Aircraft Preliminary Sizing with PreSTo

Re-Design of the Boeing B777-200LR

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Abstract

This report introduces the aircraft design process of the Hamburg University of Applied Sciences (German: Hochschule für Angewandte Wissenschaften Hamburg, HAW) with focus on the preliminary sizing process of transport jet aircraft. For that purpose, the HAW's Aircraft Preliminary Sizing Tool PreSTo is used to re-design a reference aircraft, which was chosen to be the Boeing B777-200LR 'Worldliner'. The workflow of the aircraft preliminary sizing process within PreSTo is presented as well as the results of the re-design of the B777-200LR. The determined results like masses, wing area and engine take-off thrust are of good accuracy. Three additions were made to the tool to further improve the results or to make the application of the sizing process more convenient respectively. These additions are the investigation of two instead of one reference mission, a sheet to collect 'target' values of the reference aircraft and a sketching tool for the quick graphical layout and change of the fuselage cross section and floor plan.

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Nomenclature and abbreviations

A	Aspect ratio
a	Relation of the thrust-to-weight ratio to the wing loading
	Speed of sound
AC	Aircraft
b	Span
BC	Business class
BPR	Bypass ratio
B_s	Breguet range factor
B_t	Breguet time factor

C	Coefficient (related to a finite wing)
c	Coefficient (related to a wing section or infinite wing)
	Specific fuel consumption
CS	Certification Specification
d	Diameter
DOC	Direct operating costs
E	Glide ratio = lift-to-drag ratio
e	Oswald-efficiency factor
EASA	European Aviation Safety Agency
ECS	Environmental control system
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FC	First class
FL	Flight level (FL 100 = 10,000 ft)
FPO	Future Projects Office
ft	Foot/feet (1 ft = 0.3048 m)
g	Earth acceleration
gal	Gallon (1 US gal = 3.785 l)
GE	General Electric
GF	Green Freighter
h	Height, altitude
HAW	Hochschule für Angewandte Wissenschaften
	(University of Applied Sciences)
IFL	Institut für Flugzeugbau und Leichtbau
	(Institute of Aircraft Design and Lightweight Structures)
ISA	International Standard Atmosphere
k	Correlation factor
kt	Knot(s) (1 kt = 1 NM/h = 1.852 km/h)
lb	Pound (1 lb = 0.4536 kg)
LR	Long range
L/D	Lift-to-drag ratio = glide ratio
m	Mass
M	Mach number
MAC	Mean aerodynamic chord
m_{mto}/S_w	Wing Loading
MS	Microsoft
MSL	Mean sea level
n	Number
NASA	National Aeronautics and Space Administration
NM	Nautical Mile (1 NM = 1.852 km)
OEI	One engine inoperative

PrADO	Preliminary Aircraft Design and Optimization program
PreSTo	Preliminary Sizing Tool
R	Range
S	Area
	Stall
T	Thrust
$T_{to}/(m_{mto} \cdot g)$	Thrust-to-Weight ratio
TU	Technical university
ULD	Unit load device
US	United States
V	Velocity, speed
	Volume
W	Weight
YC	Economy class

Subscript

0	Zero, at MSL
	at a point in time "0"
1	at a point in time "1"
25	at the 25-percent line
app	Approach
clb	For climb
cr	Cruise
D	Drag
desc	For descent
D,0	Lift-independent drag (coefficient)
D,p	Parasite drag (coefficient)
E	For the glide ratio = lift-to-drag ratio
extra	For extra flight distance
e	engine(s)
engine	For engine(s) start-up
f	Fuel
	Fuselage
ff	Fuel fraction
i	Inner
L	Lift
l	Landing

lfl	Landing Field Length
loiter	For loiter flight
max	Maximum
mf	Maximum fuel
md	Minimum drag
ml	Maximum landing
mpl	Maximum payload
mto	Maximum take-off
mzf	Maximum zero-fuel
o	Outer
oe	Operational empty
p	Pressure
pax	Passenger(s)
pl	Payload
res	Reserve
sa	Seats abreast
std	For standard flight mission
taxi	For taxi
to	Take-Off
tofl	Take-off field length
w	Wing
wet	Wetted
zf	Zero-fuel

Greek

$\Delta C_{D,nnn}$	Additional drag (coefficient) due to component "nnn"
γ	Flight Path Angle
	Ratio of specific heats (air: $\gamma = 1.4$)
λ	Taper ratio
μ	Bypass ratio (BPR)
ρ	Density
σ	Relative air density

1 Introduction

1.1 Motivation

The Aircraft Preliminary Sizing Tool PreSTo emerged from the aircraft design lecture of Prof. Dieter Scholz at the Hamburg University of Applied Sciences (HAW Hamburg) and pays special attention on the *quick* achievement of initial values for several aircraft parameters in order to accelerate the overall aircraft sizing and design process. This quickness makes PreSTo a valuable tool for the use within the scope of the aircraft design lecture as the students get the opportunity to experience the influences of the different aircraft parameters during the aircraft design process and to see their interdependencies.

The ability of PreSTo to quickly deliver initial aircraft design parameters for a given reference mission is also the reason why it has been used within the aircraft design research project "Green Freighter" (GF) to which this re-design project is related. Within the scope of the GF project, the HAW and its partners Airbus Future Projects Office, the Institute of Aircraft Design and Lightweight Structures (IFL) of the Technical University of Braunschweig and Bishop GmbH compare conventional to unconventional freighter aircraft regarding their economic and ecologic efficiencies. The project has been running since the end of 2006 and will last until 2009; details on the project can be found on http://gf.profscholz.de.

Over the past more than two decades the TU Braunschweig has developed the main tool being used in the GF project: the Preliminary Aircraft Design and Optimization program PrADO (see e.g. **Heinze 2008** for details). In brief PrADO is a very comprehensive and sophisticated aircraft design program, but due to its extensiveness its application becomes complex. A large number of input parameters is needed to start an aircraft design analysis or optimization which makes it very time-consuming to set up and analyze a new aircraft layout. Therefore one of the basic ideas for the Green Freighter project is to quickly create an initial aircraft layout using PreSTo and to further investigate and improve it with PrADO.

The Green Freighter project intends to investigate cargo aircraft of different sizes and reference missions. The spectrum reaches from small regional aircraft to large long-range aircraft. The reference aircraft at the upper boundary was decided to be the Boeing B777F which is based on the Boeing B777-200LR. That is reason for the selection of that aircraft as the reference for this re-design project.

1.2 Aim of this project

This project report has got three major aims: the first one is the documentation of the results of the B777-200LR re-design. Information on the Boeing B777 (main focus on the 200LR version) has been collected, edited and used to increase the knowledge about that aircraft. The fact that this project is not an open design of a generic new aircraft but a re-design of an existing reference aircraft offers the opportunity to understand the reasons that led to that aircraft the way it looks. Moreover this knowledge is valuable for the further investigation of that aircraft within the scope of the Green Freighter project.

The second major aim of this project is to give the reader an impression of the application of PreSTo within the scope of the aircraft design and preliminary sizing process. The reader is introduced to the principle design steps and requirements posed to an aircraft in general and to the way PreSTo deals with those tasks in particular. For that purpose a large number of the equations and assumptions used and the decisions made during the sizing process are shown to a detailed level. As in this project PreSTo is not used to create a new aircraft but to 'reach' the real B777-200LR as is the reader sees how to use the tool in order to learn more about the determination of the correct input parameters.

Thirdly, the recent additions made to PreSTo, which are

- A sheet for the collection of reference aircraft data,
- The use of two instead of one reference mission and
- The newly created fuselage sketching tool,

are presented and the reader gets an introduction to their tasks and functionalities.

Note: Parallel to the writing of this report, PreSTo has been under permanent development; the version shown here is the status of summer 2008.

1.3 Report structure

In **Section 2** the reference data on the Boeing B777-200LR is collected. This contains input data taken from literature as well as conditioned reference data derived from that.

Section 3 introduces PreSTo and the aircraft preliminary sizing process. The design steps are presented and the adaptations made to PreSTo are explained. The workflow of the preliminary sizing process is shown in detail: all design steps, equations, assumptions and decisions.

Section 4 introduces the layout of the aircraft fuselage as the next step into aircraft component design after the preliminary sizing.

Appendix A lists up the input as well as the intermediate and final data of the Boeing B777 re-design process in high detail level.

Appendix B contains screenshots of the final version of the B777-200LR re-design with PreSTo.

1.4 Literature review

1.4.1 Literature on aircraft design and preliminary sizing

Scholz 1999 refers to the lecture notes of the aircraft design lecture of Prof. Dieter Scholz from the Hamburg University of Applied Sciences (German: Hochschule für Angewandte Wissenschaften Hamburg, HAW Hamburg). The lecture notes consist of about 20 PDF-files that are available for the students via (password-protected) download from http://fe.profscholz.de. The lecture notes cover the aircraft design process in several steps from requirements and certification rules via preliminary sizing, component sizing and performance prediction to mass prediction, stability and control investigation and the design evaluation by means of the estimation and assessment of the direct operating costs (DOC). The aircraft Preliminary Sizing Tool PreSTo emerged from a calculation scheme, later on spreadsheet tool, that has been used as part of the aircraft design lecture. The calculation scheme used within PreSTo is partly based on **Loftin 1980** (see below).

Böttger 2004 and **Trahmer 2004** are the lecture notes to the parts of the aircraft design lecture at HAW Hamburg that have been given by Ole Böttger and Bernd Trahmer from the Airbus Future Projects Office (FPO) since 2004. These presentations are also available for download (without password) in PDF-format from http://fe.profscholz.de. They deal with the sizing of the fuselage, wing and landing gear, the mass estimation, the project aerodynamics and the economic efficiency. The covered topics of the aircraft design process are treated from a very practical and daily-business point of view.

Loftin 1980 stands for the NASA reference publication 1060 “Subsonic Aircraft: Evolution and the Matching of Size to Performance”; the main author is Laurence K. Loftin, Jr. from NASA’s Langley Research Center in Hampton, Virginia. The report gives a broad overview over the various and competing aspects that influence the sizing of an aircraft. Beyond that discussion of the general aspects it introduces a concrete sizing method including input numbers that are mostly based on statistics of existing aircraft. Though almost thirty years old, its general statements are still valid, and the sizing method is – preferably with an updated statistical base – still applicable.

Roskam 1997 is a series of nine books on aircraft design written by Prof. Jan Roskam. Each of these books is titled "Airplane Design: …" and treats one or more steps of the aircraft design process. Together they cover the complete process for practically every type of airplane from homebuilts via transport and business jets to fighter aircraft. This series of books delivers many valuable empirical estimation methods for various aircraft parameters.

Raymer 2006, "Aircraft Design: A Conceptual Approach", is a comprehensive textbook written by Daniel P. Raymer. This book is especially useful as reference book for the explanation and connections between aircraft parameters as well as empirical methods and typical input values for the estimation of a wide range of aircraft parameters.

1.4.2 Literature on the Boeing B777-200LR

Jackson 2007 stands for the 2007/2008 edition of the aircraft encyclopedia "Jane's all the World's Aircraft". This series contains broad information on every aircraft currently in production or under development and has been released yearly since 1930. This series of books is one of the most extensive and reliable sources on aircraft data. The data reach from information on the manufacturer and general descriptions of the individual aircraft versions to aircraft dimensions, masses and performance characteristics.

Boeing 2002 and **Boeing 2004** relate to subparts of the so-called airport planning manuals ("777 Airplane Characteristics for Airport Planning") of the Boeing B777 family aircraft. These manuals contain very aircraft specific and more detailed information than e.g. the editions of "Jane's all the World's Aircraft". The information goes down to detailed drawings of the door positions for ground handling, different cabin layouts, ground requirements for runway line-up etc. The documents are publicly available on the Boeing website under http://www.boeing.com/commercial/airports/777.htm and differ according to the specific aircraft version into

- 777 Freighter,
- 777-200LR/300ER/ Freighter and
- 777-200/300.

2 Boeing B777-200LR reference data

2.1 General aircraft data

The following reference data have been taken from the B777-200LR/-300ER Airport Planning Manual (**Boeing 2004**). Where to be applied, the data for an aircraft carrying additional body tanks in the aft cargo compartment has been used. The chosen type of engine is the GE90-110B. The payload-range diagram (Fig. 2.1) delivers the combinations of payload and range listed in Table 2.2.

These data describe the 'target values' of the B777-200LR re-design process. Therefore they reoccur several times throughout the design process (Section 3) and are discussed in more detail in the respective sections.

Table 2.1 Reference/input data (**Boeing 2004**)

Item	Symbol	Value
Maximum take-off mass	m_{mto}	347.8 t
Maximum landing mass	m_{ml}	223.2 t
Maximum zero-fuel mass	m_{mzf}	209.1 t
Operating empty mass	m_{oe}	145.1 t
Maximum payload	m_{mpl}	64 t
Usable fuel	m_{mf}	162.4 t (A)
Take-off thrust	T_{to}	2 x 489 kN (2 x 110,000 lb)
Typical seating capacity (2-class / 3-class)	n_{pax}	279 (42 FC + 237 YC) 301 (16 FC + 58 BC + 227 YC)
Take-off distance (ISA, SL)	s_{tofl}	3350 m
Landing distance (ISA, SL, Flaps 30°)	s_{lfl}	1676 m
Approach speed	V_{app}	140 kt (=72 m/s) (B)

(A) Includes optional 3 x 1,850 US gal body tanks in aft cargo compartment. Aft cargo compartment capacity reduced.
(B) Source: **Boeing 2007**

Table 2.2 B777-200LR payload-range diagram data

Payload m_{PL}	**Range** R	**Mission Description**
64 t	7,500 NM = 13,890 km	Maximum payload range
40.3 t	9,300 NM = 17,224 km	Maximum fuel range
0 t	10,300 NM = 19,076 km	Ferry range

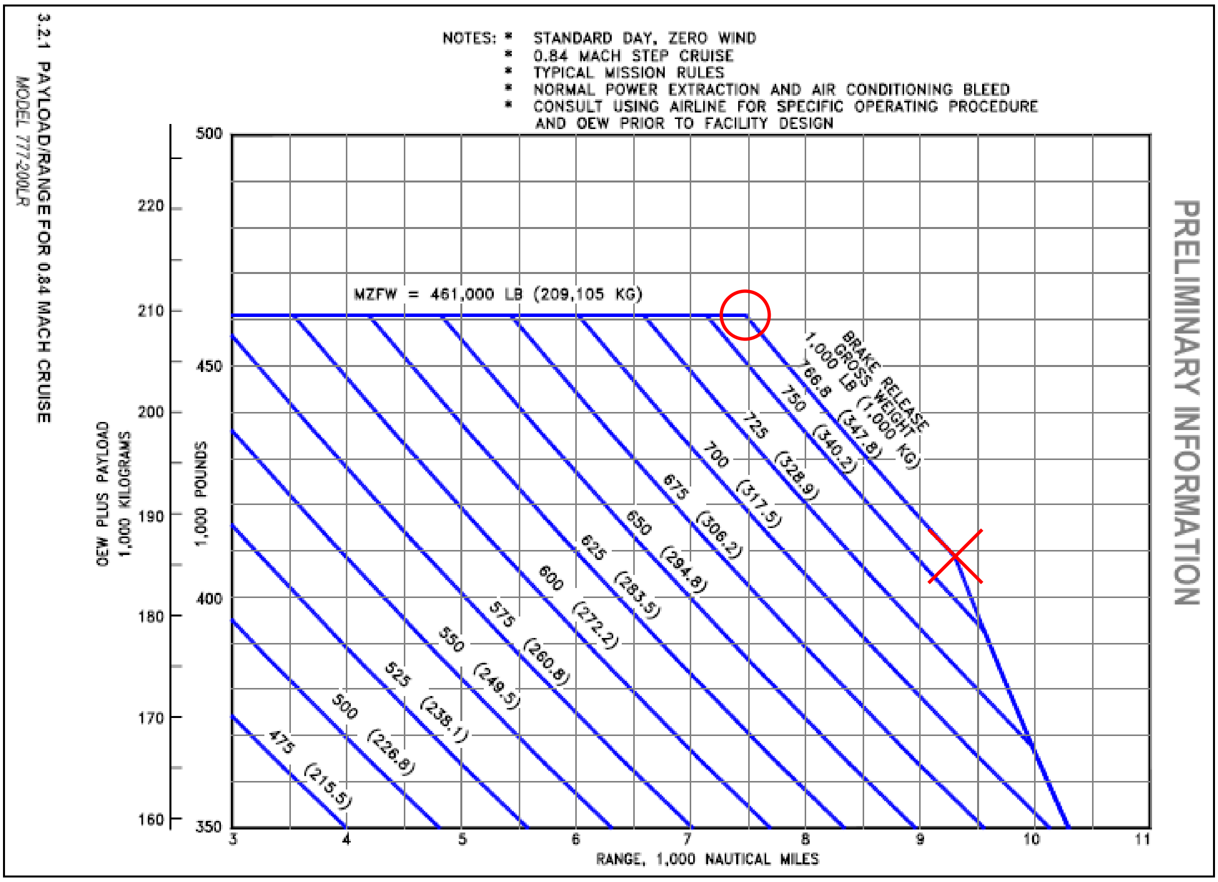


Fig 2.1 Payload-range diagram of the Boeing 777-200LR (**Boeing 2004**) – Note: The circle marks the flight mission 'flight with maximum payload'; the cross marks the mission 'flight with maximum fuel'

2.2 Reference wing

Boeing 2004 doesn't give the wing area of the B777-200LR directly but includes several scaled top-view drawings of the aircraft like the one in Figure 2.2. From these drawings the wing area has been measured and calculated. The wing area inside the fuselage has been accounted for as a rectangle (see Fig. 2.3).

The drawing in Figure 2.3 was made by means of the newly added sheet "Ref A/C Analysis". The geometry data was measured from the wing drawings and is collected in Table 2.3 which contains the characteristic values of the wing of the B777-200LR:

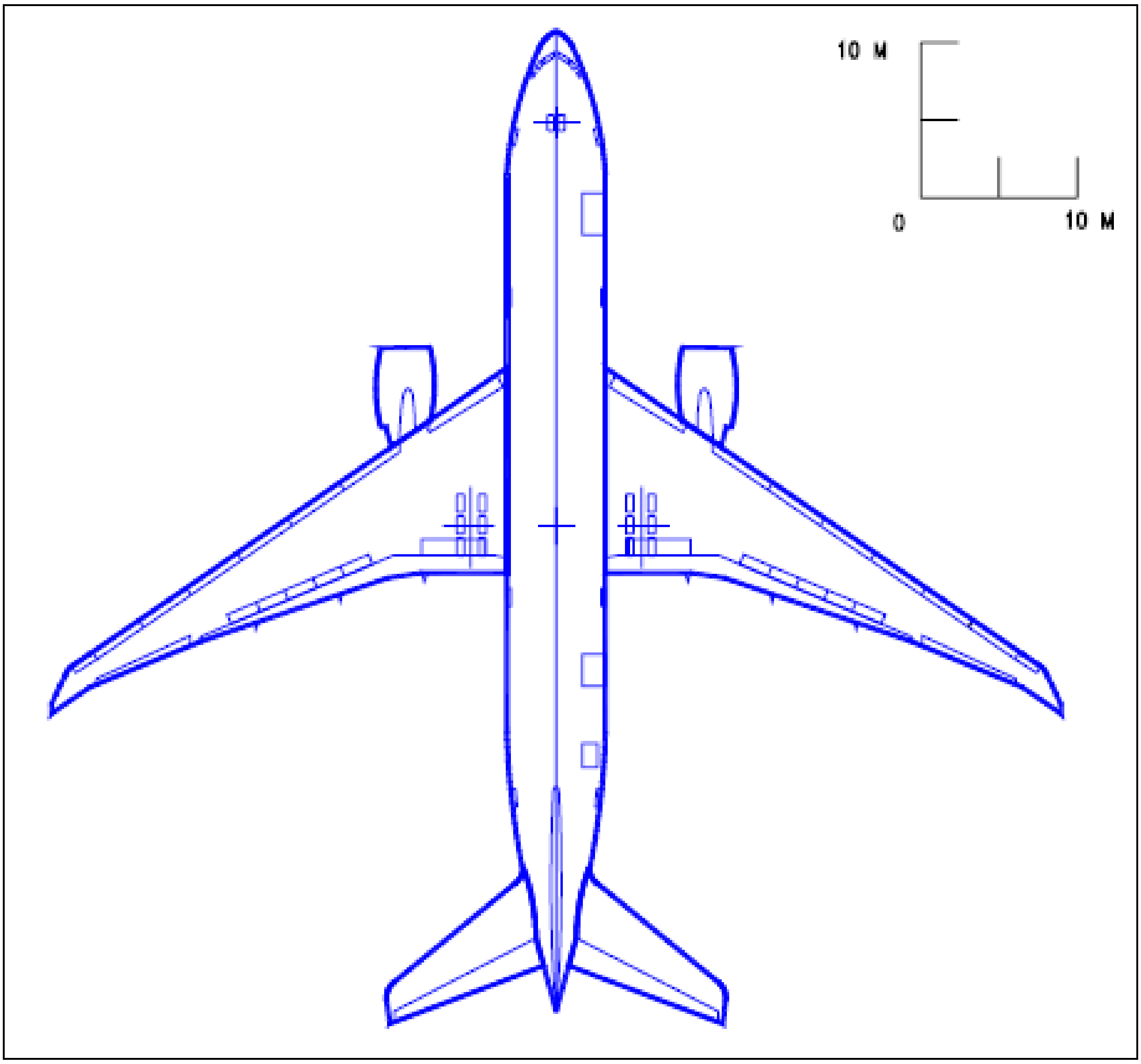


Fig 2.2 Scaled top-view drawing of the Boeing B777-200LR (**Boeing 2004**)

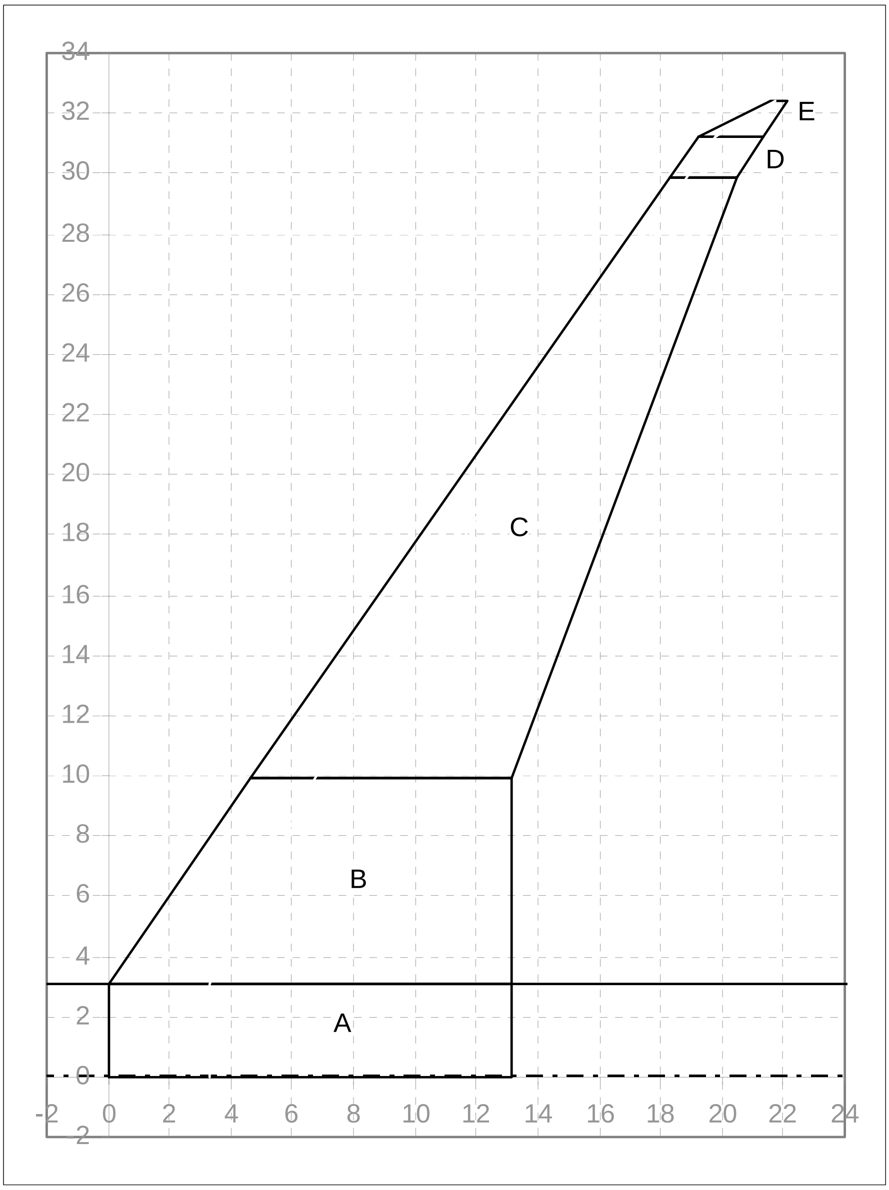


Fig 2.3 Drawing of the wing of the Boeing B777-200LR

Table 2.3 B777-200LR wing characteristics

Characteristic	Value
Wing area, S_w	450 m²
Wing span, b_w	64.8 m
Aspect ratio, A_w	9.34
Taper ratio, λ_w	0.163 (A)
25% chord sweep, $\varphi_{25,w}$	32° (B)

(A) For the calculation of the taper ratio, λ_w the outmost trapezoid has been neglected.

