Master Thesis

Revealing the Technical Secrets of the 40 Most Used Passenger Aircraft with Reverse Engineering

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Abstract

Purpose – To provide the aeronautical community with harmonized parameters of the most used passenger jets with more than 50 seats taken from a wide selection of publically available data sources. In addition, the three most important hidden (or secret) parameters are added: maximum lift coefficient (for landing and take-off), maximum glide ratio, and Specific Fuel Consumption (SFC).
Approach – The Excel-based tool "Passenger Jet Reverse Engineering" was used to reveal the secret parameters of each aircraft. Using the program's verification tool, the numbers obtained from reverse engineering could be compared to eliminate modeling insufficiencies until only a relatively small deviation was left.
Findings – The most used 47 aircraft (with first flight between 1979 and 2017) account already for more than 90% of all aircraft in service or on order based on numbers from 2017. Then 43 aircraft were evaluated. Maximum lift coefficients were obtained between 2.0 and 3.8 of which only 75% is used on average for take-off. The maximum glide ratio varied between 14 and 22. It increased with 0.11 per year (based on the new or the derivative aircraft's date of first flight). Reverse engineering revealed SFC between 11 mg/Ns and 19 mg/Ns.
Research limitations – Reverse engineering in aircraft design is based on preliminary sizing methods, which include statistical values e.g. for some of the mission segment fuel fractions.
Practical implications – Statistical trends can now be obtained to the benefit of preliminary aircraft design calculations.
Social implications – The discussion about aviation implications is facilitated as secret numbers have come to light.
Originality – Reverse engineering has not been applied to such a large number of passenger aircraft before.

HAW HAMBURG

DEPARTMENT OF AUTOMOTIVE AND AERONAUTICAL ENGINEERING

Revealing the Technical Secrets of the 40 Most Used Passenger Aircraft with Reverse Engineering

Task for a Master Thesis

Background

In aircraft design at the Hamburg University of Applied Sciences, an aircraft had to be redesigned in every exam for almost 20 years. To set the examination, manual reverse engineering was necessary to reveal the unknown (secret) technology parameters. These parameters are in particular: the lift coefficient during landing and take-off, the maximum glide ratio, and the specific fuel consumption in cruise. In the frame of a thesis entitled "Reverse Engineering of Passenger Jet Classified Parameters" an Excel-based tool "Passenger Jet Reverse Engineering" (PJRE) was created and 9 different conventional and unconventional aircraft were examined. In another thesis "Case Studies for Reverse Engineering in Passenger Aircraft Design" the previously developed tool was used for 8 new case studies.

Task

Task is the application of PJRE to about 40 most used passenger aircraft in order to cover 90% of the aircraft in service or on order. PJRE should be used to reveal the mentioned parameters kept otherwise secret. The objective is to provide the aviation community with a reliable catalogue of aircraft parameters and general information. The values determined with PJRE have to be checked for plausibility. These points should be taken into account:

- Consideration of a wide range of sources for the reliable selection of input parameters.
- Brief introduction to preliminary sizing.
- Brief introduction to reverse engineering.
- Brief description of PJRE and the method.
- Aviation market research of the most used passenger aircraft.
- Presentation of the passenger aircraft individually.
- Presentation of the results of reverse engineering.
- Discussion of the results and extraction of conclussions.

The report has to be written in English based on German or international standards on report writing.

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List of Symbols

A	Aspect ratio
A_{eff}	Effective aspect ratio
a	Speed of sound
B_s	Breguet factor, distance
B_t	Breguet factor, time
b	Wing span
C_D	Drag coefficient
$C_{D,i}$	Induced drag coefficient
$C_{D.0}$	Drag coefficient at zero lift
C_L	Lift coefficient
$(C_{L,max})_{base}$	Maximum lift coefficient of the base of an airfoil
$C_{L,MAX,TO}$	Maximum lift coefficient for take-off
$C_{L,MAX,L}$	Maximum lift coefficient for landing
$C_{L,md}$	Lift coefficient for minimum drag
c_{MAC}	Mean aerodynamic chord length
$\bar{c}_f$	Skin friction factor
c_t	Tip chord
c_r	Root chord
E	Aerodynamic efficiency
e	Oswald's span efficiency factor
g	Gravitational acceleration (9,81 m/s^2)
h	Altitude
k_{APP}	Factor for approach
k_E	Factor for aerodynamic efficiency
$k_{e,NP}$	Factor span efficiency for non-planar configurations
$k_{e,WL}$	Factor span efficiency for winglet
k_L	Factor for landing
k_{TO}	Factor for take-off
L	Temperature lapse rate (0,0065 K/m)
M	Mach number
M	Molar mass of dry air (0,0289644 kg/mol)
M_{ff}	Mission fuel fraction
m	Mass
$\dot{m}$	Fuel mass flow
m_{ML}/m_{MTO}	Relative maximum landing mass
m/S_W	Wing loading
n_E	Number of engines
p	Local atmospheric pressure
p_0	Standard atmospheric pressure at SL (101325 Pa)

q	Dynamic pressure
R	Range
R	Universal gass constant (8,31447 J/mol/K)
Re	Reynolds number
SFC	Specific fuel comsumption
S_{ref}	Reference area
S_W	Wing area
S_{wet}	Wetted area
s	Distance / length
s_{LFL}	Landing field length
s_{TOFL}	Take-off field length / reference field length
T	Thrust
T_0	Standard temperature at SL (288,15 K)
$T/(m \cdot g)$	Thrust-to-weight ratio
t	Time
t	Airfoil thickness
t/c	Relative thickness
V	Volume
V	Speed
V_{APP}	Approach speed
V_{md}	Speed for minimum drag
V_S	Stall speed
V_1	Take-off decision speed
V_2	Take-off safety speed
$x_{(y\_c),max}$	Position of maximum camber
$x_{t,max}$	Position of maximum thickness
$(y_c)_{max}/c$	Camber

Greek Symbols

ΔX (DELTA)	Additional value
Δx (DELTA)	Correction term
Δy	Leading edge sharpness parameter
γ (gamma)	Ratio for air specific heat (1,4)
γ_{CLB} (gamma)	Climb gradient
γ_{MA} (gamma)	Missed approach climb gradient
η (eta)	Efficiency
Λ (LAMBDA)	Sweep angle
λ (lambda)	Taper

μ (mu)	Bypass ratio
μ (mu)	Dynamic viscosity
φ (phi)	Sweep angle
π (pi)	3,141592653589793…
ρ (rho)	Density
σ (sigma)	Relative air density

