO} = \frac{m_{PL}}{1 - \frac{m_F}{m_{MTO}} - \frac{m_{OE}}{m_{MTO}}}.$$

5 Example Calculation: ATR 72

The sizing method was put to a test with the redesign of an ATR 72. The requirements for the sizing task were taken from the manufacturers web page.

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

Cruise altitude, determined from the design point: H_{CR} = 3888 m.



Fig, 9 — Matching chart for the sizing process of the ATR 72

6 Conclusion

A preliminary sizing method for turboprop aeroplanes was presented. The method includes — where necessary — equations based on aircraft statistics. The preliminary sizing method was tested with a redesign task of an ATR 72. The redesign with the proposed method was possible with only minor difference between the respective ATR value from the redesign case and the original ATR 72 value.

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

Tab. 2: Results from the redesign sizing process of an ATR 72 — Aerodynamic parameters and propeller efficiency

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%

Tab. 3: Results from the redesign sizing process of an ATR 72: Mass, wing area, power

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