(B) Trapezoid C

2.3 Calculated reference data

The given and determined numbers for maximum take-off mass, m_{mto} and wing area, S_w lead to a reference wing loading of the real B777-200LR of

$$\frac{m_{mto}}{S_w} = 774 \frac{\text{kg}}{\text{m}^2} \quad . \tag{2.1}$$

The real aircraft's thrust-to-weight ratio results from the given numbers for engine thrust, T_{TO} and maximum take-off mass, m_{MTO} as

$$\frac{T_{to}}{m_{mto} \cdot g} = 0.287 \quad . \tag{2.2}$$

3 The preliminary sizing process

This section describes the application of PreSTo to the Boeing B777-200LR. The way in which this is shown is a compromise between a pure list of the final results that represent the reference aircraft and the illustration of the iterative nature of the aircraft sizing process.

3.1 Overview

PreSTo consists of MS Excel spreadsheets and originated from the aircraft design lecture of Prof. Dieter Scholz at the University of Applied Sciences Hamburg (HAW Hamburg). The initial spreadsheet tool that has led to PreSTo is available in German and English on **http://fe.ProfScholz.de**. The sizing process itself is partly based on the 'Sizing Method for Jet-Powered Cruising Aircraft' introduced in the NASA Reference Publication 1060 "Subsonic Aircraft: Evolution and the Matching of Size to Performance" (**Loftin 1980**). The regulative bases for aircraft sizing with PreSTo are the FAR Part 25 (Federal Aviation Regulation) of the US-American FAA (Federal Aviation Administration) and/or the CS-25 (Certification Specification) of the EASA (European Aviation Safety Agency). That means that PreSTo is so far only applicable to large civil transport aircraft.

During this project three major changes have been made to PreSTo in order to make the work with it more convenient and to improve the accuracy of the inputs used to reach the desired final results. These changes are

- The addition of the “Ref AC Analysis”-sheet to collect important data of the reference aircraft (see below),
- The investigation of two instead of one reference mission (see Section 3.3.2) and
- The setup of an additional tool to quickly draw and change sketches of the fuselage cross section and floor plan (see Section 4.7).

The sheet “Ref AC Analysis”

On this sheet the most important reference aircraft data may be collected and the reference wing may be investigated. In the following design steps these values are shown as target values to simplify the comparison to the reference aircraft in case of a re-design (see Fig. 3.1).

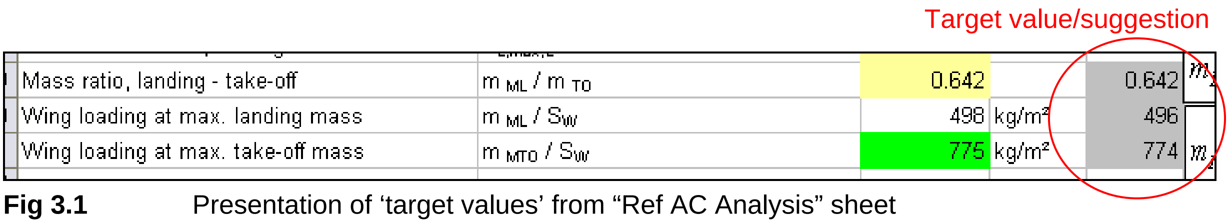


Fig 3.1 Presentation of ‘target values’ from “Ref AC Analysis” sheet

The reference aircraft data that may be collected are:

- Overall aircraft data:
    - o The number of engines
    - o The take-off thrust per engine
    - o The maximum fuel volume
    - o The design range
    - o The cruise Mach number
    - o The number of passengers for the particular design mission
- Aircraft masses:
    - o The maximum take-off mass
    - o The maximum landing mass
    - o The maximum zero-fuel mass
    - o The operating empty mass
    - o The maximum payload
    - o The mass per passenger and his baggage
    - o The cargo mass
- Operational parameters like
    - o The landing field length (ISA, SL)
    - o The approach speed and
    - o The take-off field length (ISA, SL)

For the wing investigation the measurements from an aircraft top-view drawing may be entered and scaled so that the wing planform is re-drawn (see Fig. 2.3). From that drawing further wing parameters like the wing area, aspect ratio, taper ratio, the wing sweep at different chord-wise positions and the mean aerodynamic chord (MAC) are calculated for the reference wing.

The figures B.1 and B.2 (Appendix B) show screenshots of the Sheet “Ref AC Analysis”.

3.2 Determination of the aircraft design point

This section introduces the first step in the preliminary sizing process, which is to determine the so-called aircraft design point in terms of wing loading, m_{mto}/S_w and thrust-to-weight ratio, $T_{to}/(m_{mto} \cdot g)$. In a second step a set of aircraft parameters like masses, thrust and the wing area is calculated from that point; this is described in Section 3.3.

The following five requirements posed to an aircraft for its certification according to the American and/or European certification regulations lead to the design point.

- Landing distance, s_{lfl},
- Take-off distance, s_{to},
- Take-off climb gradient, $\sin(\gamma_{to})$,
- Missed approach climb gradient, $\sin(y_{missed\ app})$ and
- Cruise Mach number, M_{cr}.

Each requirement delivers a value for either wing loading, thrust-to-weight ratio or a relation of the two, and all values are plotted into one matching chart to define the aircraft design point (see Fig. 3.2). The first priority when choosing the design point is to *minimize the thrust-to-weight ratio* to be able to select or develop the smallest and consequently cheapest possible engines. In second priority one tries to *maximize the wing loading* which leads among other things to a smaller and principally lighter and cheaper wing.

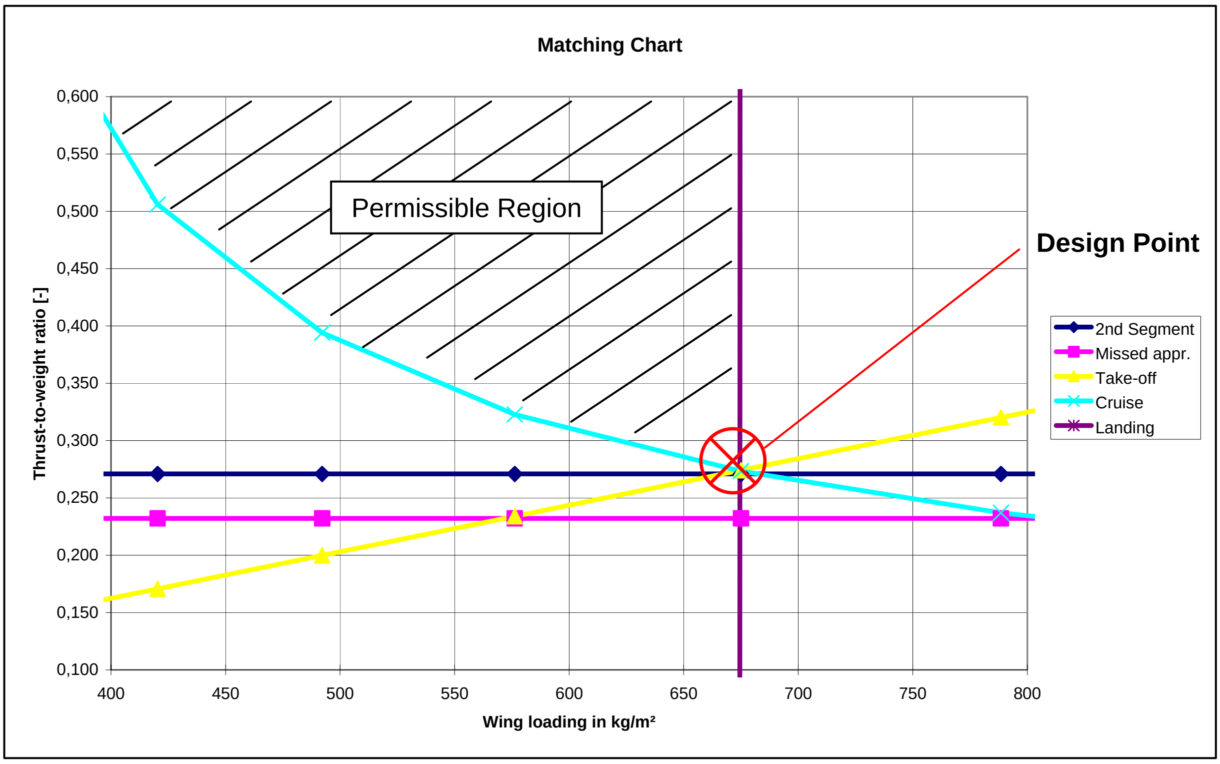


Fig 3.2 Example matching chart

3.2.1 Landing distance

The landing distance requirement delivers a maximum value for the aircraft's wing loading that cannot be exceeded at the given landing distance. See Figure B.3 to see a screenshot of the related PreSTo-spreadsheet dealing with the landing distance requirement.

The calculation doesn't use the landing distance directly but the approach speed, V_{APP} instead, which is defined in the certification specifications (CS-25, FAR Part 25) as not less than 1.3 times the stall speed, V_S of an aircraft. Statistics based on **Loftin 1980** show a correlation of landing distance and approach speed of

$$V_{app} = k_{app} \sqrt{s_{lfl}} \tag{3.1}$$

with a **typical**, statistical, value for the correlation factor k_{app} of

$$k_{app,\,typical} = 1.702 \sqrt{\mathrm{m/s^2}} \quad . \tag{3.2}$$

Consequently the approach speed of the B777-200LR **would** result as

$$\begin{aligned} V_{app} &= \sqrt{1676\ \mathrm{m}} \cdot 1.702 \sqrt{\mathrm{m/s^2}} \\ &= 69.7\ \frac{\mathrm{m}}{\mathrm{s}} = 135.4\ \mathrm{kt} \end{aligned} \quad . \tag{3.3}$$

However this is **not** the approach speed of the real Boeing B777-200LR, and the use of this value would lead to a too large required maximum lift coefficient (see below)! The following paragraphs deal with the results of the use of that value and the adaptation of k_{app} to achieve more realistic results.

At stall speed, the lift, $L = 1/2 \cdot \rho V_S^2 C_L S_w$ equals exactly the weight, $W = m \cdot g$ of the aircraft, so the wing loading is

$$\frac{m}{S_w} = \frac{\rho V_S^2 C_L}{2g} \quad . \tag{3.4}$$

The air density ρ may be expressed as the relative air density σ times the standard air density at sea level ρ_0

$$\rho = \sigma \cdot \rho_0 = \sigma \cdot 1.225 \frac{\text{kg}}{\text{m}^3} \quad . \tag{3.5}$$

Taking all these correlations into account, the wing loading **at maximum landing mass** is expressed as

$$\frac{m_{ml}}{S_w} = k_l \cdot \sigma \cdot C_{L,ml} \cdot s_{lfl} \quad , \tag{3.6}$$

with

$$k_l = \frac{\rho_0 \cdot \left(\frac{k_{app,\,typical}}{1.3} \right)^2}{2g} = 0.107 \frac{\text{kg}}{\text{m}^3} \quad . \tag{3.7}$$

So far, the calculation deals with the *landing* condition. To obtain the desired wing loading at maximum *take-off* mass, which is required for the matching chart, one has to make an assumption (e.g. again based on statistics of existing aircraft) for the relation of the maximum landing mass to the maximum take-off mass. In order to check for the accuracy of the design process, here the real value of the B777-200LR is used:

$$\frac{m_{ml}}{m_{mto}} = 0.642 \tag{3.8}$$

The still missing value for $C_{L,ml}$ can be estimated for instance with the help of Figure 3.3. The Boeing B777 features a high-lift system consisting of slats, double slotted Fowler-flaps and inboard flaperons, meaning ailerons that can be actuated downwards on both wings simultaneously for low-speed flight. These features indicate a very high value of the maximum lift coefficient of more than 3 for the **wing section**. However, this value is reduced significantly in case of a real, finite and swept wing.

A value of

$$C_{L,ml} = 2.77 \tag{3.9}$$

leads to the real aircraft's value of the wing loading of 774 kg/m^2:

$$\frac{m_{mto}}{S_w} = \frac{m_{ml}/S_w}{m_{ml}/m_{mto}} = \frac{k_l \cdot \sigma \cdot C_{L,ml} \cdot s_{lfl}}{m_{ml}/m_{mto}} = 774 \frac{\text{kg}}{\text{m}^2} \quad . \tag{3.10}$$

Taking into account the reductions due to the finite span (≈ factor 0.9) and the sweep of the wing ($\varphi_{25,w} = 32°$) leads to a $c_{L,ml}$ of the **wing section** of

$$c_{L,ml} \approx \frac{C_{L,ml}}{\cos(\varphi_{25,w}) \cdot 0.9} = \frac{2.77}{\cos(32°) \cdot 0.9} = 3.63 \quad . \tag{3.11}$$

This value is unrealistically large and results as mentioned from the standard value for $\mathbf{k_{app}}$ of 1.702 $\sqrt{\mathbf{m/s^2}}$!

However, the direct use of the given $V_{app} = 140\,\text{kt}$ and the real aircraft's wing loading delivers, applying the same equations as above, a maximum lift coefficient of the **finite wing** of

$$C_{L,ml} = 2.60 \tag{3.12}$$

and a corresponding maximum lift coefficient of the **wing section** of

$$c_{L,ml} \approx 3.4 \quad . \tag{3.13}$$

This value still is very high but, keeping in mind the very complex high-lift system, lies within a more realistic order of magnitude. The required factor k_{app} results as

$$k_{app} = V_{app} \cdot \sqrt{s_{lfl}} = 1.758 \sqrt{\text{m/s}^2} \quad . \tag{3.14}$$

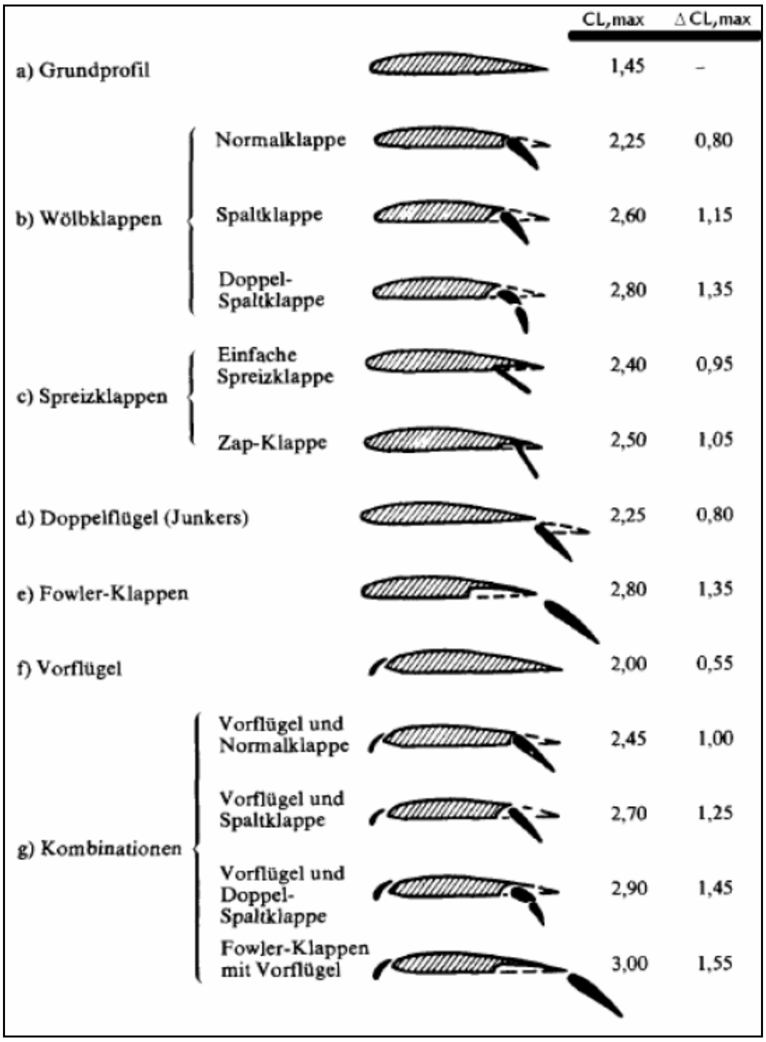


Fig 3.3 Maximum lift coefficients of different high-lift devices (**Dubs 1966**)

3.2.2 Take-off distance

This section delivers a relation, a of the thrust-to-weight ratio to the wing loading that the aircraft has to show at least in order to fulfill the take-off distance requirement. See Figure B.4 to see a screenshot of the related PreSTo-spreadsheet dealing with the take-off distance requirement.

The calculation itself is very similar to the one from the landing distance requirement. For the take-off distance, a correlation factor k_{to} is introduced which typically has the value of

$$k_{to} = 2.34 \, \frac{\mathrm{m}^3}{\mathrm{kg}} \quad . \tag{3.15}$$

This factor is used to calculate the required relation, a of the thrust-to-weight ratio to the wing loading:

$$a = \frac{T_{to}/m_{mto} \cdot g}{m_{mto} \cdot g / S_w} = \frac{k_{to}}{s_{tofl} \cdot \sigma \cdot C_{L,mto}} \quad . \tag{3.16}$$

The value of the maximum take-off lift coefficient, $C_{L,mto}$, if known, can be entered directly into PreSTo or otherwise is assumed to be 80 % of the maximum landing lift coefficient, $C_{L,ml}$. In case of the Boeing B777, however, not the full maximum take-off lift coefficient may be used as the aircraft features a very complex high-lift system to reach the highest possible maximum lift coefficient. During take-off, the high-lift devices are extended significantly less than for landing compared to other aircraft with more conventional high-lift systems on which the statistical value is based. With regard only to take-off distance, the B777 could lift off within a shorter runway distance than the given one. But after lift-off, it could not achieve the required climb performance, meaning climb gradient. Therefore, with rising take-off mass of the B777-200LR the flaps are only extended to reduced positions (see Fig. 3.4). Further extensions would cause too much drag and a too bad climb performance. Consequently in this re-design project the general estimation formula is not applicable, and the take-off lift coefficient is derived iteratively in order to achieve the known relation a of the real aircraft.

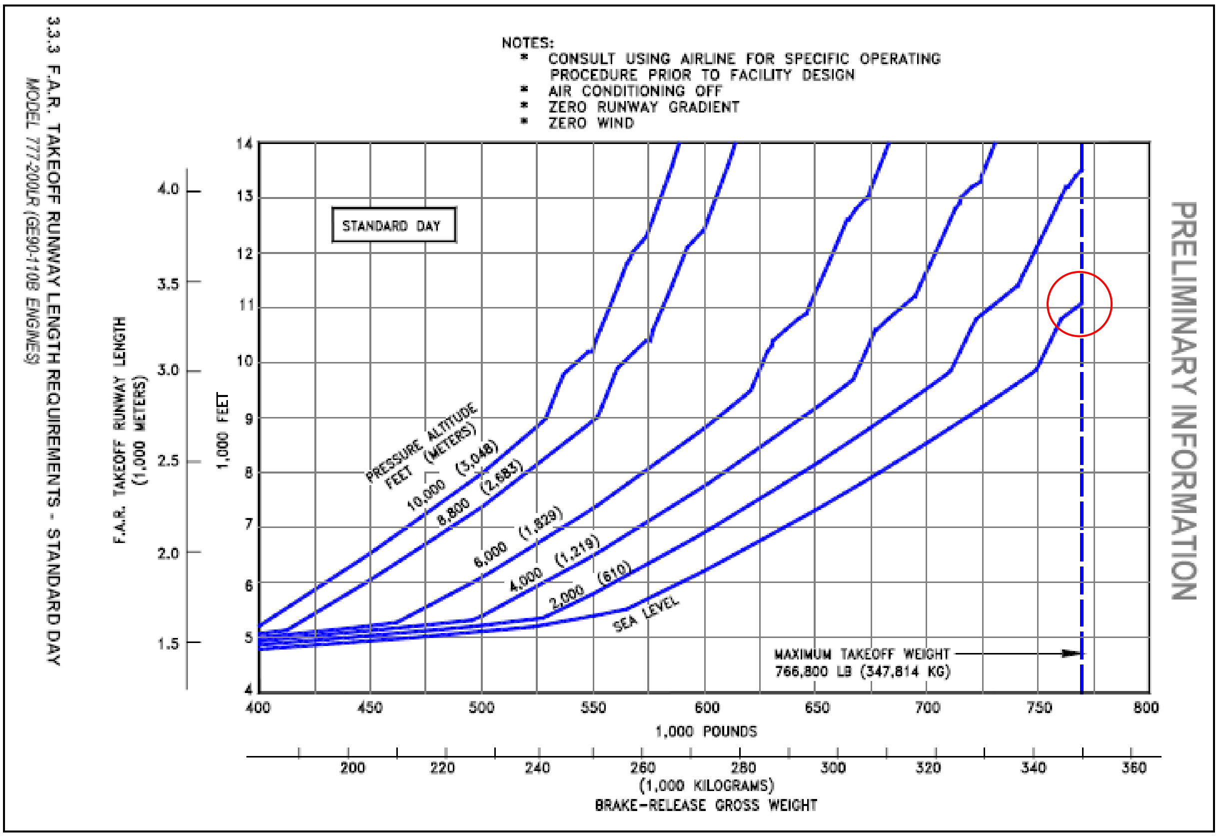


Fig 3.4 Take-off distance diagram of the B777-200LR (**Boeing 2004**) – Steeper lines indicate reduced flap positions

Iterations lead to a value of

$$C_{L,mto} = 1.88 \tag{3.17}$$

to achieve a relation a of thrust-to-weight ratio to wing loading that lies in the order of that of the real aircraft. It results as

$$a = 0.0003715 \frac{\text{m}^2}{\text{kg}} \quad . \tag{3.18}$$

In consequence, the thrust-to-weight ratio at take-off wing loading from the take-off distance requirement results as

$$\frac{T_{to}}{m_{mto}} = a \cdot \frac{m_{mto} \cdot g}{S_w} = 0.287 \quad . \tag{3.19}$$

3.2.3 Second segment

The second segment is defined as the flight segment between the complete landing gear retraction and a flight altitude of 400 ft. For this segment the certification regulations (e.g. CS-25.121) require a minimum climb gradient under one engine inoperative (OEI) condition depending on the total number of engines, n_e installed on the aircraft. In detail, the particular climb gradients (sinus of the flight path angle γ) are:

- Two engines: 2.4 % → $\sin\gamma = 0.024$
- Three engines: 2.7 % → $\sin\gamma = 0.027$
- Four engines: 3.0 %. → $\sin\gamma = 0.030$.