Subscripts

25	25% Chord
CLB	Climb
CR	Cruise
DES	Descend
E	Engine
F	Fuel
f	flap
H.L.	Hinge line
L	Landing
LE	Leading edge
LFL	Landing field length
MA	Missed approach
MAC	Mean Aerodynamic Chord
ML	Maximum Landing
MTO	Maximum Take-Off
max	Maximum
OE	Operating empty
PL	Payload
RES	Reserve
s	Slat
TO	Take-off
TOEF	Take-off field length
W	Wing

List of Abbreviations

AAC	Aircraft Approach Category
ADG	Aircraft Design Group
ARC	Aerodrome Reference Code
BAe	British Aerospace
BWB	Blended Wing Body
CAD	Computer-aided Design
CEO	Current Engine Option
CFR	Code of Federal Regulations
CG	Certification Specification
DATCOM	Data Compendium
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations (certification specs)
FL	Flight level
HAW	Hochschule für Angewandte Wischenschaften
ICAO	International Civil Aviation Organization
ISA	International Standard Atmosphere
LR	Long range
MA	Missed Approach
MD	McDonnell Douglas
MTOW	Maximum Take-Off Weight
MZFW	Maximum Zero Fuel Weight
NACA	National Advisory Committee for Aeronautics
NEO	New Engine Option
OAPR	Overall Pressure Ratio
PAX	Passenger
PW	Pratt & Whitney
SFC	Specific Fuel Comsumption
SI	International System (Système Internationale)
SL	Sea Level
SR	Short Range
SUGAR	Subsonic Ultra Green Aircraft Research
RE	Reverse Engineering
TET	Turbine Entry Temperature
ULR	Ultra-Long Range
USA	United States of America
USAF	United States Air Force
VELA	Very Efficient Large Aircraft
LAMEA	Latin America, Middle East and Africa

List of Definitions

Camber
"Camber (noun) is the degree to which an aircraft wing or other aerofoil curves up from its front edge and down again to its back edge." (Allen 2006)

Comprehensive
"Comprehensive (adj) means covering completely or broadly." (Allen 2006)

Circuitous
"Circuitous (adj) indirect in route or method; roundabout." (Allen 2006)

Drag
"Drag (noun) is the retarding force acting on a body, e.g. an aircraft, moving through air, water or other fluid, parallel and opposite to the direction of motion." (Allen 2006)

Flap
"Flap (noun) is a movable control surface on an aircraft wing for increasing lift during take-off or drag during landing." (Allen 2006)

Lift
"Lift (noun) is the component of the aerodynamic force acting on an aircraft or wing that is perpendicular to the relative wind and usu constitutes the upward force opposing the pull of gravity." (Allen 2006)

Loiter
"Loiter (adj intrans) is to remain in an area for no obious reason." (Allen 2006)

Matching chart
A matching chart shows the two-dimensional relation between the wing loading and the thrust-to-weight ratio for landing, take-off, second segment, cruise and missed approach.

Slat
"Slat (noun) is a control surface along the leading edge of a wing that can be extended forward to create a gap (slot) to improve airflow." (Allen 2006)

Turbofan
"Turbofan (noun) is a jet engine with a turbofan. It refers to the fan that is directly connected to and driven by a turbine and is used to supply air for cooling, ventiliation or combustion." (Allen 2006)

Verification
"Verification (noun) is the act or instance of verifying." (Allen 2006)

Verify
"Verify (verb trans) to ascertain the truth, accuracy, or reality of something." (Allen 2006)

1 Introduction

1.1 Motivation

For competitive reasons manufacturers try to protect their product design with its inherent parameters. This is done to protect company know-how and to maintain a possible design advantage with respect to competing products. This principle is followed not only in case of military aircraft, but also for civil passenger jets. Parameters like maximum take-off mass are known as part of the certification process. Further parameters may be given, because they are uncritical or needed for aircraft operation. Other parameters like aerodynamic efficiency or engine efficiency are classified information. It would be beneficial to know such parameters to do own flight performance calculations or even redo a preliminary sizing of the aircraft under investigation. This can be done out of interest, educational exercise or for a more in depth case study. Knowing classified parameters would enable a comparison of various similar contemporary aircraft or to investigate the evolution of aircraft with their parameters throughout aviation history. Reverse Engineering is a legal possibility to acquire the knowledge withheld.

Reverse engineering, also called back engineering, is the process by which a man-made object is deconstructed to reveal its designs, architecture, code or to extract knowledge from the object. This process is carried out with the objective of obtaining information or a design from a product, in order to determine what its components are and how they interact with each other and what was the manufacturing process. Reverse engineering was born during the Second World War, when enemy armies seized war supplies such as airplanes or other war machinery to improve theirs through exhaustive analysis.

There are many reasons for performing reverse engineering in various fields. Although reverse engineering has its origins in the analysis of hardware for commercial or military advantage, the reverse engineering process, as such, is not concerned with creating a copy or changing the artifact in some way; it is only an analysis in order to deduce design features from products with little or no additional knowledge about the procedures involved in their original production. In some cases, the goal of the reverse engineering process can simply be a redocumentation of legacy systems. Even when the reverse-engineered product is that of a competitor, the goal may not be to copy them, but to perform competitor analysis.

Software reverse engineering can help to improve the understanding of the underlying source code for the maintenance and improvement of the software, relevant information can be extracted in order to make a decision for software development and graphical representations of the code can provide alternate views regarding the source code, which can help to detect and fix a software bug or vulnerability. Frequently, as some software develops, its design information and improvements are often lost over time, but this lost information can usually be recovered with reverse engineering.

The reverse engineering application never changes the functionality of the product that is the object of the application, but rather allows to obtain products that indicate how it has been built. Its realization allows to obtain the following benefits:

- Reduce the complexity of the system: trying to understand the system facilitates its maintenance, and the existing complexity decreases.
- Generate different alternatives: from the starting point of the process, mainly source code, graphic representations are generated, which facilitates their understanding.
- Recover and/or update lost information (changes that were not documented at the time): in the evolution of the system, changes are made that are not usually updated in the representations of the highest level of abstraction, for which recovery is used of design.
- Detect side effects: changes that can be made to a system can lead to unwanted effects; This series of anomalies can be detected by reverse engineering.
- Facilitate reuse: through reverse engineering, possible reuse components of existing systems can be detected, increasing productivity and reducing maintenance costs and risks.

1.2 Definitions

'Revealing the Technical Secrets of the 40 Most Used Passenger Aircraft with Reverse Engineering' is the title of this thesis. In this section, every term will be defined, using two descriptive English dictionaries; **Longman 2009** and **Allen 2006**.