Figure 3.4 indicates a very important fact concerning the second segment requirement: **it must be sizing!** If it were not, there would be no reason to not further extend the high-lift devices of the Boeing B777-200LR to shorten the take-off distance. For this re-design project that means that the usually resulting thrust-to-weight ratio is already known and instead one can use PreSTo to derive backwards the values that are required as input values. See Figure B.4 to see a screenshot of the related PreSTo-spreadsheet dealing with the second segment requirement.

A certain climb gradient requires a certain minimum thrust-to-weight ratio, which can be calculated as follows:

$$\frac{T_{to}}{m_{mto} \cdot g} = \left(\frac{n_e}{n_e - 1} \right) \cdot \left(\frac{1}{E_{to}} + \sin\gamma \right) \quad . \tag{3.20}$$

The lift-to-drag ratio E is estimated by means of the equation

$$E = \frac{L}{D} = \frac{C_L}{C_D} = \frac{C_L}{C_{D,p} + \frac{C_L^2}{\pi A e}} \quad , \tag{3.21}$$

in which A is the aspect ratio

$$A_w = \frac{b_w^2}{S_w} = 9.34 \quad , \tag{3.22}$$

and e is the Oswald-efficiency factor which is typically estimated as

$$e = 0.7 \quad . \tag{3.23}$$

$C_{D,p}$ is the parasite drag coefficient which consists of different drag components:

- The clean lift-independent drag coefficient, $C_{D,0}$,
- The extra drag coefficient due to flaps extension, $\Delta C_{D,flap}$, and
- The extra drag coefficient due to slats extension, $\Delta C_{D,slat}$.

In case of an investigation of a generic aircraft, the user has to estimate and input these individual drag components or the complete parasite drag coefficient to achieve the desired value of the thrust-to-weight ratio. In this re-design of the Boeing B777-200LR, however, as the thrust-to-weight ratio is already known, the take-off lift-to-drag ratio and the correlating parasite drag coefficient are achieved. They result as

$$E_{to} = \frac{1}{\frac{\left(\frac{T_{to}}{m_{mto} \cdot g}\right)}{\left(\frac{n_e}{n_e - 1}\right)} - \sin\gamma} = \frac{1}{\frac{0.287}{2} - 0.024} = 8.35 \tag{3.24}$$

and therefore

$$C_{D,p} = \frac{C_L}{E} - \frac{C_L^2}{\pi A e} = 0.053 \quad . \tag{3.25}$$

3.2.4 Missed approach

The missed approach requirement is very similar to the second segment requirement. See Figure B.5 to see a screenshot of the related PreSTo-spreadsheet dealing with the missed approach requirement.

The calculation method is the same as for the second segment; only the input values are different. These are:

- The aircraft mass
- The landing lift coefficient
- The lift-to-drag ratio in landing condition due to flap setting and – only in case of certification according to FAR Part 25 – the extended landing gear. The European CS-25 doesn't require the landing gear to be extended for the missed approach requirement.
- The required climb gradient

Consequently the equation for the calculation of the required thrust-to-weight ratio (Eqn. 3.20) changes to

$$\frac{T_{to}}{m_{mto} \cdot g} = \left(\frac{n_e}{n_e - 1}\right) \cdot \left(\frac{1}{E_L} + \sin\gamma\right) \cdot \left(\frac{m_{ml}}{m_{mto}}\right) \quad . \tag{3.26}$$

The required climb gradients depending on the number of installed engines are:

- Two engines: 2.1 % → $\sin\gamma = 0.021$
- Three engines: 2.4 % → $\sin\gamma = 0.024$
- Four engines: 2.7 % → $\sin\gamma = 0.027$.

As the approach speed is 1.3 times the stall speed in landing condition, the lift coefficient is reduced by a factor of $1.3^2 = 1.69$:

$$C_{L,l} = \frac{C_{L,ml}}{1.3^2} = 1.54 \quad . \tag{3.27}$$

The profile drag in landing condition $C_{D,p,l}$ is different to the one during take-off. It is composed of four drag components; Table 3.1 holds typical reference values.

Table 3.1 Typical values for landing drag coefficient components

Drag Component	Symbol	Typical Value
Clean lift-independent drag coefficient	$C_{D,0}$	0.020
Extra drag coefficient due to flaps extension	$\Delta C_{D,flap}$	0.025
Extra drag coefficient due to slats extension	$\Delta C_{D,slat}$	0.000
Extra drag coefficient due to landing gear extension	$\Delta C_{D,gear}$	0.015

It becomes apparent that these typical values do not fit with the results of the previous Section "Second Segment". The parasite drag coefficient would only result as:

$$C_{D,p,l} = C_{D,0} + \Delta C_{D,flap} + \Delta C_{D,slat} + \Delta C_{D,gear} = 0.060 \quad , \tag{3.28}$$

which is too low for the Boeing B777-200LR.

Iterations lead to a value of

$$C_{D,p,L} = 0.081 \tag{3.29}$$

to gain realistic outputs.

In consequence, the lift-to-drag ratio in landing condition results as

$$E_l = \frac{C_{L,l}}{C_{D,p,l} + \frac{C_L^2}{\pi A e}} = 7.85 \tag{3.30}$$

and leads to a thrust-to-weight ratio for the missed approach climb gradient requirement of

$$\frac{T_{to}}{m_{mto} \cdot g} = \left(\frac{n_e}{n_e - 1}\right) \cdot \left(\frac{1}{E_L} + \sin\gamma\right) \cdot \left(\frac{m_{ml}}{m_{mto}}\right) = 0.190 \quad . \tag{3.31}$$

Among all the results achieved so far this value is the one with the poorest certainty. At first glance, it might appear too low, but a comparison to other real aircraft shows that it at least lies within a realistic order of magnitude.

The missed approach climb gradient requirement must not be sizing for the B777-200LR. The reason for that is the B777's application as a long-range aircraft. The maximum landing masses of such aircraft lie significantly below their maximum take-off masses. Hence the climb gradient requirement is a lot less demanding even though the parasite drag is larger due to the further extended high-lift devices and, in case of certification according to FAR Part 25, extended landing gear.

3.2.5 Cruise flight

The cruise flight requirement cannot be solved in a closed form as there is, besides the wing loading and the thrust-to-weight ratio, one more variable: the cruise flight altitude. The relation of the thrust-to-weight ratio to the wing loading to allow a steady flight at a specified Mach number changes with the altitude. Therefore, a set of similar calculations is conducted to determine both wing loading and thrust-to-weight ratio separately. See Figure B.7 to see a screenshot of the related PreSTo-spreadsheet dealing with the cruise flight requirement.

Cruise flight thrust-to-weight ratio

The cruise flight thrust-to-weight ratio is found using

$$\frac{T_{to}}{m_{mto} \cdot g} = \frac{1}{\frac{T_{cr}}{T_0} \cdot E} \tag{3.32}$$

wherein E is

$$E = E_{\max} \cdot \frac{2}{\frac{1}{C_L / C_{L,md}} + \frac{C_L}{C_{L,md}}} \quad . \tag{3.33}$$

Note: The index "0" (zero) indicates the available thrust at an altitude of 0 m, thus at sea level!

$E_{\max}$ is estimated using equation 3.34:

$$E_{\max} = k_E \sqrt{\frac{A}{S_{wet}/S_w}} \quad , \tag{3.34}$$

and k_E is derived (indirectly) from Figure 3.5 for civil jets as

$$k_E = 15.8 \quad . \tag{3.35}$$

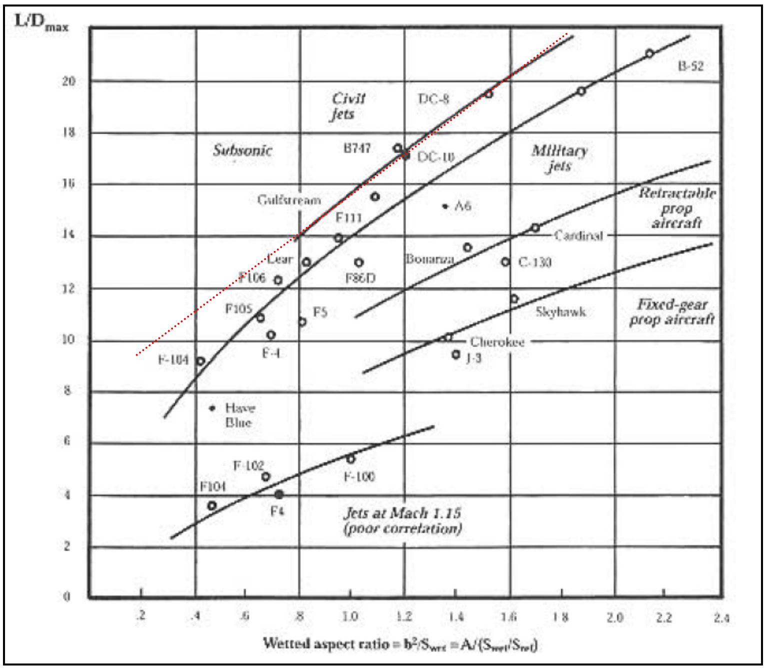


Fig 3.5 Maximum lift-to-drag ratio trends (**Raymer 2006**)

Values of S_{wet}/S_w for civil transport jets lie typically in the region of

$$\frac{S_{wet}}{S_w} \approx 6.0 \ldots 6.2 \quad ; \tag{3.36}$$

here a value of

$$\frac{S_{wet}}{S_w} = 6.0 \tag{3.37}$$

is used and leads to an estimation for a maximum lift-to-drag ratio of

$$E_{\max} = k_E \sqrt{\frac{A}{S_{wet}/S_w}} = 19.7 \quad . \tag{3.38}$$

That value lies within a realistic order of magnitude. **Böttger 2004** gives a value of

$$E_{\max,B777-200} = 19.4 \tag{3.39}$$

for the 'normal' Boeing B777-200 which has a smaller wing of less span. See Figure B.6 to see a screenshot of the related PreSTo-spreadsheet dealing with the estimation of the maximum glide ratio.

The required value of cruise lift coefficient to lift coefficient for minimum drag, $C_L/C_{L,md}$ results from the chosen relation of cruise speed V to the minimum drag speed V_{md} . For the Boeing B777-200LR, a ratio of

$$\frac{V}{V_{md}} = 0.952 \tag{3.40}$$

fits well with the results of the other aircraft requirements (see Matching Chart, Fig. 3.6).

In consequence, $C_L/C_{L,md}$ results as

$$\frac{C_L}{C_{L,md}} = \frac{1}{(V/V_{md})^2} = 1.104 \tag{3.41}$$

and hence

$$E = E_{\max} \cdot \frac{2}{\frac{1}{C_L/C_{L,md}} + \frac{C_L}{C_{L,md}}} = 19.6 \quad . \tag{3.42}$$

In order to calculate the ratio of thrust at cruise altitude to thrust at sea level, the bypass ratio (BPR) of the engines μ is needed. This value is given in **Rolls Royce 2006** as

$$\mu_{GE90-110B} = 8.9 \quad . \tag{3.43}$$

Now, the ratio of thrust at cruise altitude to thrust at sea level can be estimated from

$$\frac{T_{cr}}{T_0} = (0.0013\mu - 0.0397)\frac{1}{\text{km}} \cdot h_{cr} - 0.0248\mu + 0.7125 \tag{3.44}$$

which is given in Marckwardt 1989 (cited in **Scholz 1999**).

It follows:

$$\frac{T_{to}}{m_{mto} \cdot g}(h_{cr}) = \frac{1}{\left(-0.02891\frac{1}{\text{km}} \cdot h_{cr} + 0.50666\right) \cdot 19.3961} \quad . \tag{3.45}$$

Cruise flight wing loading

The cruise flight wing loading is found using the equation

$$\frac{m_{mto}}{S_w} = \frac{C_L \cdot M^2}{g} \cdot \frac{\gamma}{2} \cdot p(h) \quad , \tag{3.46}$$

wherein the cruise flight Mach number is given in **Boeing 2004** as

$$M_{cr,B777} = 0.84 \quad . \tag{3.47}$$

γ is the ratio of specific heats of the air:

$$\gamma = 1.4 \quad , \tag{3.48}$$

and $p(h)$ is the local air pressure calculated according to the International Standard Atmosphere (ISA):

$$p(h) = p_0 \cdot \left(1 - 0.02256 \cdot \frac{h}{\text{km}}\right)^{5.256} \quad . \tag{3.49}$$

The factor p_0 represents the air pressure at sea level

$$p_0 = 1013.25 \text{ hPa} \quad . \tag{3.50}$$

In order to find the resulting lift coefficient C_L, the wing aspect ratio A, which of course stays the same as in the second segment and missed approach requirements ($A = 9.34$), and the Oswald efficiency factor during cruise flight e_{cr} are needed. e_{cr} is typically estimated as

$$e_{cr} = 0.85 \quad . \tag{3.51}$$

That leads to a zero-lift drag coefficient of

$$C_{D,0} = \frac{\pi A e}{4E_{\max}^2} = 0.016 \quad , \tag{3.52}$$

and a lift coefficient for minimum-drag of

$$C_{L,md} = \sqrt{C_{D,0}\pi A e} = 0.63 \quad . \tag{3.53}$$

Finally, a lift coefficient during cruise flight of

$$C_L = \frac{C_{L,md}}{(V/V_{md})^2} = 0.7 \quad . \tag{3.54}$$

is the result.

It follows the equation for the cruise flight wing loading

$$\frac{m_{mto}}{S_w}(h_{cr}) = \frac{C_L \cdot M^2}{g} \cdot \frac{\gamma}{2} \cdot p(h_{cr}) \\ = 0.0351\,\frac{\mathrm{s}^2}{\mathrm{m}} \cdot 101325\ \mathrm{Pa} \cdot \left(1 - 0.02256 \cdot \frac{h_{cr}}{\mathrm{km}}\right)^{5.256} \quad . \tag{3.55}$$

The following Table 3.2 includes the specific results for the different cruise altitudes.

Table 3.2 Thrust-to-weight ratio and wing loading for different cruise altitudes

Altitude h_{cr} [km]	h_{cr} [ft]	$\frac{T_{cr}}{T_0}$	$\frac{T_{to}}{m_{mto} \cdot g}$	$p(h_{cr})$ [Pa]	$\frac{m_{mto}}{S_w}$ $\left[\frac{\mathrm{kg}}{\mathrm{m}^2}\right]$
0	0	0.492	0.104	101325	3562
1	3281	0.464	0.110	89873	3160
2	6562	0.436	0.117	79493	2795
3	9843	0.407	0.125	70105	2465
4	13124	0.379	0.134	61636	2167
5	16405	0.351	0.145	54015	1899
6	19686	0.323	0.158	47176	1658
7	22967	0.295	0.173	41056	1443
8	26284	0.267	0.191	35595	1251
9	29529	0.239	0.214	30737	1081
10	32810	0.210	0.242	26431	929
11	**36091**	**0.182**	**0.280**	**22627**	**795**
12	**39372**	**0.154**	**0.331**	**19316**	**679**
13	42653	0.126	0.404	16498	580
14	45934	0.098	0.520	14091	495
15	49215	0.070	0.730	12035	423

3.2.6 Matching chart

The results of the previous certification requirements are plotted in one preliminary sizing matching chart to find one single design point in terms of (take-off-) trust-to weight ratio and wing loading. The first priority to find the final design point is to minimize the thrust-to-weight ratio to be able to select or develop the smallest and hence cheaper engines. In second priority one tries to maximize the wing loading, which leads to a smaller, lighter and principally cheaper wing.

Figure 3.6 depicts the resulting matching chart. The chosen design point for this re-design project determined by a thrust-to-weight ratio and a wing loading of

- **Thrust-to-weight ratio: 0.287**
- **Wing loading: 775 kg/m^2.**

These values represent well the Boeing B777-200LR, as they are the same as for the real aircraft. See Figure B.8 to see a screenshot of the PreSTo spreadsheet including the matching chart.

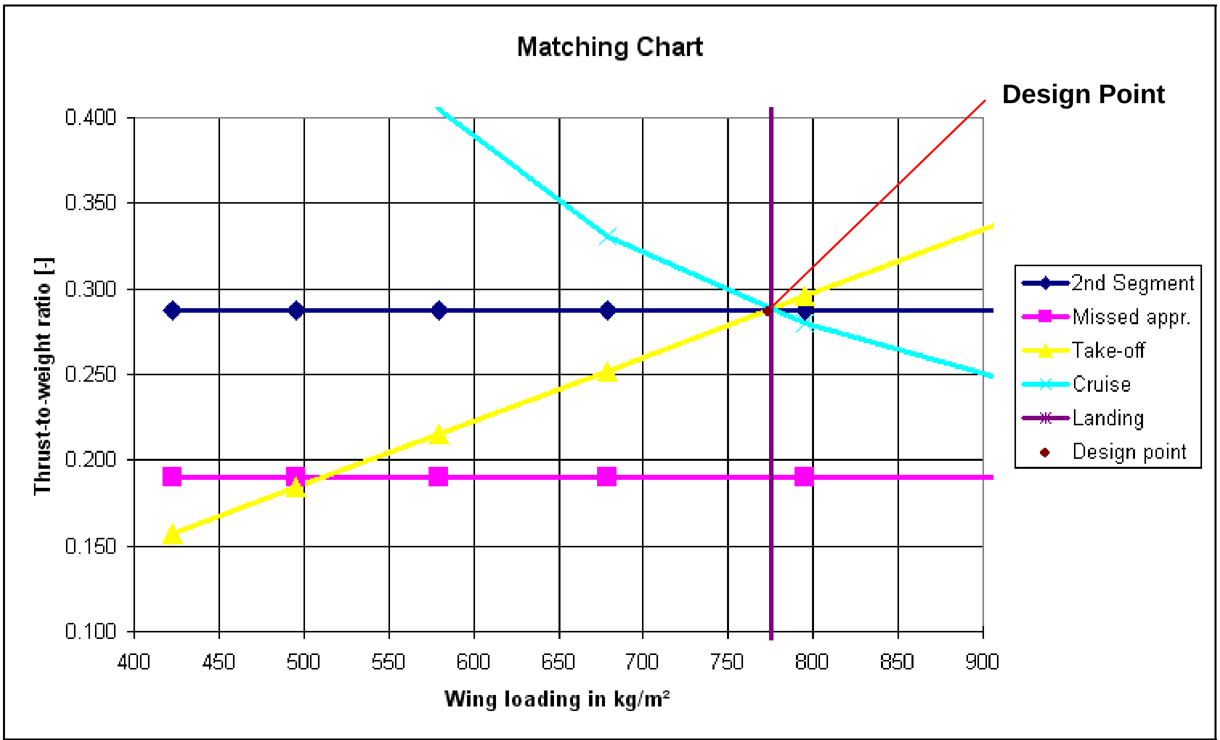


Fig 3.6 Boeing B777-200LR preliminary sizing matching chart

3.3 Estimation of the aircraft size

The next step after having determined the aircraft design point is to estimate the

- Aircraft masses:
  - Operating empty mass, m_{oe},
  - Maximum zero-fuel mass, m_{mzf},
  - Max. take-off mass, m_{mto},
  - Max. landing mass, m_{ml}, the
- Required take-off thrust, T_{to} (overall and per engine) and the

- Amount of fuel needed, m_{mf} , V_{mf} .

For that purpose one first determines the cruise flight altitude and cruise speed in order to quantify the fuel consumption and fuel reserves for the reference mission(s). These numbers make it possible to estimate the size of the aircraft, meaning to achieve initial values for the maximum take-off mass, operational empty mass, wing area etc. to go ahead with during the following phase of the aircraft design process: the conceptual design.

During these design steps many statistical data and handbook methods are applied to a reference mission. Usually this is either the ‘flight with maximum payload’ or the ‘flight with maximum fuel’ flight mission. In case of the sizing of a generic new aircraft the reference mission(s) may be chosen freely; in case of an aircraft re-design or analysis – like in this project – it/they are taken from the reference aircraft’s payload-range diagram (see Fig. 2.1). Each investigation of a real or generic aircraft performed within PreSTo should deal with at least one of the two outmost points of the payload-range diagram, as this incorporates the most demanding operational conditions and requirements that may be posed to the aircraft.

In detail those conditions are:

- Take-off at maximum take-off mass, m_{mto} , using
    - o Either maximum fuel mass, m_{mf} and corresponding payload, m_{pl}
    - o And/or maximum payload, m_{mpl} and corresponding fuel mass, m_f and
- Landing at maximum landing mass, m_{ml} .

See Figures B.9 to B.11 to see screenshots of the PreSTo spreadsheets dealing with the estimation of the aircraft size after the determination of the aircraft design point.

3.3.1 Cruise flight altitude and speed

Table 3.2 already showed values in the vicinity of the real values for thrust-to-weight ratio and wing loading in a flight altitude of about 11 to 12 km (FL 360 to FL 390). Now, the thrust-at-cruise-altitude to thrust-at-sea-level ratio can be calculated backwards from the thrust-to-weight ratio using

$$\frac{T_{cr}}{T_0} = \frac{1}{\frac{T_{to}}{m_{mto} \cdot g} \cdot E_{cr}} = 0.178 \quad . \tag{3.56}$$

This ratio delivers in combination with Equation 3.44 the cruise flight altitude h_{cr}:

$$h_{cr} = \frac{\frac{T_{cr}}{T_0} + 0.0248\mu - 0.7125}{0.0013\mu - 0.0397} \text{ km} \tag{3.57}$$

$$h_{cr} = \underline{\underline{11.2 \text{ km}}}$$
$$h_{cr} = \underline{\underline{36{,}600 \text{ ft}}} \tag{3.58}$$

At this altitude, the speed of sound a lies at 295 m/s (1062 km/h, 573 kt), hence, the designated cruise Mach number of $M_{cr} = 0.84$ corresponds to a cruise speed V_{cr} of

$$V_{cr} = \underline{\underline{248 \text{ m/s}}} \quad (893 \text{ km/h, } 482 \text{ kt}) \quad . \tag{3.59}$$

3.3.2 Mission fuel fractions

Cruise flight, reserve distance and loiter time fuel fraction

As already mentioned PreSTo initially used one reference mission of the reference aircraft to estimate the size of the aircraft from. In doing so, the final results of the real reference aircraft in terms of masses, wing area, etc. may be achieved by means of various combinations of assumptions and correlation factors. However, sometimes the assumptions that lead to realistic results for one reference mission don't fit to other missions. For that reason, PreSTo has been adapted to allow for the investigation of two reference missions in order to improve the applicability of the results respectively inputs (see Fig. 3.7).

Design points definitions						
Point 1: Maximum payload						
Design range	R	7500	NM	**Reserve flight distance:**		
Design range	R	13890	km	FAR Part 121	s_{res}	
Distance to alternate	$s_{to\_alternate}$	200	NM	domestic	370.4	km
Distance to alternate	$s_{to\_alternate}$	370.4	km	international	1064.9	km
Chose: FAR Part121-Reserves?	domestic	no				
	international	yes		**Extra time:**		
Extra-fuel for long range		5.0%		FAR Part 121	t_{loiter}	
Extra flight distance	s_{res}	1065	km	domestic	2700	s
Loiter time	t_{loiter}	1800	s	international	1800	s
Point 2: Maximum fuel						
Design range	R	9300	NM	**Reserve flight distance:**		
Design range	R	17224	km	FAR Part 121	s_{res}	
Distance to alternate	$s_{to\_alternate}$	200	NM	domestic	370.4	km
Distance to alternate	$s_{to\_alternate}$	370.4	km	international	1231.58	km
Chose: FAR Part121-Reserves?	domestic	no				
	international	yes		**Extra time:**		
Extra-fuel for long range		5.0%		FAR Part 121	t_{loiter}	
Extra flight distance	s_{res}	1232	km	domestic	2700	s
Loiter time	t_{loiter}	1800	s	international	1800	s
Point 3: Ferry range						
Design range	R	10300	NM			

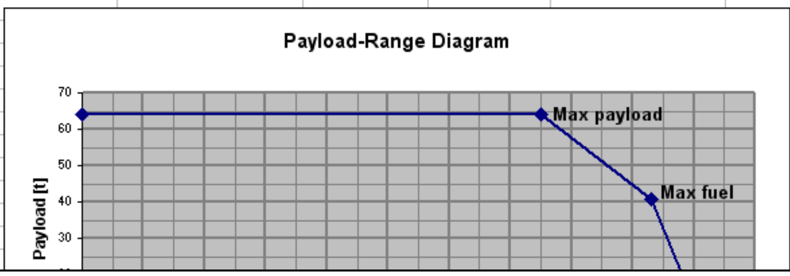


Fig 3.7 Definition of two reference missions within PreSTo

In this project the reference missions were chosen to be the missions "range at maximum payload" and "maximum fuel range". The combinations of payload, m_{PL} and range R are listed in Table 3.3.

Table 3.3 B777-200LR reference missions' data

Payload m_{PL}	Range R	Mission Description
64 t	7,500 NM = 13,890 km	Maximum payload range
40.8 t	9,300 NM = 17,224 km	Maximum fuel range

Based on international regulations, two safety aspects concerning the reference flight distance have to be accounted for:

- An extra flight distance of 200 NM to an alternate airport in case the originally planned one is closed or not available for any other reason,
- An increase in fuel consumption, expressed as an extra flight distance of 5 % of the original reference mission.

These safety aspects sum up to extra flight distances of

$$s_{extra}(\max \text{PL}) = 575 \text{ NM (1,065 km)} \tag{3.60}$$

$$s_{extra}(\max \ fuel) = 665 \text{ NM (1,232 km)} \tag{3.61}$$

The Breguet Range Equation delivers the possible range for a flight at constant speed and constant lift coefficient. Therefore it is applicable in good approximation for a transport aircraft's cruise flight. The equation reads as follows:

$$R = B_s \cdot \ln\left(\frac{m_o}{m_1}\right) \quad , \tag{3.62}$$

in which

- m_0 is the aircraft mass at a point in time "0",
- m_1 is the aircraft mass at a later point in time "1".

Of course m_1 is smaller than m_0; the difference is the burned fuel mass.

B_s is the so-called Breguet range factor

$$B_s = \frac{E \cdot V}{c \cdot g} \quad . \tag{3.63}$$

Herein, c is the specific fuel consumption in terms of fuel mass needed to produce one Newton of thrust for one second ($\text{kg}/(\text{Ns})$. The specific fuel consumption of the General Electric GE90-110B turbofan engine is given in **Rolls Royce 2006** as

$$c(\text{GE90} - 110\text{B}) = 0.539 \frac{\text{lb}}{\text{h} \cdot \text{lb}} = 15.26 \frac{\text{mg}}{\text{Ns}} \quad . \tag{3.64}$$

The so far collected values for *E*, *V* and *c* lead to a Breguet range factor B_s of

$$B_s = \frac{E \cdot V}{c \cdot g} = 32{,}486 \text{ km} \quad . \tag{3.65}$$

Calculated backwards, this Breguet range factor means cruise flight fuel fractions (without reserve distances),

$$M_{ff} = \frac{m_1}{m_0} = e^{-\frac{R}{B_s}} \tag{3.66}$$

of

$$M_{ff,cr,mpl} = e^{-\frac{13{,}890 \text{ km}}{32{,}486 \text{ km}}} = 0.652 \tag{3.67}$$

and

$$M_{ff,cr,mf} = e^{-\frac{17{,}224 \text{ km}}{32{,}486 \text{ km}}} = 0.588 \quad . \tag{3.68}$$

For the reserve flight distances the fuel fractions result as

$$M_{ff,extra,mpl} = e^{-\frac{1{,}065\ \text{km}}{32{,}486\ \text{km}}} = 0.968 \quad . \tag{3.69}$$

$$M_{ff,extra,mf} = e^{-\frac{1{,}232\ \text{km}}{32{,}486\ \text{km}}} = 0.963 \quad . \tag{3.70}$$

In order to investigate a complete flight, one has to account for one more flight segment that is not expressed as a distance but as a time: the loiter flight. For aircraft certification, one assumes a loiter time of 30 min = 1800 s in the category "International" (in contrast to 45 min in case of "Domestic"). Therefore the Breguet *time* factor, B_t is introduced:

$$B_t = \frac{E}{c \cdot g} = \frac{B_s}{V} \tag{3.71}$$

Here the Breguet time factor results as

$$B_t = \frac{32{,}486\ \text{km}}{248\ \text{m/s}} = 131{,}044\ \text{s} \quad . \tag{3.72}$$

In consequence the fuel fraction for the loiter flight is calculated as

$$M_{ff,loiter} = e^{-\frac{1{,}800\ \text{s}}{131{,}044\ \text{s}}} = 0.986 \quad . \tag{3.73}$$

Other segments' fuel fractions

Average values for fuel fractions of the other flight segments are given e.g. in **Roskam 1997**. For transport jet aircraft they read as follows:

- Engine start, $M_{ff,engine}$: 0.990
- Taxi, $M_{ff,taxi}$: 0.990
- Take-off, $M_{ff,to}$: 0.995
- Climb, $M_{ff,clb}$: 0.998
- (Descent, $M_{ff,des}$: 0.990) ! See discussion below.
- Landing, $M_{ff,l}$: 0.992

These individual fuel fractions lead to the following combined fuel fractions:

- Standard flight fuel fraction, $M_{ff,std}$:

$$M_{ff,std} = M_{ff,TO} \cdot M_{ff,CLB} \cdot M_{ff,CR} \cdot M_{ff,DES} \cdot M_{ff,L} \tag{3.74}$$

- All-reserves fuel fraction (for go-around and flight to alternate airport), $M_{ff,res}$:

$$M_{ff,res} = M_{ff,clb} \cdot M_{ff,extra} \cdot M_{ff,loiter} \cdot M_{ff,des} \tag{3.75}$$

- Total fuel fraction, M_{ff}:

$$M_{ff} = M_{ff,std} \cdot M_{ff,res} \tag{3.76}$$

$\Rightarrow$ **Mission fuel fraction**, $\frac{m_f}{m_{mto}}$:

$$\frac{m_f}{m_{mto}} = 1 - M_{ff} \tag{3.77}$$

Note: When dealing with fuel fractions in general and handbook values in particular, the user has to be very cautious. The given numbers represent statistical average values over a broad range of reference aircraft or are based on judgment. It is therefore very likely that the used value is not the accurate one for the investigated aircraft, and the results based on the use of such values can only be estimations. **Roskam 1997** states: ”There is no substitute for common sense! If and when common sense so dictates, the reader should substitute other values for the fractions suggested...” That is especially important as fuel fractions have a very large influence on the accuracy of the results of the whole preliminary sizing process.

Outlook and example

The usage of the given numbers for engine start fuel fraction to landing fuel fraction leads, among others, to the following results for the “flight with maximum payload” reference mission:

- Mission fuel fraction, $\frac{m_f}{m_{mto}}$: 0.422,
- Maximum take-off mass, m_{mto}: 397 t.

Of course, a variation in maximum take-off mass of 50 t or about 14 percent is far from acceptable, and the reasons for these variations have to be ascertained. In that context it becomes apparent that descent flight is being accounted for *twice*: first, when the cruise flight segment is calculated using the complete reference range (7,500 NM resp. 9,300 NM), and second, when the stated descent flight fuel fraction is also included in the standard flight fuel fraction. Of course the same is true for the flight segments take-off, climb and landing, but in case of the descent flight the effects are largest as, in contrast to take-off and climb the aircraft uses *less* fuel than during cruise flight. The landing flight segment shall be excluded in these considerations and be accepted as a ‘safety margin’. This allows for the concentration on the descent flight segment and reduces the number of variables to adjust and to improve the preliminary sizing results.

The latter paragraphs indicate again the iterative nature of the preliminary design process. During the work, the user either has to come across irregularities as the mentioned one and then search for an explanation and solution or has to have the experience from previous similar investigations. In order to find a compromise between the description of the nature and workflow of the preliminary sizing process and nevertheless comprehensible results, the following sections will investigate two scenarios (see Table 3.4). The first scenario uses the initial handbook value for the descent flight fuel fraction and the second one uses a value for the descent flight fuel fraction of

$$M_{ff,des} = 1.005 \quad . \tag{3.78}$$

This value was found searching for the real Boeing B777-200LR's masses etc. and mathematically means that the aircraft *gains* 0.5 percent of its maximum take-off mass during cruise flight. That is, of course, **not** the case, but keeping in mind that the descent flight has already been accounted for as part of the cruise flight, the meaning of that value changes to 'the aircraft *loses* 0.5 percent of the maximum take-off mass *less* during descent than it would if it continued its cruise flight'.

Table 3.4 B777-200LR fuel fractions

Flight mission		Maxim payload		Maximum fuel	
Descent Flight Fuel Fraction	$M_{ff,des}$	0.990	1.005	0.990	1.005
Standard flight fuel fraction	$M_{ff,std}$	0.624	0.634	0.564	0.572
All-reserves fuel fraction	$M_{ff,res}$	0.926	0.940	0.921	0.935
Total fuel fraction	M_{ff}	0.578	0.596	0.519	0.535
Mission fuel fraction	$\frac{m_f}{m_{MTO}} = 1 - M_{ff}$	0.422	0.404	0.481	0.465

Remark: Changing the descent flight fuel fraction is only one of several possible attempts to improve the final results. The large amount of input parameters 'offers' a vast number of approaches. One further possibility would be the reduction of the cruise flight segment to its real length. However, this estimation of the leg lengths would have to be done by means of further assumptions as well.

3.3.3 Aircraft mass fractions

According to **Loftin 1980** the relative operating empty mass m_{oe}/m_{mto} can be estimated from the thrust-to-weight ratio as follows:

$$\frac{m_{oe}}{m_{mto}} \approx 0.23 + 1.04 \cdot \frac{T_{to}}{m_{mto} \cdot g} = 0.528 \quad . \tag{3.79}$$

However, PreSTo also allows to enter own values, if known. **Boeing 2004** gives the desired numbers to determine the Boeing B777-200LR's real relative operating empty mass as

$$\frac{m_{OE}}{m_{MTO}} = 0.417 \quad . \tag{3.80}$$

For long range aircraft such as the B777 one typically uses a mass per passenger, m_{pax}/n_{pax} including check-in and carry-on baggage of

$$\frac{m_{pax}}{n_{pax}} = 97.5 \text{ kg} \quad , \tag{3.81}$$

which leads to a mass of all 301 passengers, m_{pax} including their baggage of

$$m_{pax} = n_{pax} \cdot \frac{m_{pax}}{n_{pax}} = 29.35 \text{ t} \quad . \tag{3.82}$$

This allows for an additional cargo mass, m_{cargo} of

$$m_{cargo,mpl} = 34.7 \text{ t} \tag{3.83}$$

$$m_{cargo,mf} = 11.5 \text{ t} \tag{3.84}$$

and results in a payload, m_{pl} of

$$m_{mpl} = 64 \text{ t} \tag{3.85}$$

$$m_{pl,mf} = 40.8 \text{ t} \quad . \tag{3.86}$$

The take-off mass is made up of the operating empty mass, the payload and the fuel mass:

$$m_{to} = m_{oe} + m_{pl} + m_f \quad . \tag{3.87}$$

In terms of mass fractions this is expressed as

$$1 = \frac{m_{oe}}{m_{mto}} + \frac{m_{pl}}{m_{mto}} + \frac{m_f}{m_{mto}} \quad . \tag{3.88}$$

and therefore leads to a maximum take-off mass, m_{mto} of

$$m_{mto} = \frac{m_{pl}}{1 - \frac{m_{oe}}{m_{mto}} - \frac{m_f}{m_{mto}}} \tag{3.89}$$

and further on to

- A maximum landing mass of

$$m_{ml} = m_{mto} \cdot \frac{m_{ml}}{m_{mto}} \quad , \tag{3.90}$$

- An operating empty mass of

$$m_{oe} = m_{mto} \cdot \frac{m_{oe}}{m_{mto}} \quad , \tag{3.91}$$

- A mission fuel mass for a standard flight of

$$m_f = m_{mto} \cdot \frac{m_f}{m_{mto}} \quad \text{and} \tag{3.92}$$

- A needed fuel mass (including engine start up and taxi) of

$$m_{f,needed} = m_{mto} \cdot \left(1 - M_{ff,engine} \cdot M_{ff,taxi} \cdot M_{ff}\right) \quad . \tag{3.93}$$

The final results of the various mass fractions are collected in the following Table 3.5.

Table 3.5 B777-200LR mass fractions

Flight mission		Maxim payload		Maximum fuel		Real A/C
Descent Flight Fuel Fraction	$M_{ff,des}$	0.990	1.005	0.990	1.005	/
Payload	m_{pl}	64.0 t	64.0 t	40.8 t	40.8 t	64 t / 40.8 t
Maximum Take-Off Mass	m_{mto}	397.0 t	357.9 t	399.5 t	345.9 t	347.8 t
Maximum Landing Mass	m_{ml}	254.9 t	229.8 t	256.5 t	222.1 t	223.2 t
Operating Empty Mass	m_{oe}	165.6 t	149.2 t	166.6 t	144.2 t	145.1 t
(Maximum) Zero-Fuel Mass	m_{zf}	229.6 t	213.3 t	207.4 t	185.1 t	209.1 t (m_{mzf})
Mission Fuel Mass for Standard Flight	m_f	167.4 t	144.6 t	192.1 t	160.8 t	-
Needed Fuel Mass	$m_{f,needed}$	172.0 t	148.8 t	196.2 t	164.5 t	162.4 t (m_{mf})

3.3.4 Aircraft parameters

The so far determined aircraft masses etc. lead to the following further aircraft parameters of the Boeing B777-200LR. The results are collected in Table 3.6.

The needed fuel tank capacity for the maximum fuel mission (including engine start up and taxi) is calculated as

$$V_{f,needed} = \frac{m_{F,needed}}{\rho_F} \tag{3.94}$$

with

$$\rho_f = 803 \frac{\text{kg}}{\text{m}^3} \quad (\textbf{Boeing 2004}) \quad . \tag{3.95}$$

The determined maximum take-off masses lead, in combination with the calculated wing loading, to wing areas of

$$S_w = \frac{m_{mto}}{m_{mto}/S_w} \tag{3.96}$$

and, in combination with the calculated thrust-to-weight ratio, to maximum take-off thrusts of

$$T_{to} = m_{mto} \cdot g \cdot \frac{T_{to}}{m_{mto} \cdot g} \quad . \tag{3.97}$$

Table 3.6 B777-200LR aircraft parameters

Flight mission		Maxim payload		Maximum fuel		Real A/C
Descent Flight Fuel Fraction	$M_{ff,des}$	0.990	1.005	0.990	1.005	/
Needed Fuel Tank Volume	$V_{f,needed}$	214 m^3	185 m^3	244 m^3	205 m^3	202 m^3
Wing Area	S_w	512 m^2	462 m^2	516 m^2	446 m^2	450 m^2
Take-Off Thrust (all engines)	T_{to}	1118 kN	1008 kN	1125 kN	974 kN	978 kN
Take-Off Thrust (one engine)	T_{to}/n_e	559 kN	504 kN	562 kN	487 kN	489 kN

3.3.5 Validity check

Finally, a check concerning the relation of maximum landing mass to maximum zero-fuel mass plus fuel reserves is being performed. The aircraft must be able to land with maximum zero-fuel mass and *none* of the reserve fuel being used. Otherwise, it would simply not be possible to conduct a trouble-free flight if the reserve fuel mass kept the aircraft from landing.

So the requirement is:

$$m_{ml} \overset{!}{>} m_{zf} + m_{f,res} \quad , \tag{3.98}$$

with

$$m_{zf} = m_{oe} + m_{pl} \tag{6.99}$$

$$m_{f,res} = m_{mto} \cdot \left(1 - M_{ff,res}\right) \quad . \tag{3.100}$$

Table 3.7 holds the results of that check.

Table 3.7 B777-200LR re-design validity check

Flight mission	Maxim payload		Maximum fuel	
Descent Flight Fuel Fraction, $M_{ff,des}$	0.990	1.005	0.990	1.005
Difference m_{ml} to $m_{mzf} + m_{f,res}$	-4.1 t	-5.0 t	17.6 t	14.6 t
Check pass/fail	**Fail**	**Fail**	**Pass**	**Pass**

It can be seen that, principally, the design is not valid in the current form. The aircraft is not allowed to land with the reserve fuel onboard in case of the maximum payload reference mission. The mass discrepancy is about 4 to 5 t, which corresponds to 1.1 to 1.5 % of the maximum take-off mass.

In case of the sizing of a new aircraft, the user would have to start a new iteration step and enlarge the chosen/estimated ratio of maximum landing mass to maximum take-off mass in the very beginning of the design process. Afterwards, the whole sizing process would be performed one more time with changed values.

That change of the ratio of maximum landing to maximum take-off mass is not done in this project. The reason for that decision is that most of the input data used is based on original Boeing data. Therefore, it is very probable that this mass discrepancy results from too conventional (reserve) fuel fraction and that, in reality, this discrepancy does not exist.

In order to stay able to use the original Boeing data, the ratio of maximum landing to maximum take-off mass is *not* adopted.

3.4 Collection of aircraft and design process data

Table 3.8 summarizes the most important input parameters as well as the intermediate and final results of the preliminary sizing process of the B777-200LR. For more detailed information see Appendices A and B. Appendix A includes an extensive list of process data and final results, while Appendix B shows screenshots of the original PreSTo spreadsheets.

Table 3.8 Design process data and final results of the preliminary sizing of the B777-200LR

Parameter		Flight mission: Maxim payload	Flight mission: Maximum fuel
Landing field length	s_{lfl}	1,676 m	
Approach speed	V_{app}	140 kt (= 72 m/s)	
(Wing) aspect ratio	A	9.34	
Glide ratio in take-off configuration	E_{to}	8.35	
Number of engines	n_e	2	
Take-off field length	s_{tofl}	3350 m	
Glide ratio in landing configuration	E_l	7.85	
Maximum glide ratio	$E_{\max}$	19.7	
Engine bypass ratio	μ , BPR	8.9	
Cruise Mach number	M_{cr}	0.84	
Wing loading (at maximum take-off mass)	$\frac{m_{mto}}{S_w}$	**775 kg/m²**	
Thrust-to-weight ratio (at max. take-off mass)	$\frac{T_{to}}{m_{mto} \cdot g}$	**0.287**	
Design range	R	7,500 NM	9,300 NM
Distance to alternate airport	$s_{to\_alternate}$	200 NM	200 NM
Mission fuel fraction	$\frac{m_f}{m_{mto}}$	0.404	0.465
Number of passengers	n_{pax}	301	301
Cargo mass	m_{cargo}	34.7 t	11.5 t
Payload	m_{pl}	64.0 t	40.8 t
Zero fuel mass	m_{zf}	213.3 t	185.1 t
Maximum take-off mass	m_{mto}	**357.9 t**	**345.9 t**
Maximum landing mass	m_{ml}	229.8 t	222.1 t

Operating empty mass	m_{oe}	149.2 t	144.2 t
Mission fuel fraction, standard flight	m_f	144.6 t	160.8 t
Wing area	$\boldsymbol{S_w}$	**462 m²**	**446 m²**
Take-off thrust, all engines	T_{to}	1,008 kN	974 kN
Take-off thrust, one engine	$\boldsymbol{\frac{T_{to}}{n_e}}$	**504 kN** (113,000 lb)	**487 kN** (109,000 lb)
Needed fuel mass	$m_{f,needed}$	148.8 t	164.5 t
Needed fuel tank volume	$V_{f,needed}$	185.3 m³	204.8 m³

4 The next step: cabin and fuselage layout

As mentioned, the aircraft fuselage lends itself very much to the first step in the aircraft design process after the preliminary sizing. Consequently the fuselage layout is also the next design step to be incorporated into PreSTo; the current status of a preliminary sketching tool is shown in Section 4.7.

This section gives insight into the most important aspects of the layout of a passenger aircraft's fuselage – more precisely: into the first iteration loop, as the fuselage layout is not closed as long as the whole aircraft layout is not finished.

4.1 General

The fuselage's final shape and construction do not only have to fit to the already known aircraft requirements but also to the demands and capabilities of all involved design and manufacturing departments. It must be physically and economically producible. Moreover the passenger cabin layout is highly driven by comfort and operational flexibility demands of the customer airlines.

One of the most important numbers in the context of cabin design is the number of seats abreast, which means the number of passenger seats per row. Certification regulations (e.g. **CS-25** Paragraph 817) require that no passenger may have to cross more than two adjacent seats in order to reach an aisle. Therefore the maximum number of seats is limited to six seats abreast for single aisle and twelve for twin aisle aircraft. The second important parameter when dealing with cabin layout is the seat pitch. This parameter is usually given in full inches and is highly dependent on the airline's comfort level. Its values reach from less than 30 inches (0.76 m) in high-density configurations to 60 and more inches (1.52 m) in first class sections.

Besides such passenger comfort parameters the certification regulations pose further minimum safety requirements like minimum longitudinal aisle widths, cross aisle widths, number and arrangement of flight attendant seats, etc. The required longitudinal aisle width for example is defined in **CS-25,** Paragraph 815 as not less than 15 inches on floor level and not less than 20 inches at 25 inches or higher above floor level. Further installations that influence the cabin floor plan are lavatories, galleys, stowage compartments and, on ultra-long range aircraft, cabin and flight crew rest compartments. The space on the lower deck is usually used for cargo compartments forward and aft of the center wing box. In case it is intended to launch a later freighter version, the main deck also should fit to the standard container and cargo pallet sizes.

Often neither the maximum allowable payload mass nor the available cabin space limit the amount of passenger seats in the cabin but the number and types of emergency exits. The certification regulations (e.g. **CS-25** Paragraph 807) distinguish between several types of emergency exits of different opening sizes. On aircraft with 300 or more passenger seats (as in case of the Boeing B777) only so-called Type A and Type 1 may be used (see below). For each pair of Type A exits a number of 110 passenger seats may be allocated in the cabin; in case of Type 1 exits it is 45 passenger seats per pair of exits. In CS-25.807 those exits are defined as follows:

- Type A: Floor level exit with a rectangular opening not less than 24 inches (609.6 mm) wide by 48 inches (1.219 m) high, with corner radii not greater than one-third of the width of the exit
- Type 1: Floor level exit with a rectangular opening not less than 42 inches (1.067 m) wide by 72 inches (1.829 m) high, with corner radii not greater than one-sixth of the width of the exit

Along the largest part of the fuselage its cross section stays constant – preferably circular or close – which forms a (nearly) cylindrical tube. Such a tube allows for easily shrunk and stretched versions by 'just' adding or removing sections of the fuselage. Forward and aft of that tube are a nose cone and a tail cone to create an aerodynamical shape and, in case of the tail cone, to provide space for the rotation of the aircraft during take-off and landing.

The slenderness of the fuselage, meaning the ratio of its length to diameter, is of great importance and always a trade-off between different aspects: if the fuselage is too stubby it leads to a declined aerodynamic performance and a (too) short lever arm of the tailplane. Furthermore the doors would be very close together, which would cause problems during emergency evacuation and bad accessibility for ground vehicles during turn-around. In contrast, if the aircraft gets too slender, the extra surface area, bending moments and bending stresses (smaller fuselage diameter) would increase the aircraft's drag and weight. **Trahmer 2004** gives a slenderness ratio of 10 to 11 as the best value. **Scholz 1999** names a ratio of fuselage length to diameter of 8 as optimum; a ratio of 6 leads to minimum drag.

4.2 Cross section

The optimum cross section for a pressurized fuselage is a circle in order to optimally lead the internal pressure loads into the structure and avoid bending moments. The inner contour of the passenger cabin must fit to the seat allocation. Especially the most outboard seats raise requirements regarding the free space between the passengers' bodies and the wall panels and overhead stowage compartments. According to **Trahmer 2004**, the distance between the head of the passenger sitting on an outboard seat and the wall panel should not be less than 10 centimeter, between shoulder and wall panel, there should be a distance of at least two centimeter, and aisles should have a minimum height of 2 meter.