Reveal

The term *reveal* is defined as follows (according to **Longman 2009**):

> *re·veal (verb [transitive]): to make known something that was previously secret or unknown.*

The plain meaning of this word serves exactly for the purpose of this title since we are about to calculate parameters that otherwise would remain unknown.

Technical

According to **Longman 2009**, the term *technical* is defined as follows:

> *tech·ni·cal (adjective): connected with knowledge of how machines work.*

The word has several meanings but the first one is the one that concers us since it is related to *machines*, given that the data that is going to be used and revealed is related to aircraft.

Secrets
According to **Longman 2009**, the term *secret* is defined as follows:

> *se·cret (adjective): known about by only a few people and kept hidden from others.*

In the context of this thesis, the few people that know the secrets would be the manufacturers, who will keep the parameters hidden from their competitors in order safeguard their interests.

Used
The present tense of the verb *to use* is defined by **Longman 2009** as follows:

> *Use (verb[transitive]): if you use a particular tool, method, service, ability etc, you do something with that tool, by means of that method etc, for a particular purpose*

In this case, the thing, tool or service that is used for a particular purpose is the aircraft. Particulary, the most used passenger aircraft will be studied throughout this thesis.

Passenger
The term *passenger* is defined as follows according to **Longman 2009**:

> *A pas·sen·ger (noun) is a person who travels in any vehicle (boat, aeroplane, car, etc.) but who is not the driver or anyone working there.*

A similar definition is provided by **Allen 2006**:

> *A passenger (noun) is somebody who travels in, but does not operate, a public or private conveyance.*

In the context of this thesis, both meanings of *passenger* can be taken literally. The focus lies on passenger aeroplanes only. This excludes cargo flights and military operations.

Aircraft
The term *aircraft* is defined as follows according to **Longman 2009**:

> *air·craft (noun [countable]): a plane or other vehicle that can fly*

This simple definition is enough to assure that aircrafts are going to be measured and weighted, specifically passenger airplanes.

Reverse
The term *reverse* is defined as follows (according to **Longman 2009**):

Re·verse (verb trans) is to change something, such as a decision, judgment or process so that it is the opposite of what it was before.

In this thesis, reverse has the meaning to change a calculation method in a way that the inputs become the outputs. Aircraft technology requires a big amount of parameters, therefore the term reverse cannot be taken literally in its meaning. Not every input becomes an output and vice versa. In this thesis, the reversing is done by aiming on specific parameters which has to become an output. All the other parameters are unchanged in there meaning and thus remain inputs.

Engineering
According to **Allen 2006**, the definition of the term *engineering* is as follows:

En·gi·neer·ing (noun) the application of science and mathematics by which the properties of matter and the sources of energy in nature are made useful to human beings in machines, structures, pro-cesses, etc.

This definition corresponds with the context of *engineering* in this thesis. Science and mathematics that are used, are the main tool for designing an aeroplane. The engineering in this thesis is pure theoretical engineering.

1.3 Objective of the Thesis

The main objective of this thesis is to provide the aviation community with a reliable catalogue of aircraft parameters and general information. The determination of the secret parameters opens up a multitude of possibilities as they are essential and fundamental basic values for many calculations in aircraft technology. In order for this catalogue to be competent and appealing to the community members, it must cover the vast majority of aircraft models and manufacturers. Here is where the first question arises: How many aircraft models it is necessary to study to cover a fairly broad spectrum of the market? Not only that but, which are the currently most sold and delivered commercial airplanes?

The answer comes from doing research on the sales of every aircraft ever manufacture. **DVB 2018** provides useful information about this field of study, describing the position of almost every commercial airplane in the aviation market, analysing how was its market impact and comparing it with its direct competitors. According to the aircrafts' sales, a ranking of the most used commercial airplanes can be elaborated and it turned out that, in order to cover the 90% of the current in service aircraft, just the first 40 aircraft must be taken into account.

The aim of this work is to determine the secret parameters of these 40 conventional passenger aircraft using the PJRE tool. In addition, it should be checked how reliable the results of the tool are by comparing them with results from the verification calculation. The secret parameters are estimated with certain methods in order to do the verification. The maximum lift coefficient for take-off and landing is calculated taking into account the aerodynamics of the high-lift contribution. Here, formulas according to **Bhatia 2010** are used. The verification uses an estimation method from **Scholz 2017a** for the maximum aerodynamic efficiency. The specific fuel consumption is calculated according to **Scholz 2016**. All these methods for verifying the secret parameters are also integrated in the PJRE tool. In other words, the tool delivers results for the secret parameters from the reverse engineering calculation as well as from the verification calculation.

Finally, an attempt on extracting some interesting conclusions and patterns has been made. Taking into account parameters like the first flight of each aircraft or its range, it would be interesting to find a logical evolution on the behavior of the revealed secret parameters such as the increase of the specific fuel consumption with range or the increase of the aerodynamic efficienty with the date of the first flight.

1.4 Literature Review

The most important source is the Master's thesis **De Grave 2017** as well as the Master's thesis **Cheema 2019**. The focus of these master's thesis is a detailed description and use of the PJRE tool. All important information on the structure and use of the tool was taken from these works. In the master's thesis, the formulas for the secret parameters are also derived using the reverse engineering method. In addition, 9 different conventional and unconventional aircraft have already been examined in **De Grave 2017** master's thesis and 8 conventional aircraft in the case of **Cheema 2019** master's thesis.

Fort the aviation market research, **DVB 2018** is the main source. It provides useful information about every commercial aircraft, wheather if it is a passenger aircraft or a freighter. For each airplane, a detailed description of its position in the aviation market is provided, as well as relevant sales information, such as the in service and on order number of aircrafts of each model, which is key to carry out the research of the most commercial aircraft. Further information is also available such us the number of operators, the first flight, the class, the seat capacity, the range and the engine option, which will be useful to decide the engine thrust when searching the public parameters of each aircraft.

The books **Jane's 2007**, **Jane's 2008**, **Roux 2007a** and **Roux 2007b** were used to research the input parameters for the PJRE tool. Besides these books, the aircraft characteristic for airport planning (**Boeing 2020**, **Airbus 2020**, **Bombardier 2020**, **Embraer 2020** and **ATR 2020**) proved to be reliable and updated sources of information, as well as the website for the book Civil Jet Aircraft Design by L. Jenkinson, P. Simkin and D. Rhodes (**Jenkinson 2019a** and **Jenkinson 2019b)** which contains information about all required input parameters. Detailed and reliable data can be obtained from these sources. In this thesis, the remaining sources for researching the input parameters are listed again.

The lecture script according to **Scholz 2015** is used again and again in various places throughout the work. Most of the information from this script is used for preliminary sizing of an aircraft, along with **Loftin 1980** which uses the same five subsections: landing, take-off, missed approach, second segment and cruise.