The definition of the cross section is, as well as the floor plan layout (see Section 4.3), highly driven by passenger comfort demands and operational demands like e.g. the capability to transport standard cargo pallets and containers. In a first attempt it is favorable to investigate the *maximum* number of passenger seats to be installed in the aircraft, as this is usually a one-class high-density configuration. Although for the Boeing B777-200LR a typical number of 301 passengers has been used during the preliminary sizing the maximum number of possible seats is larger: 4 pairs of Type A exits allow for a maximum number of 440 passengers:

$$n_{pax,\max}(B777-200) = 4 \cdot 110 = 440 \quad . \tag{4.1}$$

It must be kept in mind that aircraft are not developed in only one configuration, but the manufacturer usually plans to offer stretched and/or shrunk versions later on. For the determination of the number of seats abreast, this is of special importance due to the aircraft slenderness mentioned above. Therefore, in case of this re-design project of the Boeing B777-200LR, the stretched B777-300 version has to be taken into account as well, and the determined number of seats abreast must fit to both versions. The maximum number of passenger seats in the stretched B777-300 version with five pairs of Type A exits results as

$$n_{pax,\max}(B777-300) = 550 \quad . \tag{4.2}$$

Scholz 1999 gives the following equation to determine the number of seats abreast on the basis of the maximum number of passengers to be carried. The equation is only valid for single-class layouts:

$$n_{sa} = 0.45 \cdot \sqrt{n_{pax}} \quad . \tag{4.3}$$

That means for the Boeing B777 that the optimum number of seats abreast lies between nine and eleven:

$$\begin{aligned} n_{sa}(B777-200) &= 9.44 \\ n_{sa}(B777-300) &= 10.55 \end{aligned} \quad . \tag{4.4}$$

Hence, ten seats abreast fits best to both versions:

$$n_{sa}(B777) = 10 \quad . \tag{4.5}$$

For the B777-200LR in the high-density configuration, the following values for aisle, seat cushion and armrest width fit well to reality (high-density configuration):

- Aisle: 17 in (= 43,2 cm),
- Seat cushion: 17 in (= 43,2 cm),
- Armrest: 2 in (= 5,1 cm).

These values lead to the following total furniture width and inner fuselage diameter, $d_{f,i}$ of

- Aisles: 2 x17 in = 34 in
- Seat cushions: 10 x17 in = 170 in
- Armrests: 13 x 2 in = 26 in

$$d_{f,i} = 230 \text{ in} = 5.84 \text{ m} \tag{4.6}$$

and, according to **Scholz 1999**, to an outer fuselage diameter of

$$\begin{aligned} d_f &= 0.084 \text{ m} + 1.045\, d_{f,i} \\ &= 6.19 \text{ m} \end{aligned} \quad . \tag{4.7}$$

The outer fuselage diameter of the real B777 is 6.1 m.

Figure 4.1 shows a sketch of the B777 cross section including a passenger sitting on one of the most outboard seats. It was drawn in the newly setup sketching tool which is presented in detail in Section 4.7. The dimensions of the passenger’s body are taken from Schmitt 1998, cited in **Scholz 1999**. This simple geometrical check shows the general compliance of the cross section definition to the given passenger comfort requirements. It can also be seen that, with the cabin floor in that vertical position, there is enough space for a sufficient aisle height and system installations above the cabin ceiling.

The thickness of the floor is estimated as

$$h_{floor} = 0.28 \text{ m} \quad , \tag{4.8}$$

with the floor lowered from the horizontal cross section median line by

$$h_{floor\ lowering} = 0.43 \text{ m} \quad . \tag{4.9}$$

All these values were found iteratively in combination with the height and width requirements for the lower deck cargo compartment (see Section 4.4).

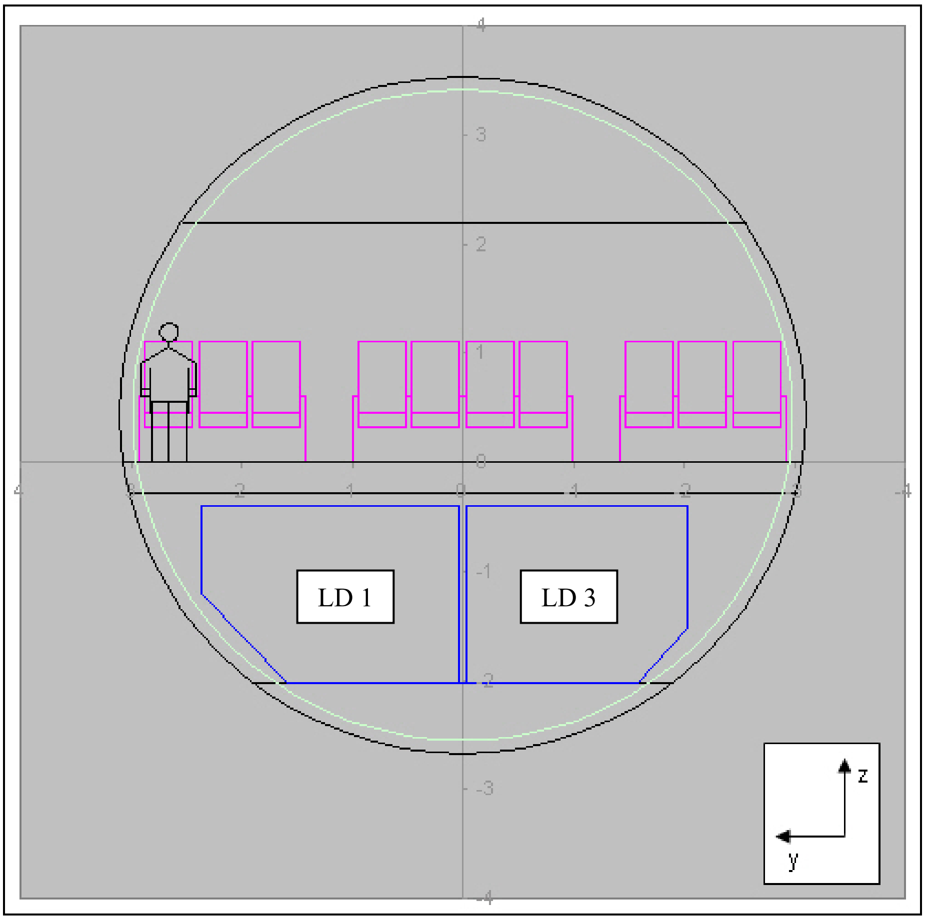


Fig 4.1 Initial sketch of the B777 cross section

4.3 Floor plan

The determination of a floor plan is very important to each airline and follows different rules for each of them. In case of long range aircraft this is even more the case than for smaller range aircraft. In the cabin, the airlines have the opportunity to distinguish from their competitors. Here, the passengers spend the whole flight time, and here is the place where they experience flying. This great importance of the cabin design makes the definition of the cabin floor plan a far more extensive process than can be handled and described within the scope of this project. Dedicated cabin layout tools like Pacelab Cabin (see e.g. **Seeckt 2004**) are available, and many airline and manufacturer departments are involved in that process. So this section concentrates on the determination of the cabin length from statistics to go ahead with in this first sizing loop.

The length of the cabin may be estimated by means of the following equation taken from **Scholz 1999**; it is valid for single class layouts:

$$l_{cabin} = k_{cabin} \cdot \frac{n_{pax}}{n_{sa}} \tag{4.10}$$

with

$$k_{cabin} \approx 1.0 \text{ m} \ldots 1.1 \text{ m} \quad . \tag{4.11}$$

A value of

$$k_{cabin} = 1.1 \text{ m} \tag{4.12}$$

delivers the real cabin length of the Boeing B777-200LR of

$$l_{cabin} = 48.4 \text{ m} \quad . \tag{4.13}$$

Now these 48.4 meter are available for different cabin layouts and floor plans in various combinations of classes and comfort standards (see Fig 4.2 to 4.4). The determined cabin length is used further in Section 4.5 to obtain the overall fuselage length.

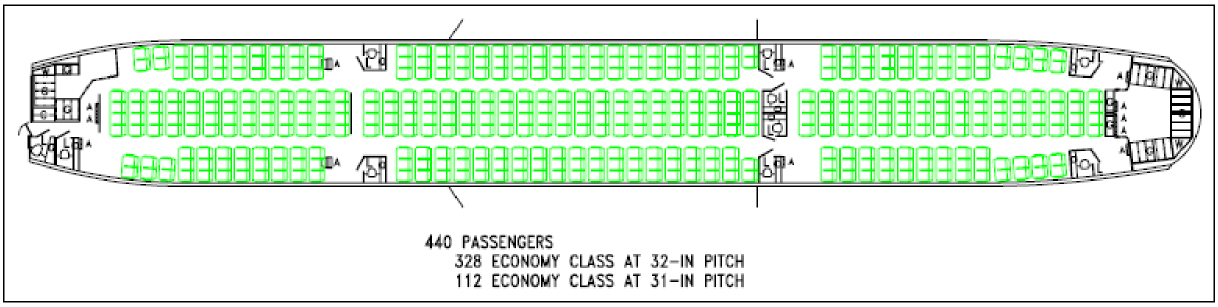


Fig 4.2 B777-200 floor plan in 440 passengers layout (**Boeing 2004a**)

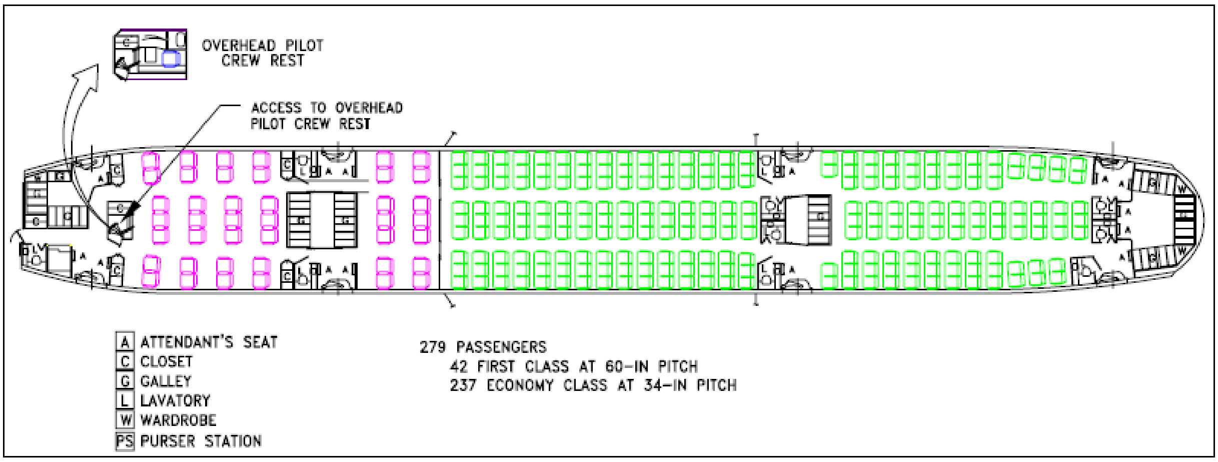


Fig 4.3 B777-200LR floor plan in 279 passengers layout (**Boeing 2004**)

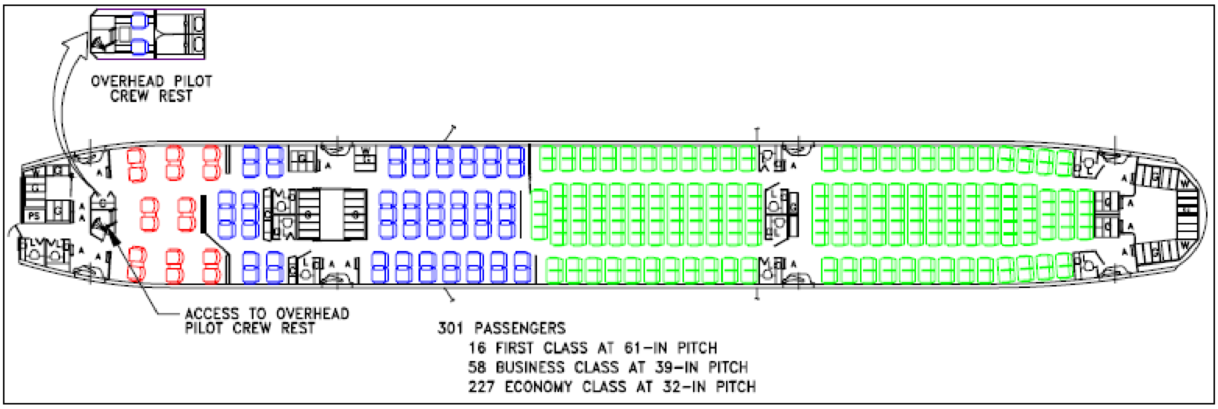


Fig 4.4 B777-200LR floor plan in 301 passengers layout (**Boeing 2004**)

Figure 4.5 shows a principal sketch of the floor plan of the Boeing B777-200LR cabin in the 440 passengers version. It becomes apparent that, compared to the real floor plan in Figure 4.2, there are important discrepancies. The so far missing capabilities of the fuselage sketching tool (see Section 4.7) concerning the integration of cross aisles, emergency exits, galleys, lavatories, etc. make the currently available floor plan a very preliminary result of limited value.

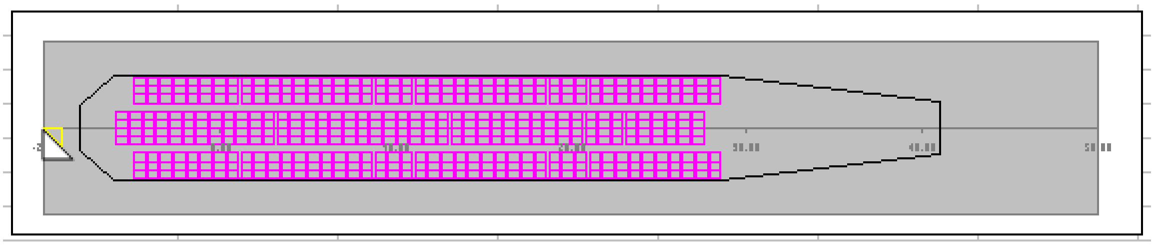


Fig 4.5 Initial floor plan sketch of the Boeing B777-200 (440 passengers)

4.4 Lower deck

The lower deck compartments are used to carry the passengers' check-in baggage as well as additional cargo. This cargo is most often transported in containers (so-called ULDs = unit load device) of which there are a lot of different types. The most commonly used type is the so called LD3 (see Fig. 4.5).

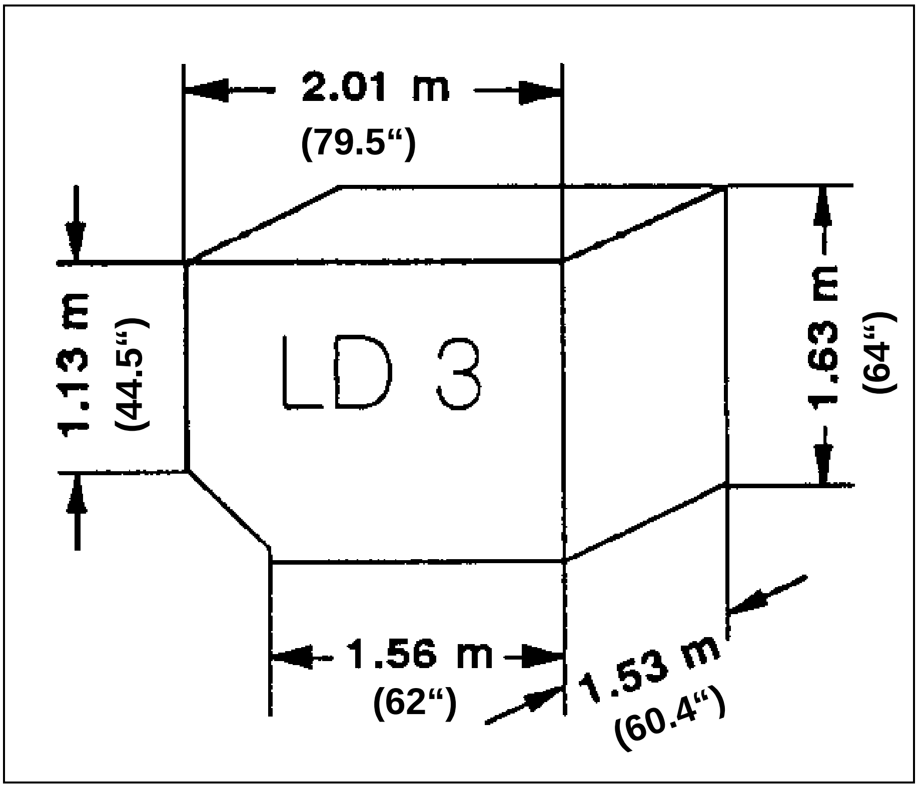


Fig 4.6 Dimensions of an LD3 container (Marckwardt 1998 in **Scholz 1999**)

On low-wing aircraft it is not possible to create a single end-to-end cargo compartment due to the structural bulkheads of the wing center section. That part of the aircraft is therefore used for systems installations like the environmental control system (ECS), the waste- and fresh-water tanks, the center tank and of course the main landing gear bay.

The very aft part of the lower deck cannot be used for the storage of containers or pallets due to the tail cone. But this so-called bulk cargo section is often used to store the passengers' check-in baggage. Figures 4.6 and 4.7 show different loading possibilities for the Boeing B777-200LR lower deck compartments.

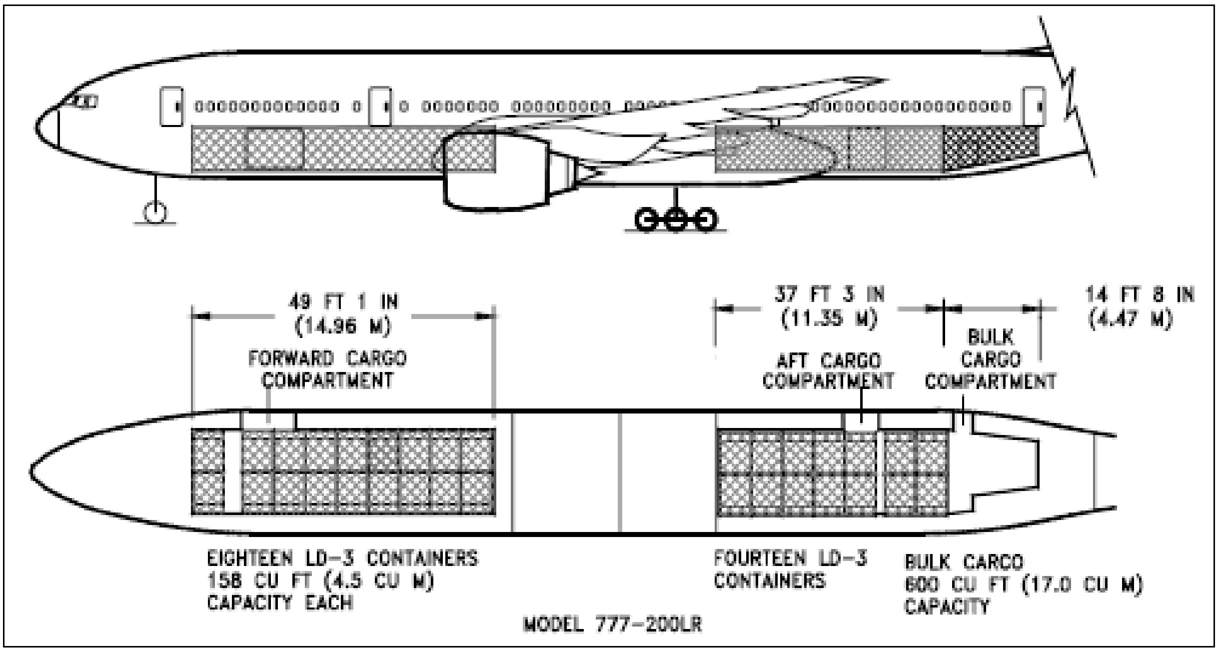


Fig 4.7 B777-200LR lower deck dimensions – 32 LD3 containers loaded (**Boeing 2004**)

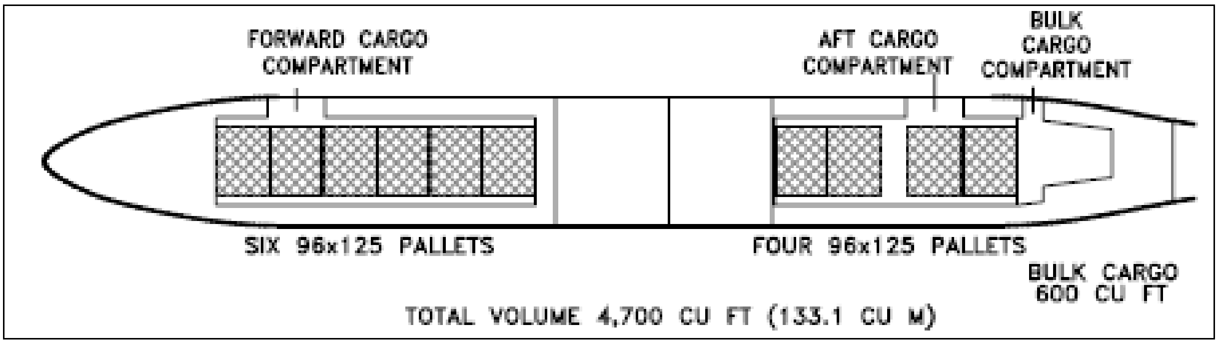


Fig 4.8 B777-200LR lower deck dimensions – 10 pallets loaded (**Boeing 2004**)

In case of ultra-long range aircraft like the Boeing B777-200LR or executive jets, the lower deck compartments are occasionally partly used to install additional fuel tanks. The B777-200LR offers the feature for optional 3 x 1,850 US gal (= 21,000 l) body tanks in the aft cargo compartment (see Fig 4.8).

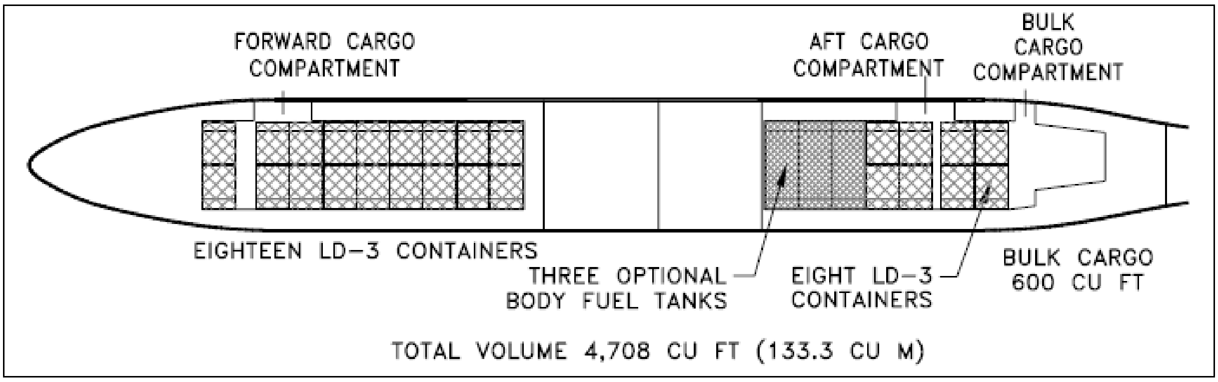


Fig 4.9 B777-200LR lower deck with optional body tanks (**Boeing 2004**)

All these touched on aspects have to be taken into account when searching for the best overall compromise as the final aircraft layout. In case of the Boeing B777, for example, the real cross section differs from the one sketched in Section 4.2. One reason for that is that although it would have been possible for the manufacturer to incorporate the capability to store LD1 containers, it would have resulted in a wider cargo compartment with all its negative consequences like the need for a stiffer and heavier cabin floor structure and less installation space for ducts and systems behind the cargo compartment side walls etc.

Thus Boeing decided to withdraw the capability to transport that uncommon container size, concentrate on the LD3 container and benefit from the available space (see Fig 4.10). The only civil aircraft that is capable to transport two adjacent LD1 containers on its lower deck is the Boeing B747.

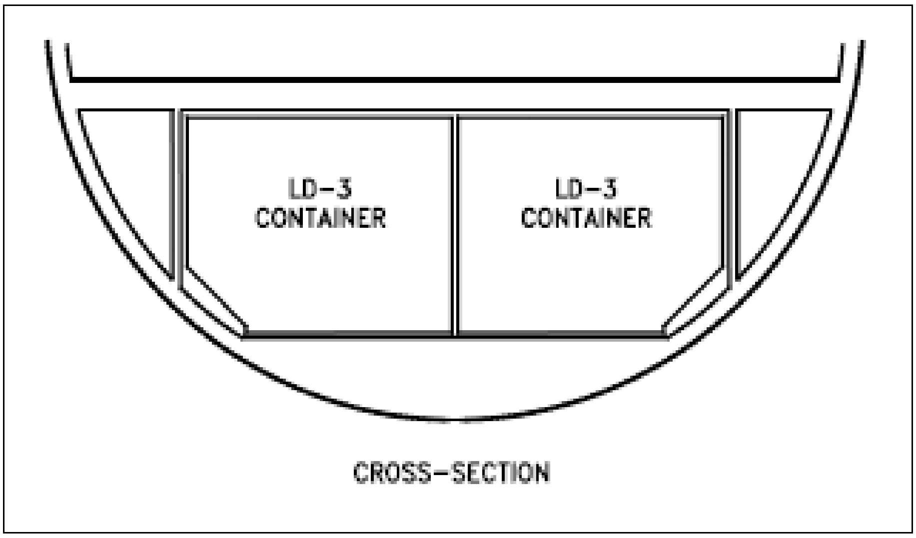


Fig 4.10 Boeing B777 lower deck cross section (**Boeing 2004**)

4.5 Fuselage length

The largest part of the fuselage is of course determined by the cabin length. In later design steps the missing parts (nose and tail cone) are shaped carefully and with much respect to aerodynamics. At this time in the design process however, they are estimated by means of statistical methods. **Scholz 1999** gives the following equation for a first estimation:

$$l_f = l_{cabin} + 1.6 \cdot d_f + 4 \text{ m} \tag{4.14}$$

The overall fuselage length consequently results as

$$l_f(B777-200) = 62.3 \text{ m} \tag{4.15}$$

which fits very well to reality. The real aircraft has a fuselage length of 62.94 m (see Fig 4.10).

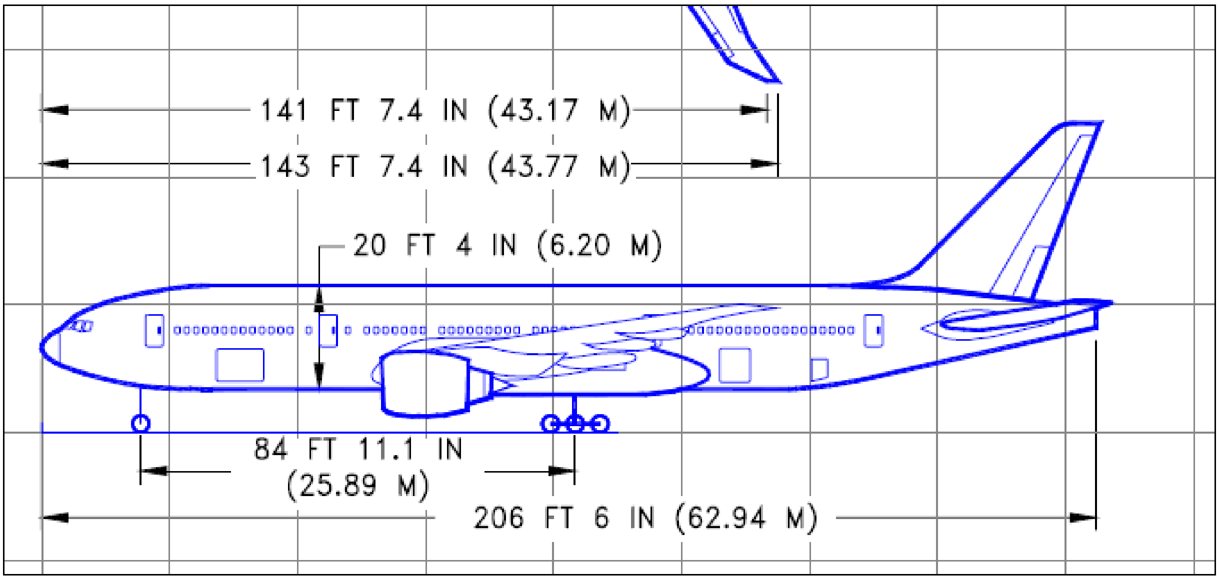


Fig 4.11 Side view of the Boeing B777-200LR (**Boeing 2004**)

4.6 Boeing B777-200LR fuselage and cabin parameters

Table 4.1 Chosen/determined Boeing B777 fuselage and cabin parameters

Parameter	**Value**
Seats abreast, n_{sa}	10
Fuselage diameter, $d_{f,o}$	6.2 m
Ratio of outer to inner diameter, $\frac{d_{f,o}}{d_{f,i}}$	1.04
Floor lowering, $h_{floor\ lowering}$	0.43 m
Floor thickness, h_{floor}	0.28 m
Cabin height, h_{cabin}	2.2 m
Lower deck height, $h_{lower\ deck}$	1.75 m
Seat pitch, $l_{seat\ pitch}$	30 in (= 76.2 cm)
Armrest width, $b_{armrest}$	2 in (= 5.1cm)
Seat cushion width, $b_{cushion}$	17 in (= 43.2 cm)
Aisle width, b_{aisle}	17 in (= 43.2 cm)

4.7 The fuselage sketching tool

Figure 4.11 shows a screenshot of the user interface section of the fuselage sketching tool, which is, as mentioned, the last of the three changes to PreSTo within the scope of this project. This tool allows the user to quickly sketch a principal fuselage cross section and set up a basic floor plan to get an immediate impression of the current status of the fuselage layout.

The tool consists of three main parts:

- A section to define the dimensions of the fuselage cross section and floor plan (a),
- A section to define the seat and aisle arrangement per row (b), and
- The sketches of the defined cross section and floor plan as graphical output (c).

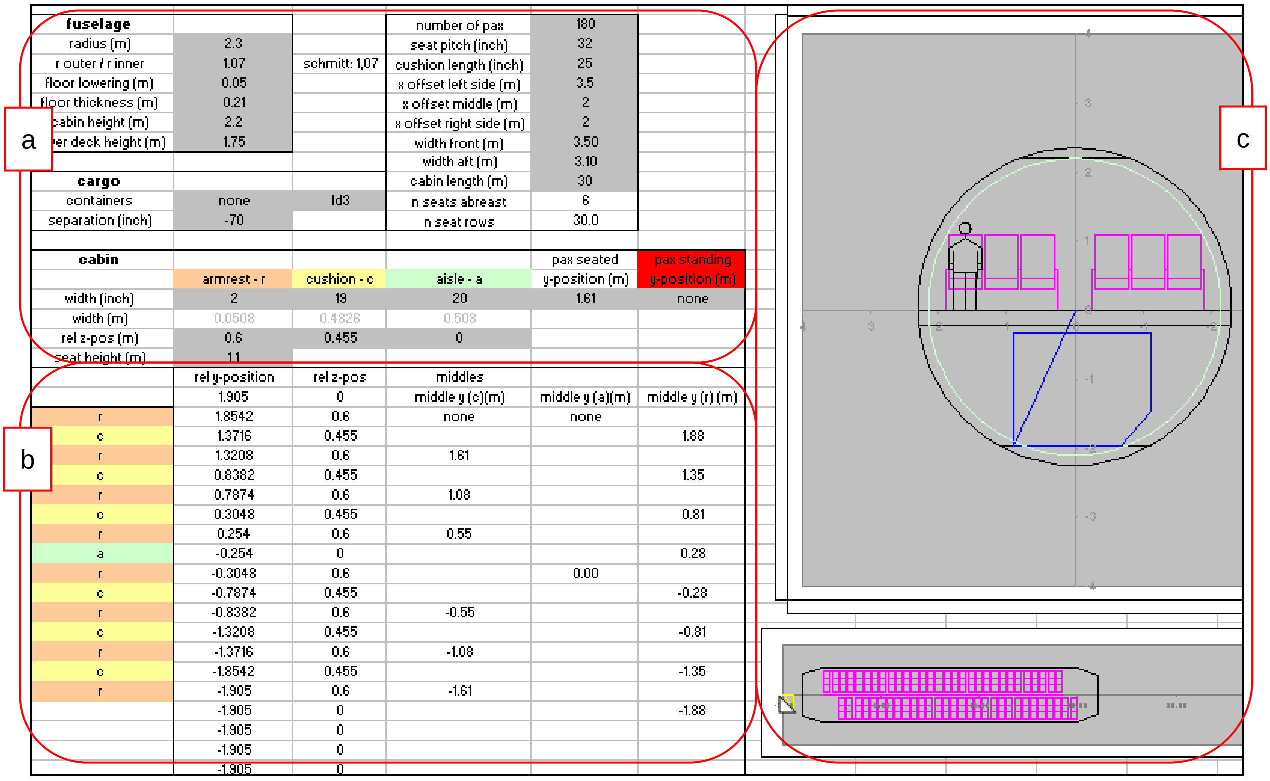


Fig 4.12 User interface section of fuselage sketching tool

Fuselage cross section and floor plan definition

This part consists of four further subparts called ‘fuselage’, ‘cargo’, ‘cabin’ and ‘floor plan’.

In the section ‘**fuselage**’ the user defines the structure of the fuselage cross section:

- The outer diameter,
- The ratio of the outer to the inner diameter,
- The distance which the cabin floor is lowered compared to the horizontal median line of the fuselage cross section,
- The thickness of the floor structure,

- The height of the cabin ceiling above the cabin floor, and
- The height of the lower deck compartment.

fuselage	
radius (m)	3.1
r outer / r inner	1.04
floor lowering (m)	0.43
floor thickness (m)	0.28
cabin height (m)	2.2
lower deck height (m)	1.75

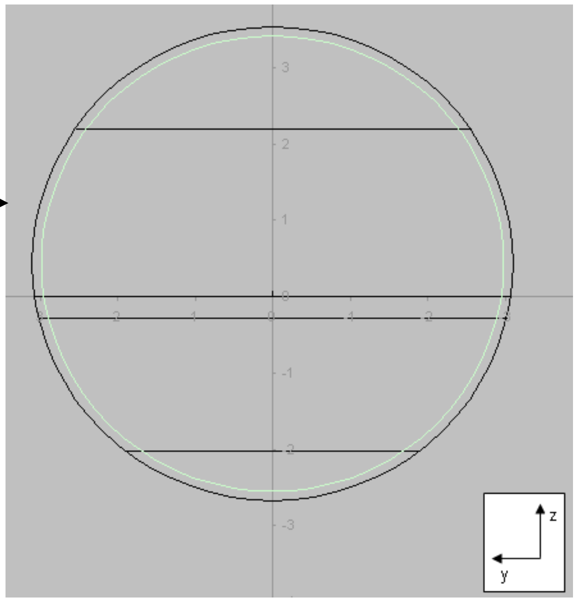


Fig 4.13 Fuselage structure definition

In the section '**cargo**' the user defines the arrangement of the cargo containers on lower deck. Two adjacent containers are possible which are placed symmetrically to the vertical median line. It is also possible to place only one container (like in Fig. 4.11). The user may input/choose

- The type(s) of containers used and
- Their lateral distance.

cargo		
containers	ld3	ld1
separation (inch)	2	

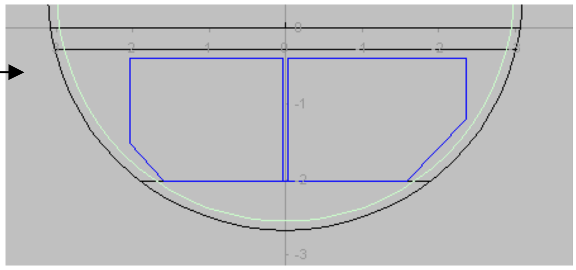


Fig 4.14 Lower deck container arrangement

In the section '**cabin**' the user defines the widths of

- The longitudinal cabin aisle(s),
- The passenger seat cushion and
- The armrest between two passenger seats.

Furthermore the vertical position of the backrest, seat cushion and the armrest are defined relative to the cabin floor. For the graphical output the user may allocate a sketch of a sitting and a standing (still under development) passenger. This allows checking for the mentioned clearance requirements between head/shoulder and cabin wall etc. Figure 4.14 gives an example.

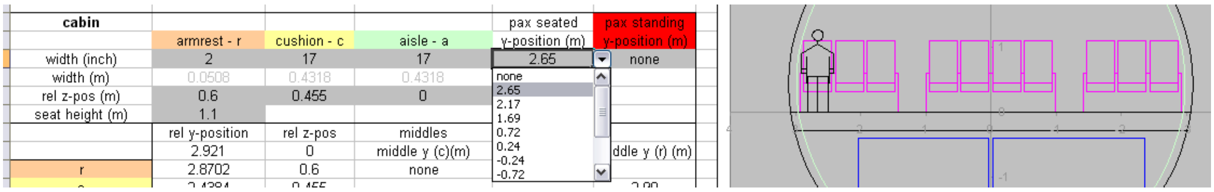


Fig 4.15 Definition of the widths of seat row components

In the section ‘**floor plan**’ the user gives the basic information for the cabin floor plan sketch:

- The number of passenger seats to be positioned,
- The seat pitch (in inches),
- The length of a seat cushion (or passenger seat).

In order to complete the floor plan sketch the user may also account for the cabin parts reaching into the nose and tail cone by defining the cabin width at the front and aft end of the cabin (see Fig 4.15). Finally for each of the maximum three longitudinal seat blocks a longitudinal offset may be defined. In the current form of the sketching tool the positioning of exits, cross aisles, galleys, lavatories etc. has not been included yet. The integration of those components is still under development.

floor plan	
number of pax	120
seat pitch (inch)	30
cushion length (inch)	25
x offset left side (m)	2
x offset middle (m)	3
x offset right side (m)	3
width front (m)	2.60
width aft (m)	3.10
cabin length (m)	30
n seats abreast	5
n seat rows	24.0

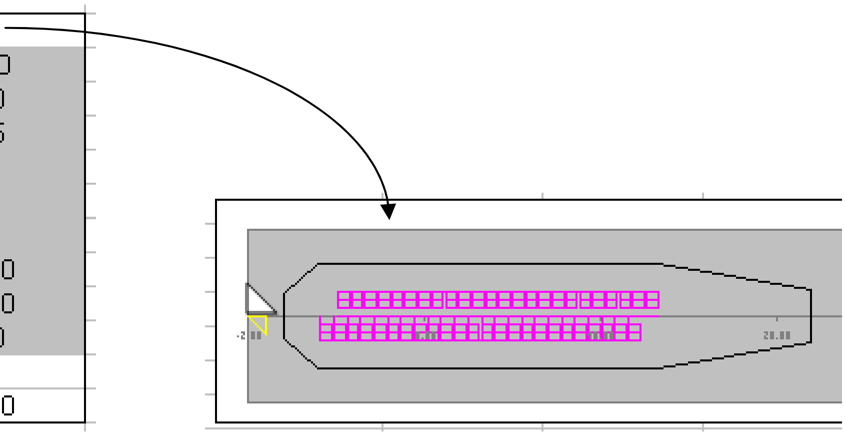
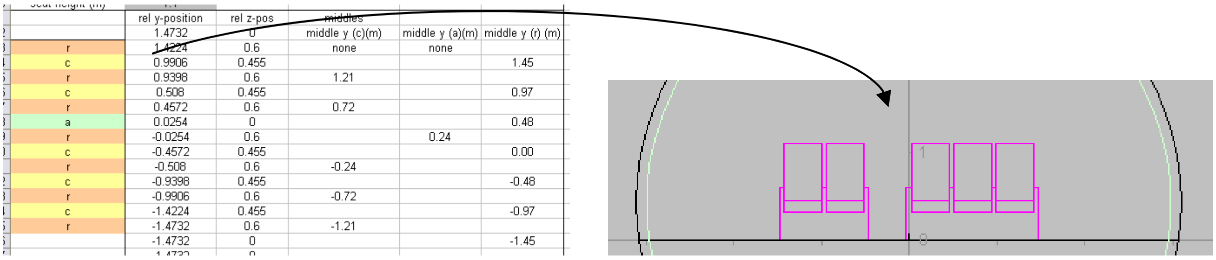


Fig 4.16 Floor plan definition

Seat row composition

In this block the basic lateral arrangement of each seat row is defined. The user may compose the row of three possible alternatives: armrest (r), cushion (c) and aisle (a). Their individual widths have been defined in the Section ‘cabin’. The composition of the row happens top-bottom (= left-right in the sketch). Figure 4.16 gives an example as explanation.



	rel y-position	rel z-pos	middles		
	1.4732	0	middle y (c)(m)	middle y (a)(m)	middle y (r) (m)
r	1.4224	0.6	none	none	
c	0.9906	0.455			1.45
r	0.9398	0.6	1.21		
c	0.508	0.455			0.97
r	0.4572	0.6	0.72		
a	0.0254	0			0.48
r	-0.0254	0.6		0.24	
c	-0.4572	0.455			0.00
r	-0.508	0.6	-0.24		
c	-0.9398	0.455			-0.48
r	-0.9906	0.6	-0.72		
c	-1.4224	0.455			-0.97
r	-1.4732	0.6	-1.21		
	-1.4732	0			-1.45

Fig 4.17 Seat row composition

Summary and discussion

In this report the aircraft design process of the Hamburg University of Applied Sciences (HAW Hamburg) and the HAW's Aircraft Preliminary Sizing Tool PreSTo have been applied and described in detail. For that purpose the Boeing B777-200lR 'Worldliner' was chosen as reference aircraft and re-designed. Moreover, the three newly implemented additions to further improve the consistency of the results and to make the application of the tool more convenient were presented. These additions are the investigation of two instead of one reference mission, a sheet to collect 'target' values of the real reference aircraft and a sketching tool for the quick graphical layout and change of the fuselage cross section and floor plan.

The first step within the re-design process was to determine the so-called aircraft design point in terms of thrust-to-weight ratio and wing loading. The five initial requirements 'landing distance', 'take-off distance', 'second segment', 'missed approach' and 'cruise flight' posed to the reference aircraft for its certification according to CS-25 and/or FAR Part 25 were each evaluated separately and the results were plotted into one matching chart, from which the aircraft design point was read. Afterwards the second step was to estimate basic aircraft parameters like aircraft masses (maximum take-off, operating empty, etc.), the wing area and the required fuel volume from the determined design point.

It was shown that, although PreSTo simplifies and expedites the aircraft preliminary sizing process significantly, the user nevertheless has to pay attention on the input and statistical values used. The sections 3.2.1 'Landing distance' and 3.3.2 'Mission fuel fractions' show examples of required adaptations of the default values by the user.

The exact data of the reference aircraft have not been met, and the results differ among the two regarded reference missions 'flight with maximum payload' and 'flight with maximum fuel'. However, the final results of the re-design of the B777-200LR using PreSTo are acceptably accurate for the first iteration loop for which PreSTo is intended to be used for.

Further improvements to achieve exactly the same results for both reference missions would have to be done to both missions differently. A reduction of the extra flight distance in case of the ‘maximum payload’ mission, for example, would bring the Boeing B777-200LR’s maximum take-off mass and all following data into the same order of magnitude as those of the ‘maximum fuel’ mission. Although such steps have been undertaken in the course of this project, it was abstained from presenting those steps in this report as such steps lack well-founded explanations.

The change of the descent flight fuel fraction, $M_{ff,des}$ from 0.99, as given in **Roskam 1997**, to 1.005 is only one way to handle the too large masses resulting from the use of the handbook value. Others are possible. Reducing the cruise flight distance from the total range including all flight segments to its real length, for instance, would be another approach. However, in that case the difficulty lies in the realistic estimation of the segment lengths.

References

Boeing 2002
BOEING COMMERCIAL AIRPLANES: 777 Freighter. Seattle, WA, USA : Boeing Commercial Airplanes, 2002 – corporate literature,
URL: http://www.boeing.com/commercial/startup/pdf/freighters/777f_ext.pdf (2008-03-11)

Boeing 2004
BOEING COMMERCIAL AIRPLANES: 777-200LR/-300 ER Airplane Characteristics for Airport Planning. Seattle, WA, USA : Boeing Commercial Airplanes, 2004 – corporate literature,
URL: http://www.boeing.com/commercial/airports/777.htm (2007-10-05)

Boeing 2004a
BOEING COMMERCIAL AIRPLANES: 777-200/300 Airplane Characteristics for Airport Planning. Seattle, WA, USA : Boeing Commercial Airplanes, 2004 – corporate literature,
URL: http://www.boeing.com/commercial/airports/777.htm (2007-10-05)

Boeing 2007
BOEING COMMERCIAL AIRPLANES: Airport Reference Code and Approach Speeds for Boeing Airplanes. Seattle, WA, USA : Boeing Commercial Airplanes, 2007 – corporate literature,
URL: http://www.boeing.com/commercial/airports/faqs/arcandapproachspeeds.pdf
(2008-03-11)

CS-25
EUROPEAN AVIATION SAFETY AGENCY: Certification Specifications for Large Aeroplanes – CS-25, Amendment 4, 27 December 2007.
URL: http://www.easa.europa.eu/ws_prod/g/doc/Agency_Mesures/Agency_Decisions/CS-25_Amdt4.pdf (2008-03-11)

Böttger 2004
BÖTTGER, OLE: Projektaerodynamik - Ermittlung der Aerodynamik für den Gesamtentwurf. Hamburg University of Applied Sciences, Department of Automotive and Aeronautical Engineering, Lecture Notes, 2004 – URL: http://fe.profscholz.de (2008-03-11)

Dubs 1987
DUBS, F.: Aerodynamik der reinen Unterschallströmung, Basel : Birkhäuser, 1987

Heinze 2008
HEINZE, WOLFGANG: Methodisches Entwerfen von Verkehrsflugzeugen.
URL: http://www.ifl.tu-bs.de/data/forschung/flugzeugbau/wolfgang.php (2008-03-11)

Jackson 2007
JACKSON, Peter (Ed.): Jane's all the World's Aircraft 2007/2008. Coulsdon, Surrey, UK : Jane's Information Group, 2007

Loftin 1980
LOFTIN, L.K., Jr.: Subsonic Aircraft: Evolution and the Matching of Size to Performance, NASA Reference Publication 1060, 1980

NASA 2003
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION: Supercritical Wing Technology, 2003. – URL: http://oea.larc.nasa.gov/PAIS/Concept2Reality/supercritical.html (2008-03-11)

Raymer 2006
RAYMER, Daniel P.: Aircraft Design: A Conceptual Approach. 4th Ed. Washington D.C. : AIAA, 2006

Rolls Royce 2006
ROLLS-ROYCE PLC: Aero Data. London, England : Rolls-Royce plc, 2006 – corporate literature

Roskam 1997
ROSKAM, Jan: Airplane Design. Part 1 : Preliminary Sizing of Airplanes, Ottawa, Kansas : Analysis and Research Corporation, 1997

Scholz 1999
SCHOLZ, DIETER: Dimensionierung (Preliminary Sizing). Hamburg University of Applied Sciences, Department of Automotive and Aeronautical Engineering, Lecture Notes, 1999 – URL: http://fe.profscholz.de (2007-10-05)

Seeckt 2004
SEECKT, KOLJA: Kabinenauslegung_mit_Pacelab_Cabin. Hamburg University of Applied Sciences, Department of Automotive and Aeronautical Engineering, Student Project, 2004 – URL: http://www.fzt.haw-hamburg.de/pers/Scholz/arbeiten/TextSeeckt.pdf (2008-03-11)