1.5 Structure of the Work

This thesis has associated published data in Harvard Dataverse and is divided into the following sections:

Chapter 2 explains the state of the art. As such, the current situation of the topic that is going to be discuss and analyzed is described. The specific content of this chapter summerize the previous work of **De Grave 2017** and **Cheema 2020**.

Chapter 3 explains how to carry out one of the most important tasks: the data research. So as to the collected information to be as detailed and reliable as possible, some useful piece of advise regarding sources of information (such as **Jane's 2007**, **Roux 2007**or **Jenkinson 2019**) is given.

Chapter 4 makes an overview on the aviation market, explaining trends and focusing deeper in the commercial aviation market. In addition, a more comprehensive study of the commercial aircraft sales relying on **DVB 2018** is carried out in order to unravel which are the most used passenger aircraft.

Chapter 5 explains the most important part of this thesis. Every aircraft that is object of this study is analyzed individually regarding its position in the aviation market, the sales and their competitors. Finally, the parameters that are necessary to run the Excel-based tool are shown and the secret parameters are revealed.

Chapter 6 discusses the reliability and accuracy of the results obtained with the Excel-based tool and attempts to extract useful conclusions based on the evolution of the secret parameters in chronological order, looking for trends and patterns graphically.

Appendix A shows the results of the program 1.RevEng_737-800.xlms
Appendix B shows the results of the program 2.RevEng_A320-200.xlsm
Appendix C shows the results of the program 3.RevEng_A320-200Neo.xlsm

Appendix D shows the results of the program 4.RevEng_737-8.xlsm
Appendix E shows the results of the program 5.RevEng_A321-200.xlsm
Appendix F shows the results of the program 6.RevEng_A321-200 Neo.xlsm
Appendix G shows the results of the program 7.RevEng_A319-100.xlsm
Appendix H shows the results of the program 8.RevEng_737-700.xlsm
Appendix I shows the results of the program 9.RevEng_777-300ER.xlsm
Appendix J shows the results of the program 10.RevEng_A330-300.xlsm
Appendix K shows the results of the program 11.RevEng_787-9.xlsm
Appendix L shows the results of the program 12.RevEng_A350-900.xlsm
Appendix M shows the results of the program 13.RevEng_A330-200.xlsm
Appendix N shows the results of the program 14.RevEng_190.xlsm
Appendix O shows the results of the program 15.RevEng_175.xlsm
Appendix P shows the results of the program 17.RevEng_737-900ER.xlsm
Appendix Q shows the results of the program 18.RevEng_CRJ200.xlsm
Appendix R shows the results of the program 19.RevEng_767-300.xlsm
Appendix S s hows the results of the program 20.RevEng_CRJ900.xlsm
Appendix T shows the results of the program 21.RevEng_ERJ-145.xlsm
Appendix U shows the results of the program 22.RevEng_787-8.xlsm
Appendix V shows the results of the program 23.RevEng_777-200ER.xlsm
Appendix W shows the results of the program 24.RevEng_MD-83.xlsm
Appendix X shows the results of the program 25.RevEng_757-200.xlsm
Appendix Y shows the results of the program 26.RevEng_A380-800.xlsm
Appendix Z shows the results of the program 28.RevEng_CRJ700.xlsm
Appendix AA shows the results of the program 29.RevEng_C919.xlsm
Appendix AB shows the results of the program 33.RevEng_MRJ90.xlsm
Appendix AC shows the results of the program 35.RevEng_737-300.xlsm
Appendix AD shows the results of the program 36.RevEng_A350-1000.xlsm
Appendix AE shows the results of the program 39.RevEng_CS300.xlsm
Appendix AF shows the results of the program 40.RevEng_767-300F.xlsm
Appendix AG shows the results of the program 41.RevEng_ARJ21-700.xlsm
Appendix AH shows the results of the program 42.RevEng_ARJ21-900.xlsm
Appendix AI shows the results of the program 43.RevEng_787-10.xlsm
Appendix AJ shows the results of the program 44.RevEng_747-400.xlsm
Appendix AK shows the results of the program 45.RevEng_737-500.xlsm
Appendix AL shows the results of the program 46.RevEng_777F.xlsm
Appendix AM shows the results of the program 47.RevEng_195.xlsm
Appendix AN shows the results of the program 48.RevEng_717-200.xlsm
Appendix AO shows the results of the program 49.RevEng_737-400.xlsm
Appendix AP shows the results of the program 50.RevEng_A300.xlsm
Appendix AQ shows the results of the program 51.RevEng_747-8.xlsm

2 State of the Art

The Excel-based tool "Passenger Jet Reverse Engineering" (PJRE) for determining the secret parameters is based on the reverse engineering method. More precisely, theoretical reverse engineering was used to develop formulas for the secret parameters. For this, well-known formulas from the dimensioning of aircraft from the aircraft design subject were used. The basic knowledge of aircraft design will be explained very briefly in this thesis. If necessary, the lecture notes **Scholz 2015** are recommended. The work by **De Grave 2017** also summarizes the most important components of the lecture on the subject of dimensioning.

2.1 Aircraft Preliminary Sizing

The aircraft development consists of several phases: project phase, definition phase and development phase. The project phase consists of the dimensioning and design activities. This means that, among other things, market analysis is carried out, configurations are found and engines are selected.

The most important design parameters are determined in the dimensioning of the aircraft. These include the take-off mass, the fuel mass, the operating empty mass, the wing area and the take-off thrust. The configuration and geometry are defined in the draft.

Requirements and design parameters are parameters of aircraft design. The requirements for payload, Mach number, range, landing and take-off distance as well as the climb gradient in the 2nd segment and missed approach must be given at least at the beginning of the aircraft design.

Furthermore, boundary conditions, which are derived from approval regulations and technology limits, must be observed. Since this study focuses only on jet powered aircrafts, two distinctions are made in the regulations which an aeroplane has to meet to obtain a certification. For light jets (weights less than 12 500 lb or 5700 kg) FAR Part 23 or CS-23 applies to obtain a certification. For large jet powered aeroplanes FAR Part 25 or CS-25 is applied. The EASA-CS-25 is applied in this case because the emphasis is placed on large aeroplanes. The EASA developed the Certification Specification (CS) which are quite similar to the FAR, the rules developed by the Federal Aviation Administration (FAA, United States of America).

The preliminary sizing consists out of five different parts: landing, take-off, second segment, missed approach and cruise. For each of them, certain input values are necessary and the aircraft design parameters are the output.

The method to find the thrust-to-weight ratio and the wing loading for every section will be briefly explaned, according to **Scholz 2015** and **Loftin 1980**. In the end, the relation between the thrust-to-weight ratio and the wing loading of every part will be plotted in a 'matching chart'. This chart makes it possible to visualise the design point. In the end, the aircraft design parameters are calculated according to the design point.

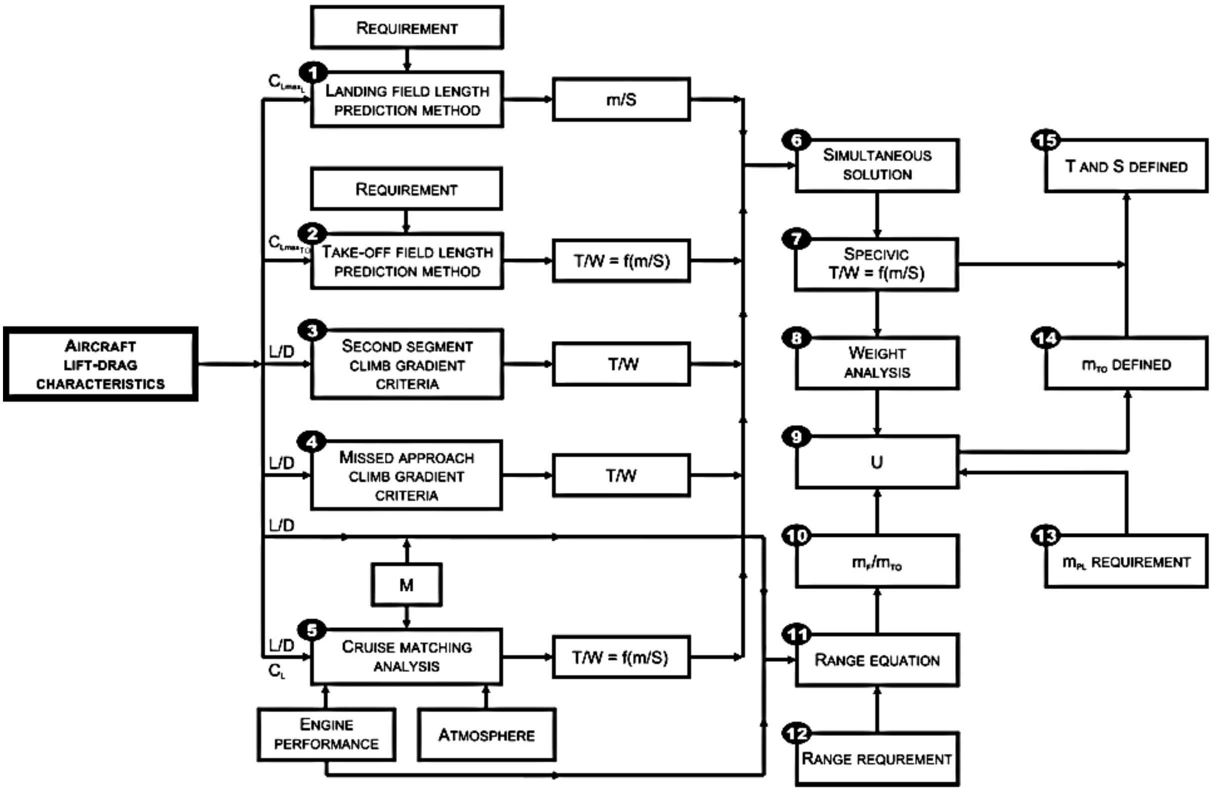


Figure 2. 1 Aircraft-sizing flow diagram for preliminary sizing for jet powered aircraft (**Scholz 2015** based on **Loftin 1980**)

The aircraft preliminary sizing is widely explained in detail in **De Grave 2017**. Each one of the parts is analyzed and provided with the necessary equations to explain mathematically the aircraft sizing that will be submitted to the reverse process in the next section in order to turn the process around and develop the Excel-based tool.

2.2 Reverse Engineering

Common specifications for commercial aeroplanes are easily to find, but there are a few exceptions. These exceptions are called “the companies’ secrets”. These parameters are not released by the design company because that way everybody could produce duplicates of the design and all the investments of research, work and money could be abused by third parties. But there is a way to find these parameters. By uniting the knowledge of preliminary sizing and reverse engineering, a good approximation of these parameters can be made. These parameters are the maximum lift coefficient for landing and take-off, the maximum aerodynamic efficiency and the specific fuel consumption.

The aim is to dissect a designed aeroplane using reverse engineering. By doing this, specific parameters are revealed which, in most designs, are concealed by the designing company. Since this case is a study, guided by the Hochschule für Angewandte Wissenschaften Hamburg, an exception on intellectual ownership is applicable. This means that it is not necessary to ask the owners of the copyright for permission to reproduce or publicly share the protected information.

The reverse engineering starts with the research of the product. The next step is the build-up of the black box which consists out of the inputs and outputs of the product without knowing the mutual relation. To find the internal relations between the inputs and outputs, a function analysis is performed. This results in functions that are determined by input-output-relations and contraints. Eventually the black-box is transformed into a white-box.

Therefore, to perform a reverse engineering process, a knowledge of several engineering areas is required. The entire process starts with the understanding of the product, how the separate parts work together. What is their function? What is their mutual interaction? Thereafter the reverse process starts, which requires skills in problem solving. In the end, the product is theoretically reverse engineered and the inputs and outputs are determined in a way that the product can satisfy the requirements of the customer.

Prescreening and Black-box

The theoretical reverse engineering starts with the prescreening of the product. Therefore, a product must be chosen, in this case a certain airplane is selected. To determine the reverse engineering parameters from the selected airplane, it is important that the common specifications of the concerned aeroplane are known. Therefore, it is prescreened by doing research on information about the airplane specifications. To perform a successful reverse engineering, it is important that the following specifications for jet powered aeroplanes are known from the prescreening:

Table 2. 1 Necessary specifications for jet powered aeroplanes

Parameter	**Symbol**	**Units**
PAX		
Landing field length (ISA)	s_{LFL}	m
Approach speed	V_{APP}	m/s
Take-off field length (ISA)	s_{TOFL}	m
Range (max payload)	R	km
Cruise Mach number	M_{CR}	
Cruise speed	V_{CR}	m/s
Cruise altitude	h_{CR}	m
Wing area	S_W	m²
Wing span	b_W	m
Aspect ratio	A	
Maximum take-off mass	m_{MTO}	kg
Payload mass	m_{PL}	kg
Mass ratio, payload - take-off	m_{PL}/m_{MTO}	
Maximum landing mass	m_{ML}	kg
Mass ratio, landing - take-off	m_{ML}/m_{MTO}	
Operating empty mass	m_{OE}	kg
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	
Maximum zero fuel mass	m_{MZF}	kg
Wing loading	m_{MTO}/S_W	kg/m²
Number of engines	n_E	
Engine type		
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN
Total take-off thrust	T_{TO}	kN
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$
Bypass ratio	μ	
Overall pressure ratio	OAPR	
Specific fuel comsumption (dry)	SFC (dry)	kg/N s
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s
Available fuel volume	$V_{fuel,available}$	m³
Sweep angle	ϕ_{25}	°
Mean aerodynamic chord	c_{MAC}	m
Position of maximum camber	$x_{(y\_c),max}$	%c
Camber	$(y_c)_{max}/c$	%c
Position of maximum thickness	$x_{t,max}$	%c
Relative thickness	t/c	%
Taper	λ	

Once the prescreening is done, the next step is to build-up the black-box. The outputs are the reverse engineering results; maximum lift coefficient for landing and take-off, maximum aerodynamic efficiency and the specific fuel consumption. The inputs are the aeroplanes specifications shown in Table 2.1. To make things easier, subfunctions are implemented on; landing, take-off and cruise. The subfunction cruise consists out of two additional subfunctions, because it contains relations for two outputs that are determined a different way. As a result, the Figure 2.2 shows the final black-box for the reverse engineering process for jet powered aeroplanes.

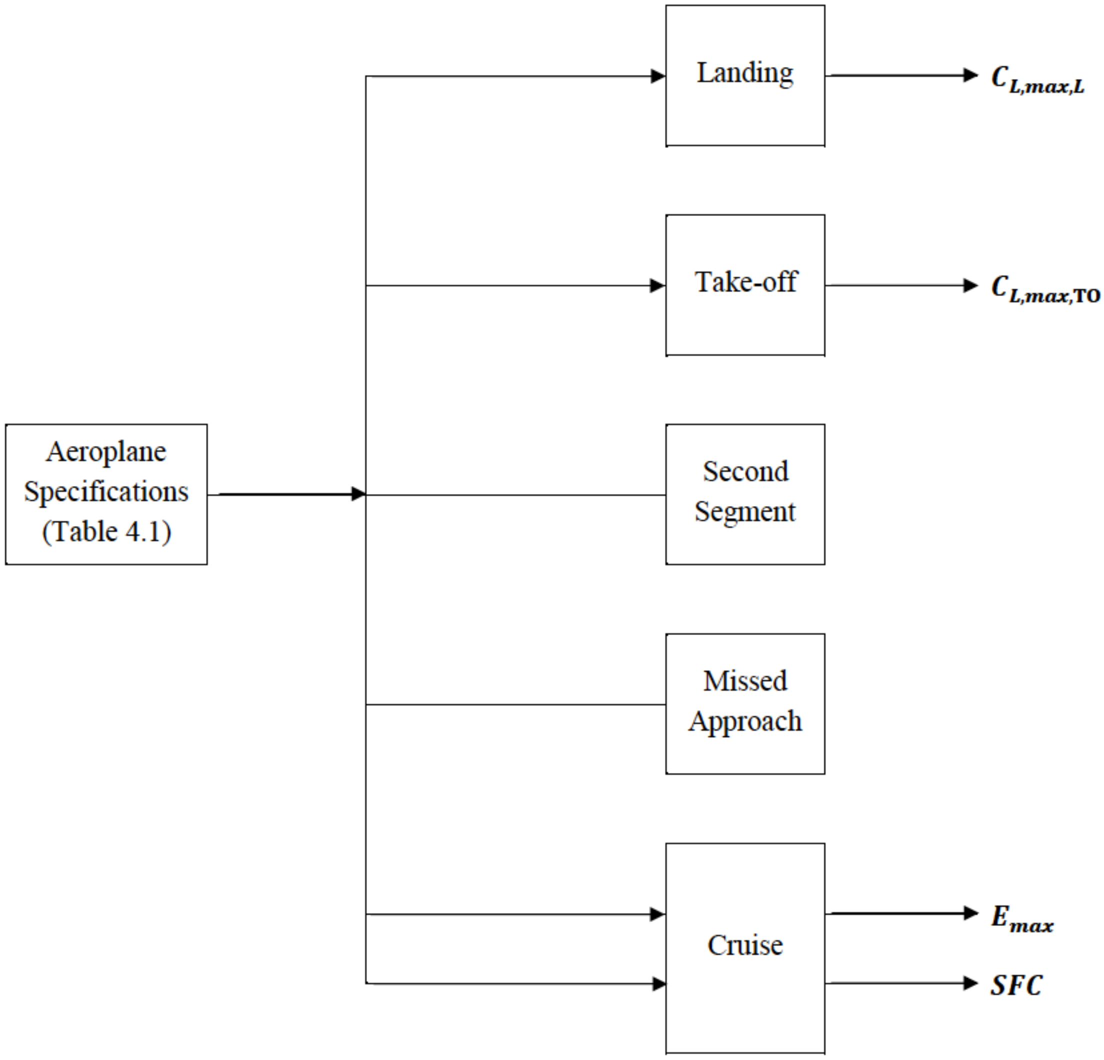


Figure 2. 2 Black-box for jet powered aircraft (**De Grave 2017**)

Functional Analysis

Every function and subfunction is built. The entire black-box can be replaced by a white-box. Figure 2.3 represents the entire reverse engineering process. The inputs are the values found with the prescreening. The outputs are the reverse engineering values. And the mutual relation is shown by the equations between brackets. The process to reverse engineer an aeroplane consists of out of four subfunctions; landing, take-off and two times climb. Each subfunctions require certain inputs.