Trahmer 2004
TRAHMER, BERND: Rumpf-Aspekte beim Flugzeugentwurf. Hamburg University of Applied Sciences, Department of Automotive and Aeronautical Engineering, Lecture Notes, 2004 – URL: http://fe.profscholz.de (2008-03-11)

Appendix A – Detailed design process data

Table A.1 Design process data and final results of the preliminary sizing of the B777-200LR

Parameter		Flight mission: Maxim payload	Flight mission: Maximum fuel
Approach correlation factor	k_{app}	1.758 $(m/s^2)^{0.5}$	
Landing field length	s_{lfl}	1,676 m	
Approach speed	V_{app}	140 kt (= 72 m/s)	
Maximum landing lift coefficient	$C_{L,ml}$	2.6	
Max landing to max take-off mass ratio	$\frac{m_{ml}}{m_{mto}}$	0.642	
(Wing) aspect ratio	A	9.34	
Profile drag coefficient (take-off configuration)	$C_{D,P}$	0.053	
Oswald efficiency factor (landing configuration)	e	0.7	
Glide ratio in take-off configuration	E_{to}	8.35	
Number of engines	n_e	2	
Take-off field length	s_{tofl}	3350 m	
Take-off correlation factor	k_{to}	2.34 m^3/kg	
Maximum take-off lift coefficient	$C_{L,mto}$	1.88	
Profile drag coefficient (landing configuration)	$C_{D,P}$	0.081	
Glide ratio in landing configuration	E_l	7.85	
Correlation factor for max. glide ratio estimation	k_E	15.8	
Relative wetted area	$\frac{S_{wet}}{S_w}$	6.0	
Maximum glide ratio	$E_{\max}$	19.7	
Engine bypass ratio	μ, BPR	8.9	
Oswald efficiency factor (cruise configuration)	e	0.85	
Cruise Mach number	M_{cr}	0.84	
Ratio of cruise speed to minimum drag speed	$\frac{V}{V_{md}}$	0.952	
Cruise flight glide ratio	E	19.6	
Wing loading (at maximum take-off mass)	$\frac{m_{mto}}{S_w}$	**775 kg/m²**	

Thrust-to-weight ratio (at max. take-off mass)	$\frac{T_{to}}{m_{mto} \cdot g}$	**0.287**	
Type of aircraft	-	Long range	
Specific cruise flight fuel consumption	c_{cr} , SFC	15.26 mg/(Ns)	
Fuel density	ρ_f	803 kg/m^3	
Design range	R	7,500 NM	9,300 NM
Distance to alternate airport	$s_{to\_alternate}$	200 NM	200 NM
FAR Part 121-reserves	-	international	
Fuel fraction, engine start	$M_{ff,engine}$	0.99	
Fuel fraction, taxi	$M_{ff,taxi}$	0.99	
Fuel fraction, take-off	$M_{ff,to}$	0.995	
Fuel fraction, climb	$M_{ff,clb}$	0.98	
Fuel fraction, descent	$M_{ff,des}$	1.005 (0.99)*	
Relative operating empty mass	$\frac{m_{oe}}{m_{mto}}$	0.417	
Fuel fraction, cruise	$M_{ff,des}$	0.652	0.588
Fuel fraction, extra flight distance	$M_{ff,extra}$	0.968	0.963
Fuel fraction, loiter	$M_{ff,loiter}$	0.986	0.986
Fuel fraction, standard flight	$M_{ff,std}$	0.634	0.572
Fuel fraction, all reserves	$M_{ff,res}$	0.940	0.935
Fuel fraction, total	M_{ff}	0.596	0.535
Mission fuel fraction	$\frac{m_f}{m_{mto}}$	0.404	0.465
Number of passengers	n_{pax}	301	301
Cargo mass	m_{cargo}	34.7 t	11.5 t
Payload	m_{pl}	64.0 t	40.8 t
Zero fuel mass	m_{zf}	213.3 t	185.1 t
Maximum take-off mass	m_{mto}	**357.9 t**	**345.9 t**
Maximum landing mass	m_{ml}	229.8 t	222.1 t
Operating empty mass	m_{oe}	149.2 t	144.2 t
Mission fuel fraction, standard flight	m_f	144.6 t	160.8 t

Wing area	S_w	**462 m²**	**446 m²**
Take-off thrust, all engines	T_{to}	1,008 kN	974 kN
Take-off thrust, one engine	$\frac{T_{to}}{n_e}$	**504 kN**	**487 kN**
Needed fuel mass	$m_{f,needed}$	148.8 t	164.5 t
Needed fuel tank volume	$V_{f,needed}$	185.3 m^3	204.8 m^3
Fuel mass, all reserves	$m_{f,res}$	21.4 t	22.4 t
Validity check ($m_{ml} - (m_{mzf} + m_{f,res})$)	-	-5.0 t -> Fail	14.6 t -> Pass

* See Section 3.3.2 for explanation

Appendix B – PreSTo Screenshots

Note: Status of summer 2008 shown

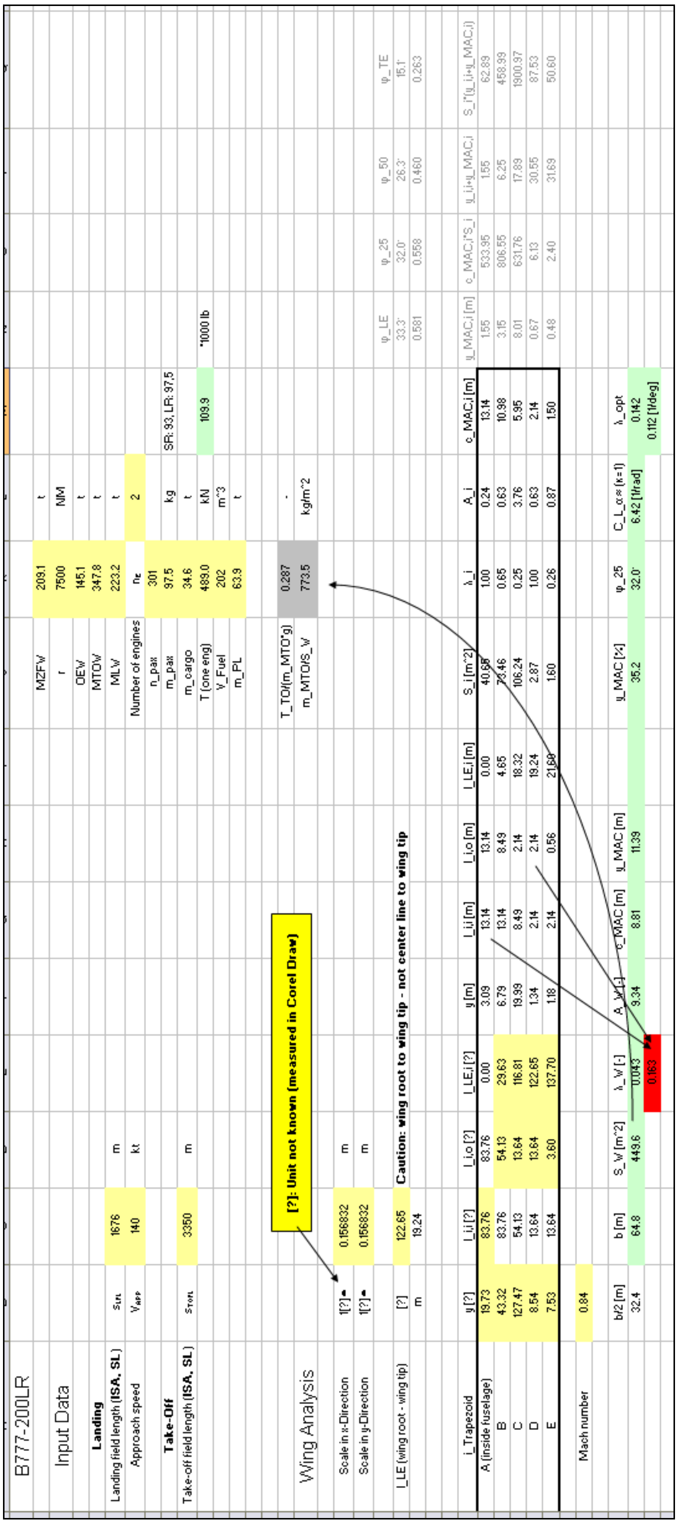


Fig B.1 Screenshot of PreSTo – Sheet "Ref AC Analysis", No. 1/2

	x	y	25%	25%
Center line	-5	0.0		
	27.16	0.00		
Body axis	-5.00	3.09		
	27.16	3.09	25%	25%
A	0.00	0.00	3.28	0.00
	13.14	0.00	3.28	3.09
	13.14	3.09	25%angle:	#DIV/0!
	0.00	3.09		
	0.00	0.00		
B	0.00	3.09	3.28	3.09
	13.14	3.09	6.77	9.89
	13.14	9.89	25%angle:	27.16°
	4.65	9.89		
	0.00	3.09		
C	4.65	9.89	6.77	9.89
	13.14	9.89	18.85	29.88
	20.46	29.88	25%angle:	31.15°
	18.32	29.88		
	4.65	9.89		
D	18.32	29.88	18.85	29.88
	20.46	29.88	19.77	31.22
	21.37	31.22	25%angle:	34.37°
	19.24	31.22		
	18.32	29.88		
E	19.24	31.22	19.77	31.22
	21.37	31.22	21.74	32.40
	22.16	32.40	25%angle:	59.02°
	21.60	32.40		
	19.24	31.22		

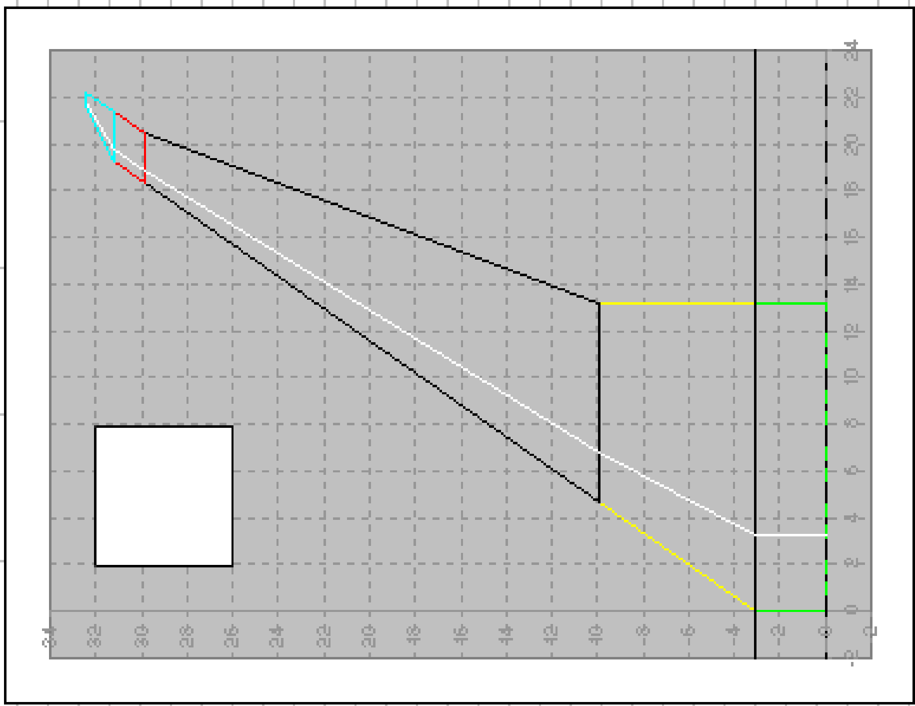


Fig B.2 Screenshot of PreSTo – Sheet "Ref AC Analysis", No. 2/2

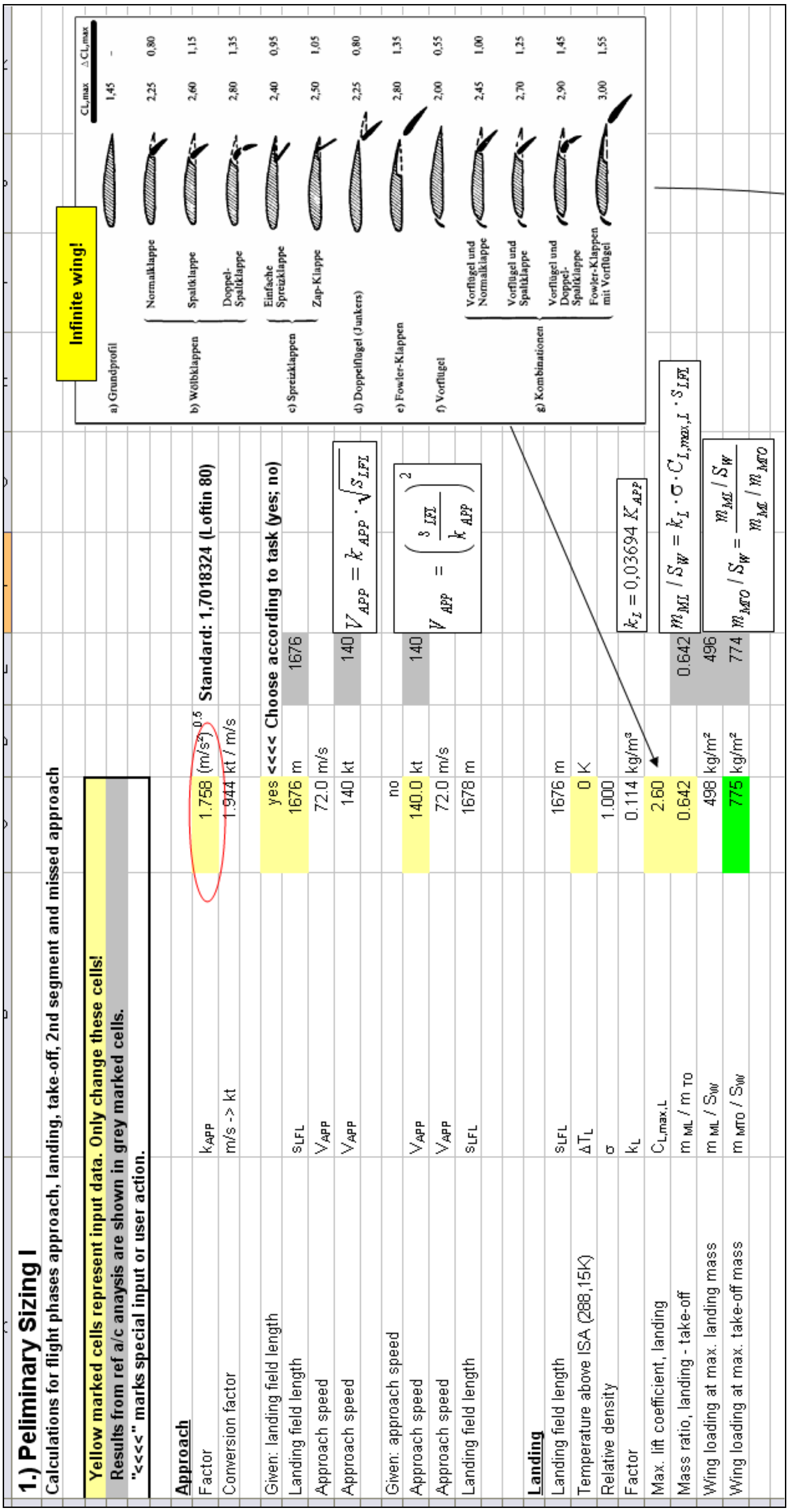


Fig B.3 Screenshot of PreSTo – Sheet "1.) Preliminary Sizing I", No. 1/3

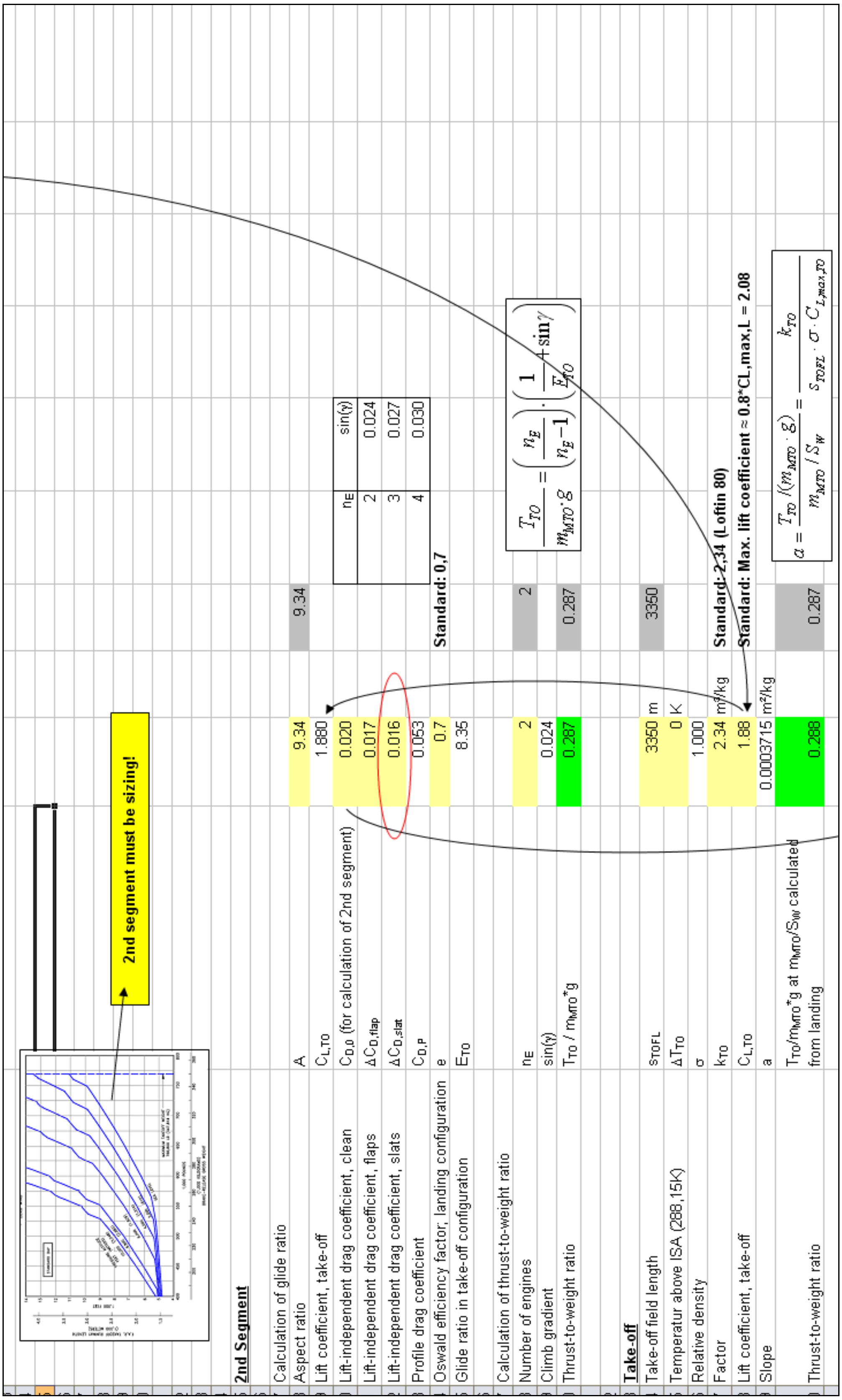
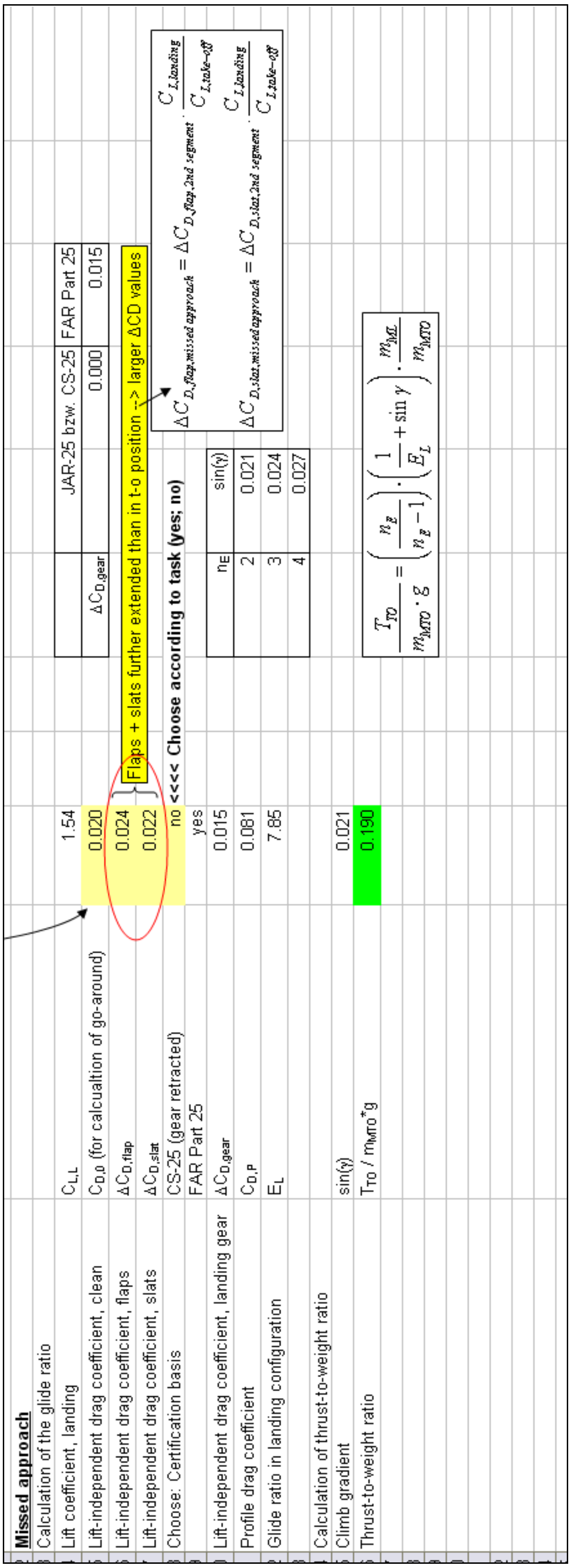


Fig B.4 Screenshot of PreSTo – Sheet "1.) Preliminary Sizing I", No. 2/3



Missed approach		
Calculation of the glide ratio		
Lift coefficient, landing	$C_{L,L}$	1.54
Lift-independent drag coefficient, clean	$C_{D,0}$ (for calcualtion of go-around)	0.020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0.024
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0.022
Choose: Certification basis	CS-25 (gear retracted)	no
	FAR Part 25	yes
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0.015
Profile drag coefficient	$C_{D,P}$	0.081
Glide ratio in landing configuration	E_L	7.85
Calculation of thrust-to-weight ratio		
Climb gradient	sin(γ)	0.021
Thrust-to-weight ratio	T_{TO} / m_{MTO}*g	0.190

Flaps + slats further extended than in t-o position --> larger ΔCD values

<<<< Choose according to task (yes; no)

	JAR-25 bzw. CS-25	FAR Part 25
$\Delta C_{D,gear}$	0.000	0.015

n_E	sin(γ)
2	0.021
3	0.024
4	0.027

$$\Delta C_{D,flap,missed\,approach} = \Delta C_{D,flap,2nd\,segment} \cdot \frac{C_{L,landing}}{C_{L,take-off}}$$

$$\Delta C_{D,slat,missed\,approach} = \Delta C_{D,slat,2nd\,segment} \cdot \frac{C_{L,landing}}{C_{L,take-off}}$$

$$\frac{T_{TO}}{m_{MTO} \cdot g} = \left(\frac{n_E}{n_E - 1}\right) \cdot \left(\frac{1}{E_L} + \sin\gamma\right) \cdot \frac{m_{ML}}{m_{MTO}}$$

Fig B.5 Screenshot of PreSTo – Sheet “1.) Preliminary Sizing I”, No. 3/3

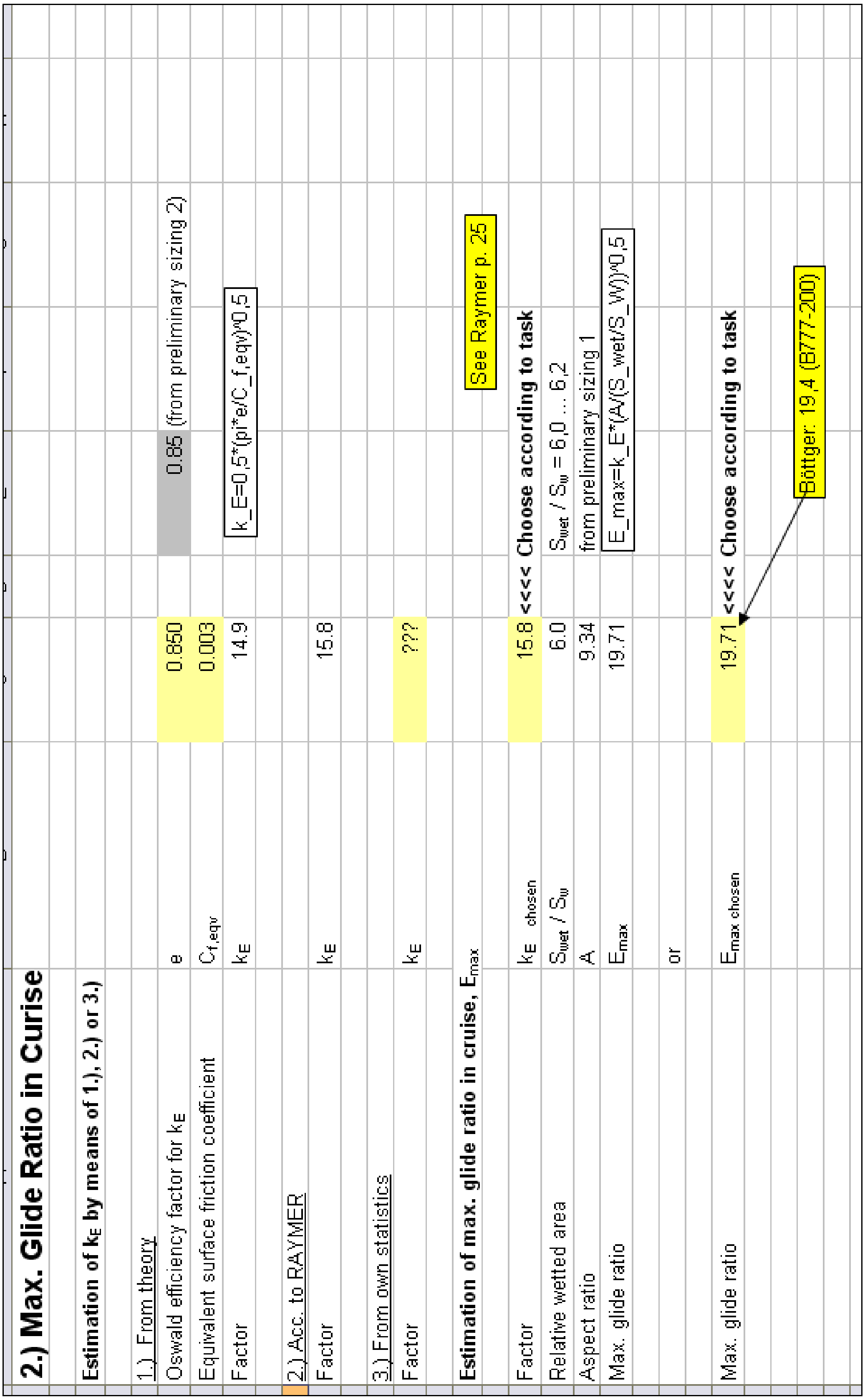
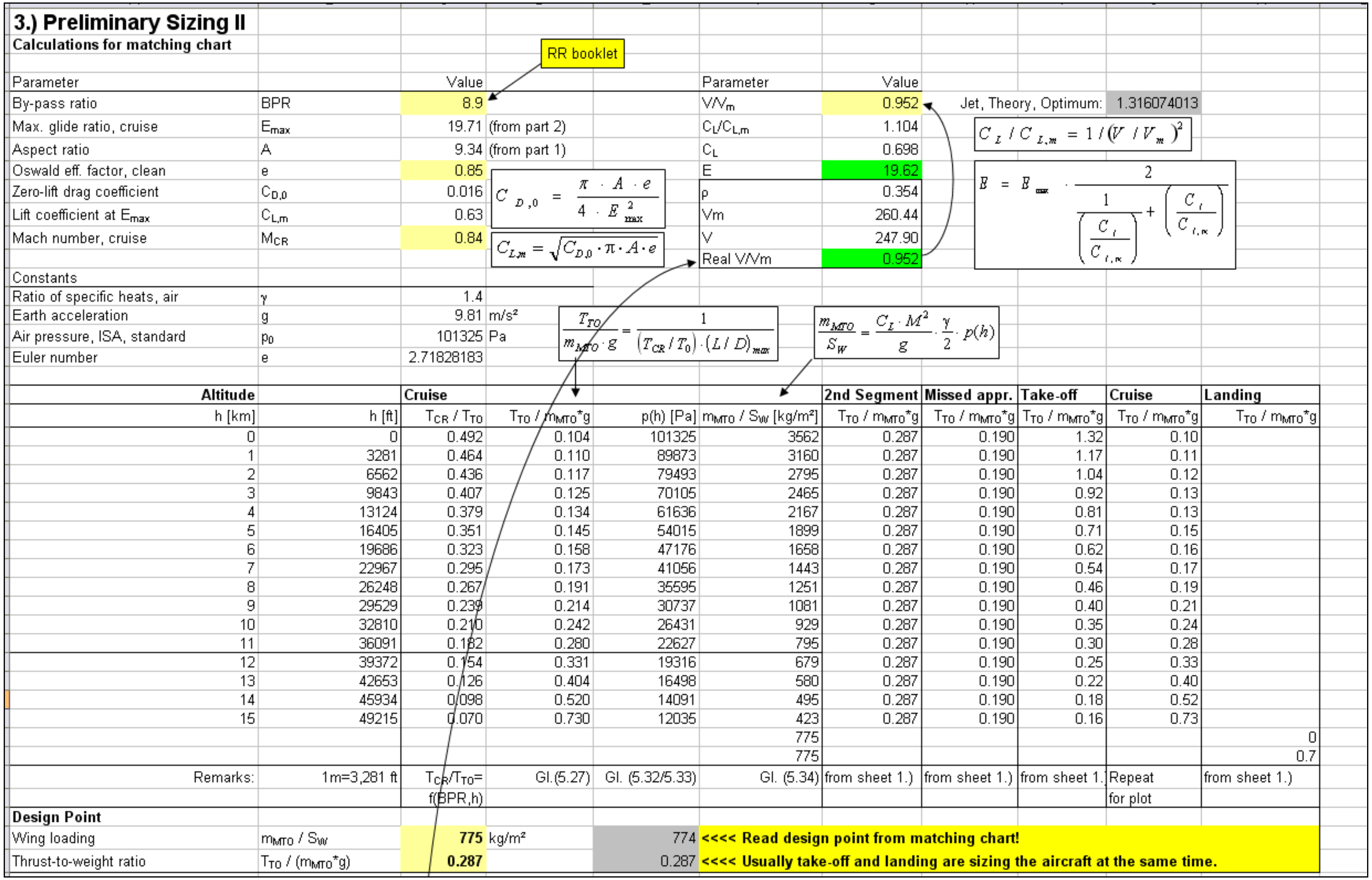


Fig B.6 Screenshot of PreSTo – Sheet "2.) Max. Glide Ratio in Cruise"



3.) Preliminary Sizing II

Calculations for matching chart

RR booklet

Parameter		Value		Parameter	Value
By-pass ratio	BPR	8.9		V/V_m	0.952
Max. glide ratio, cruise	E_{max}	19.71	(from part 2)	$C_L/C_{L,m}$	1.104
Aspect ratio	A	9.34	(from part 1)	C_L	0.698
Oswald eff. factor, clean	e	0.85		E	19.62
Zero-lift drag coefficient	$C_{D,0}$	0.016		ρ	0.354
Lift coefficient at E_{max}	$C_{L,m}$	0.63		Vm	260.44
Mach number, cruise	M_{CR}	0.84		V	247.90
				Real V/Vm	0.952

Jet, Theory, Optimum: 1.316074013

$$C_{D,0} = \frac{\pi \cdot A \cdot e}{4 \cdot E_{max}^2}$$

$$C_{L,m} = \sqrt{C_{D,0} \cdot \pi \cdot A \cdot e}$$

$$C_L / C_{L,m} = 1/(V/V_m)^2$$

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

Constants			
Ratio of specific heats, air	γ	1.4	
Earth acceleration	g	9.81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Euler number	e	2.71828183	

$$\frac{T_{TO}}{m_{MTO} \cdot g} = \frac{1}{(T_{CR}/T_0) \cdot (L/D)_{max}}$$

$$\frac{m_{MTO}}{S_W} = \frac{C_L \cdot M^2}{g} \cdot \frac{\gamma}{2} \cdot p(h)$$

Altitude		Cruise				2nd Segment	Missed appr.	Take-off	Cruise	Landing
h [km]	h [ft]	T_{CR}/T_{TO}	T_{TO}/m_{MTO}*g	p(h) [Pa]	m_{MTO}/S_W [kg/m²]	T_{TO}/m_{MTO}*g	T_{TO}/m_{MTO}*g	T_{TO}/m_{MTO}*g	T_{TO}/m_{MTO}*g	T_{TO}/m_{MTO}*g
0	0	0.492	0.104	101325	3562	0.287	0.190	1.32	0.10	
1	3281	0.464	0.110	89873	3160	0.287	0.190	1.17	0.11	
2	6562	0.436	0.117	79493	2795	0.287	0.190	1.04	0.12	
3	9843	0.407	0.125	70105	2465	0.287	0.190	0.92	0.13	
4	13124	0.379	0.134	61636	2167	0.287	0.190	0.81	0.13	
5	16405	0.351	0.145	54015	1899	0.287	0.190	0.71	0.15	
6	19686	0.323	0.158	47176	1658	0.287	0.190	0.62	0.16	
7	22967	0.295	0.173	41056	1443	0.287	0.190	0.54	0.17	
8	26248	0.267	0.191	35595	1251	0.287	0.190	0.46	0.19	
9	29529	0.239	0.214	30737	1081	0.287	0.190	0.40	0.21	
10	32810	0.210	0.242	26431	929	0.287	0.190	0.35	0.24	
11	36091	0.182	0.280	22627	795	0.287	0.190	0.30	0.28	
12	39372	0.154	0.331	19316	679	0.287	0.190	0.25	0.33	
13	42653	0.126	0.404	16498	580	0.287	0.190	0.22	0.40	
14	45934	0.098	0.520	14091	495	0.287	0.190	0.18	0.52	
15	49215	0.070	0.730	12035	423	0.287	0.190	0.16	0.73	
					775					0
					775					0.7
Remarks:	1m=3,281 ft	T_{CR}/T_{TO}= f(BPR,h)	Gl.(5.27)	Gl. (5.32/5.33)	Gl. (5.34)	from sheet 1.)	from sheet 1.)	from sheet 1.	Repeat for plot	from sheet 1.)

Design Point					
Wing loading	m_{MTO}/S_W	775	kg/m²	774	<<<< Read design point from matching chart!
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}$*g)	0.287		0.287	<<<< Usually take-off and landing are sizing the aircraft at the same time.

Fig B.7 Screenshot of PreSTo – Sheet “3.) Matching Chart”, No. 1/2

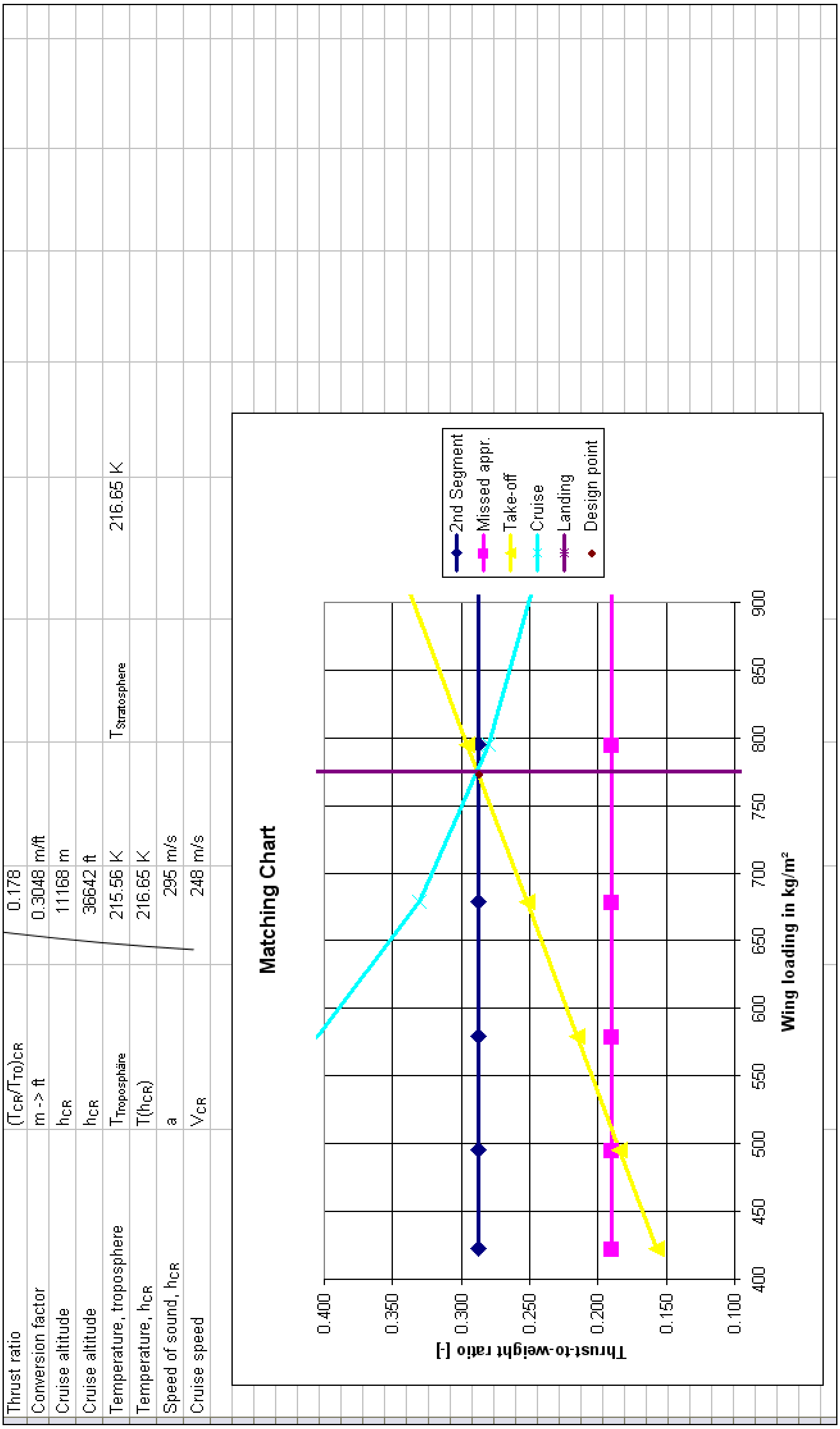


Fig B.8 Screenshot of PreSTo – Sheet "3.) Matching Chart", No. 2/2

4.) Payload-Range Diagram

Calculations for cruise, matching chart, fuel mass, operating empty mass
and aircraft parameters m_{MTO}, m_L, m_{OE}, S_W, T_{TO}, ...

Choose: type of a/c	short / medium range	no		**<<<< Choose according to task**				
	long range	yes		in kg	Short- and Medium Range	Long Range		
Mass: Passengers, including baggage	m_{PAX}	97.5	kg	m_{PAX}	93.0	97.5		
Spec.fuel consumption, cruise	SFC_{CR}	15.26	mg/N/s	**Typical value: 16 mg/(N*s)**				
Fuel density	ρ_F	803	kg/m³	**Typical value: 800 kg/m³ (Kerosin)**				
Breguet-Factor, cruise	B_s	32485.657	km					
Breguet-Factor, flight time	B_t	131044	s					
Breguet-Factor, flight time	B_t	36.4	h					

15,43 from Jenkinson for GE90-**85B** (0,545 lb/hr/lb)
15,26 from Rolls-Royce Booklet f. GE90-**110/115B** (0.539 lb/hr/lb)
14,95 from Rolls-Royce Booklet f. GE90-**75...94B** (0.528 lb/hr/lb)

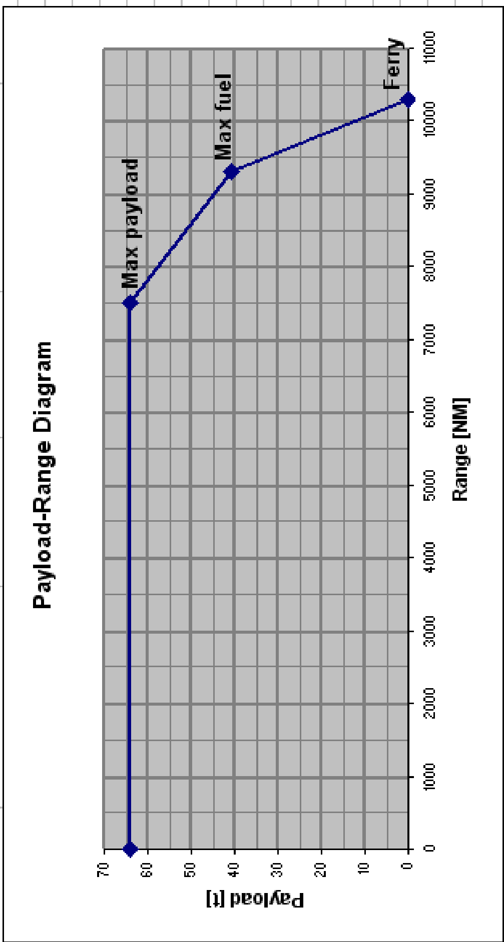
From B777-200LR -300ER airport planning manual p.9

Design points definitions

Point 1: Maximum payload								
Design range	R	7500	NM	**Reserve flight distance:**				
Design range	R	13890	km	FAR Part 121	s_{res}			
Distance to alternate	$s_{to\_alternate}$	200	NM	domestic	370.4	km		
Distance to alternate	$s_{to\_alternate}$	370.4	km	international	1064.9	km	pl	R
Chose: FAR Part121-Reserves?	domestic	no					64.0	0
	international	yes		**Extra time:**			64.0	7500
Extra-fuel for long range		5.0%		FAR Part 121	t_{loiter}		40.8	9300
Extra flight distance	s_{res}	1065	km	domestic	2700	s	0	10300
Loiter time	t_{loiter}	1800	s	international	1800	s		
Point 2: Maximum fuel								
Design range	R	9300	NM	**Reserve flight distance:**				
Design range	R	17224	km	FAR Part 121	s_{res}			
Distance to alternate	$s_{to\_alternate}$	200	NM	domestic	370.4	km		
Distance to alternate	$s_{to\_alternate}$	370.4	km	international	1231.58	km		
Chose: FAR Part121-Reserves?	domestic	no						
	international	yes		**Extra time:**				
Extra-fuel for long range		5.0%		FAR Part 121	t_{loiter}			
Extra flight distance	s_{res}	1232	km	domestic	2700	s		
Loiter time	t_{loiter}	1800	s	international	1800	s		

Fig B.9 Screenshot of PreSTo – Sheet "4.) PL-R Diagram", No. 1/3

Point 3: Ferry range			
Design range	R	10300	NM



Fuel-fraction, engine start	$M_{ff,engine}$	0.990	**<<<< Copy**
Fuel-fraction, taxi	$M_{ff,taxi}$	0.990	**<<<< values**
Fuel-fraction, take-off	$M_{ff,TO}$	0.995	**<<<< from**
Fuel-fraction, climb	$M_{ff,CLB}$	0.980	**<<<< table**
(Fuel-fraction, descent)	($M_{ff,DES}$)	(0.990)	**<<<< on the**
Fuel-fraction, landing	$M_{ff,L}$	0.992	**<<<< right !**
Factor to account for descent included in design range		1.60%	
Adjusted fuel-fraction, descent	$M_{ff,DES}$	1.00500	1.00584

Phase	M_{ff} per flight phases [Roskam]	
	transport jet	business jet
engine start	0.990	0.990
taxi	0.990	**0.995**
take-off	0.995	0.995
climb	0.980	0.980
descent	0.990	0.990
landing	0.992	0.992

Fig B.10 Screenshot of PreSTo – Sheet "4.) PL-R Diagram", No. 2/3

Calculation of aircraft parameters

Parameter	Symbol	Max payload	Max fuel	Ref a/c (max. values)	Unit	
Realtive operating empty mass	m_{OE}/m_{MTO}	0.528	acc. to Loftin			
Realtive operating empty mass	m_{OE}/m_{MTO}	xxx	from statistics (if given)			
Realtive operating empty mass	m_{OE}/m_{MTO}	0.417	0.417			
Fuel-Fraction, cruise	$M_{ff,CR}$	0.652	0.588			
Fuel-Fraction, extra flight distance	$M_{ff,RES}$	0.968	0.963			
Fuel-Fraction, loiter	$M_{ff,loiter}$	0.986	0.986			
Fuel-Fraction, standard flight	$M_{ff,std}$	0.634	0.572			
Fuel-Fraction, all reserves	$M_{ff,res}$	0.940	0.935			
Fuel-Fraction, total	M_{ff}	0.596	0.535			
Mission fuel fraction	m_F/m_{MTO}	0.404	0.465			
Number of passengers	n_{PAX}	301	301	301		
Cargo mass	m_{cargo}	34.7	11.5	34.6	t	
Payload	m_{PL}	64.0	40.8	63.9	t	
Zero-fuel mass	m_{ZF}	213.3	185.1	209.1	t	
Take-off mass	m_{MTO}	357.9	345.9	347.8	t	
Landing mass	m_{ML}	229.8	222.1	223.2	t	
Operating empty mass	m_{OE}	149.2	144.2	145.1	t	
Mission fuel fraction, standard flight	m_F	144.6	160.8		t	
Wing area	S_w	462	446	450	m²	
Take-off thrust	T_{TO}	1008	974	978	kN	**all engines together**
T-O thrust of ONE engine	T_{TO} / n_E	504	487	489	kN	**one engine**
T-O thrust of ONE engine	T_{TO} / n_E	113.3	109.5	110	* 1000 lb	**one engine**
Fuel mass, needed	$m_{F,erf}$	148.8	164.5	162.206	t	
Fuel volume, needed	$V_{F,erf}$	185.3	204.8	202.0	m³	
Fuel mass, all reserves	$m_{F,res}$	21.4	22.4	(MLW - MZFW) 14.1	t	
Check of assumptions	m_ML > m_ZF + m_F,res ?	no	yes			
	Difference	-5.0	14.6		t	

Increase value mML/mMTO in table '1.) Preliminary Sizing I' !

$$M_{ff,cr} = e^{-\frac{R}{B_s}} \qquad M_{ff,loiter} = e^{-\frac{t_{loiter}}{B_t}} \qquad M_{ff,RES} = e^{-\frac{s_{res}}{B_s}}$$

$$M_{ff,std} = M_{ff,cr} \cdot M_{ff,to} \cdot M_{ff,clb} \cdot M_{ff,des} \cdot M_{ff,l}$$

$$M_{ff,res} = M_{ff,extra} \cdot M_{ff,loiter} \cdot M_{ff,clb} \cdot M_{ff,des}$$

$$M_{ff} = M_{ff,std} \cdot M_{ff,res}$$

(PL/R)-Diagram: 410.000 lb = 185976 kg (=m_PL+m_OE)

185976 kg - 145149 kg (m_OE) = 40827 kg

40827 kg - 301 * 97,5 kg = 11479,5 kg

Fig B.11 Screenshot of PreSTo – Sheet "4.) PL-R Diagram", No. 3/3