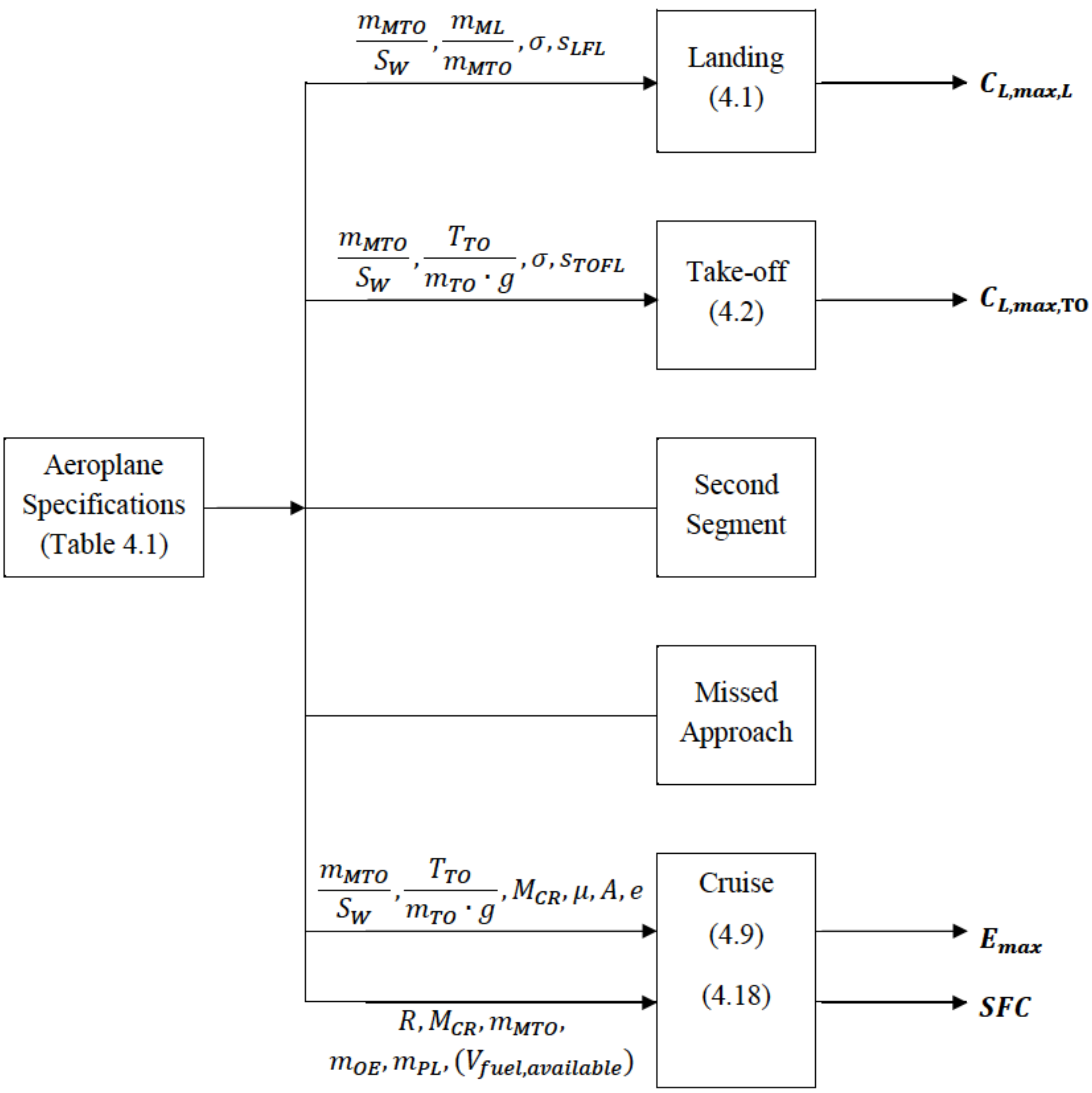


Figure 2. 3 Complete white-box for jet powered aeroplanes (**De Grave 2017**)

In order to carry out the complete white-box, smaller white-boxes had to be built first along with the equations that allow the user to extract the outputs by introducing the inputs. The following equations according to **De Grave 2017** were determined for the individual secret parameters:

Maximum Lift Coefficient for Landing

$$C_{L,max,L} = \frac{\frac{m_{MTO}}{S_W} \frac{m_{ML}}{m_{MTO}}}{k_L \; \sigma \; s_{LFL}} \tag{2.1}$$

With $k_L = 107 \; kg/m^3$

Maximum Lift Coefficient for Take-off

$$C_{L,max,TO} = \frac{k_{TO}}{\sigma \; s_{TOFL}} \frac{m_{MTO}}{S_W} \left(\frac{T_{TO}}{m_{MTO} \; g}\right)^{-1} \tag{2.2}$$

With $k_{TO} = 2{,}34 \; m^3/kg$

Maximum Aerodynamic Efficiency

$$\frac{2 \cdot \frac{T_{TO}}{m_{MTO} \cdot g}}{\frac{1}{\left(\frac{V}{V_{md}}\right)^2} + \left(\frac{V}{V_{md}}\right)^2} \cdot \left[E_{max}^{1,19} \cdot (0{,}0576\mu - 1.76) \cdot \left(\frac{4 \cdot g \cdot \frac{m_{MTO}}{S_W} \cdot \left(\frac{V}{V_{md}}\right)^2}{\pi \cdot A \cdot e \cdot M^2 \cdot \gamma \cdot p_0} \right)^{\frac{1}{5.258}} \right]$$
$$\frac{2 \cdot \frac{T_{TO}}{m_{MTO} \cdot g}}{\frac{1}{\left(\frac{V}{V_{md}}\right)^2} + \left(\frac{V}{V_{md}}\right)^2} \cdot (-E_{max}) \cdot (0{,}0328\mu - 1{,}05) \; + 1 = 0 \tag{2.3}$$

Specific Fuel Consumption (according to operating empty mass and the payload mass)

$$SFC = -\frac{E \cdot ln\left(\frac{1 - \frac{V_{fuel,available} \cdot \rho_{fuel}}{m_{MTO}}}{M_{ff,TO} \cdot M_{ff,CLB}^2 \cdot M_{ff,DES}^2 \cdot M_{ff,L} \cdot M_{ff,engine\;start} \cdot M_{ff,taxi}} \right)}{g \cdot \left(\frac{R + s_{RES}}{V_{CR}} + t_{loiter} \right)} \tag{2.4}$$

Specific Fuel Consumption (according to available fuel volume)

$$SFC = -\frac{E \cdot ln\left(\frac{\frac{m_{PL}}{m_{MTO}} + \frac{m_{OE}}{m_{MTO}}}{M_{ff,TO} \cdot M_{ff,CLB}^2 \cdot M_{ff,DES}^2 \cdot M_{ff,L}} \right)}{g \cdot \left(\frac{R + s_{RES}}{V_{CR}} + t_{loiter} \right)} \tag{2.5}$$

Now that all the reverse engineering values are theoretically discovered, it can be applied to a model. If the user is interested in studying how the individual White boxes were developed and which are the equations of each part of the reverse engineering, **De Grave 2017** carries out a comprehensive study in this topic. However, this is not the aim of this thesis, but to continue building over this previous work.

2.3 The Tool

The tool is based on the dimensioning method according to Loftin 1980. By using the reverse engineering method, the design parameters take-off mass, fuel mass, operating empty mass, wing area, take-off thrust and others are assumed to be known, in order to infer the secret parameters. The PJRE tool is an Excel file that consists of a total of 10 tabs. This chapter briefly describes each of the eight tabs according to **De Grave 2017**. A detailed description of the tabs contained in the tool can be found in the **De Grave 2017** master's thesis.

2.3.1 Data

The "Data" tab contains technical and empirical data. The tool takes information from this tab in order to verify the secret parameters. This data is also used when input parameters are specified by the user as "Unknown".

The "Data" tab consists of the following sections:

- SKYbrary
- Airfoil
- High lift systems
- Winglets
- Conversions

<u>SKYbrary</u>

The tool uses an upper and lower limit for the input parameters wingspan, safety take-off distance and approach speed, if these are specified as unknown. This upper and lower limit is obtained by using the information provided by "SKYbrary". In certain cases, the user has to enter the aircraft category in "SKYbrary". To do this, the aircraft category must be selected in the Aircraft Design Group (ADG), ICAO Aerodrome Reference Code and Aircraft Approach Category (AAC) classes. Limits for the wingspan are determined by selection in the Aircraft

Design Group and ICAO Aerodrome Reference Code classes. The ICAO Aerodrome Reference Code also provides limits to the safety start distance. The tool draws limits on approach speed from the Aircraft Approach Category class. In the subsection of "SKYbrary", auxiliary tables are given so that the user knows which number or letter that is appropriate for the aircraft under investigation must be selected for the respective class.

AIRCRAFT	1. ADG	2. ICAO	3. AAC
A320-200	III	4 C	C

	Specification limits			
No conflict between ADG and ICAO		LL	UL	Unit
	Wing span	24	36	m
	Tail Height	9,1	13,7	m
	OMGW span	6	9	m
	s_{TOFL}	1800	3000	m
	V_{APP}	121	140	kt

Figure 2. 4 Screenshot: Reverse Engineering.xlsm – _Data – _SKYbrary

Airfoil

The “Airfoil” section contains airfoil data that the tool uses to verify the maximum lift coefficient for take-off and landing. For example, it contains data on which airfoil type contains which ratio of leading edge sharpness and the relative thickness Δy / (t / c). The data listed in the “Airfoil” section contain fixed values and equations. The equations are based on **Bhatia 2010**. In this work, every diagram is plotted and approached by equations. These equations are used in the Excel file in order to get the correct data. The airfoil data is used in the ‘4) Verification’ tab. The master thesis **De Grave 2017** explains in detail which equations are used and how Excel uses and processes this information.

Table 2. 2 *Δy*-parameter for known NACA airfoils (determined from **DATCOM 1978**)

Airfoil type	**Δy/(t/c)**
Use own type & values	**0**
NACA 4 digit	26,0
NACA 5 digit	26,0
NACA 63 series	22,0
NACA 64 series	21,3
NACA 65 series	19,3
NACA 66 series	18,3

<u>High-lift Systems</u>

By referring to the information from the "High-lift systems" section, the tool integrates the influence of the high lift systems on the leading and trailing edges on the maximum lift coefficient for take-off and landing. In this way, the theoretical aerodynamic calculation of the maximum lift coefficient for take-off and landing is guaranteed.

Table 2. 3 Flap characteristics (**Stinton 1983**)

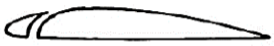
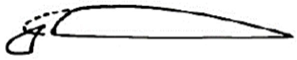
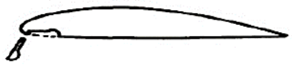
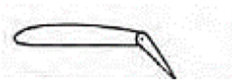
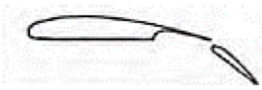
Description	Profile	Increase of lift coefficient
0,3c Nose flap deflected 30° - 40°		62%
Fixed slat forming a slot		37%
Handley Page automatic slat		43%
0,1c Kruger flap		46%

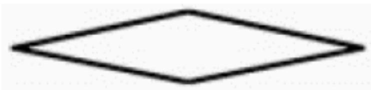
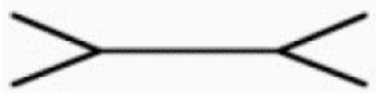
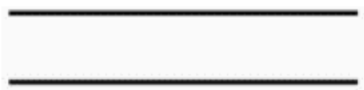
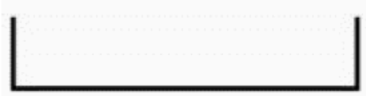
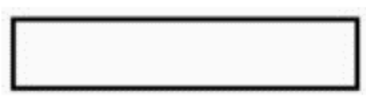
Table 2. 4 Slat characteristics (**Stinton 1983**)

Description	Profile	Increase of lift coefficient
0,3c Plain flap deflected 45°		51%
0,3c Single slotted flap deflected 45°		53%
Double slotted flap[2]		98%
0,3c Split flap deflected 45°		67%
0,3c Split (Zap) flap hinged at 0,8c - deflected 45°		75%
0,3c Split (Zap) flap hinged at 0,9c - deflected 45°		80%
0,3c Fowler flap deflected 40°		119%
0,4c Fowler flap deflected 40°		140%

Winglets

The section "Winglets" provides information to carry out the verification for the maximum aerodynamic efficiency. This influences the effective aspect ratio. Different winglet types are listed with the associated $ke_{,NP}$ value, which the user can select during verification for the maximum glide ratio. For the maximum aerodynamic efficiency, the verification uses an estimation method from **Scholz 2017a**.

Table 2. 5 Span efficiency for various optimally loaded non-planar configurations (h/b = 0,2) (**Kroo 2005**)

Non-planar configuration		$k_{e,NP}$
V-wing		1,03
Diamond wing		1,05
X-flat wing		1,32
X-wing		1,33
Double wing		1,36
H-wing		1,38
End plate (k_{WL} = 2,13)		1,41
Quasi-closed C-wing		1,45
Box wing		1,46

Conversions

In the section "Conversions" some conversions of sizes are listed. In order for the tool to run correctly, the input parameters must be entered in the correct units. The user can use these conversion data to convert the input parameters into the correct units.

2.3.2 Instructions

This tab is a guide and describes, among other things, what must be observed if some input parameters are specified as unknown. The tab also summarizes what needs to be entered in the respective tabs and which tabs do not have to be filled out. In any case, the user should read these instructions through before using the tool.

2.3.3 Data Collection

This table can be used by the user to create an overview of the input parameters and the associated sources. Some sources are entered on the top line of the diagram and others can be added. The left column contains the input parameters that are required for using the tool.
Nothing needs to be entered in the fields with an error message, as these values are calculated by the tool. This "Data Collection" table can be of use to other users. If another user uses the tool for the same aircraft but has different values, he can understand the cause of the deviation by looking at this table.

Data Collection			737-300	Source:	1		2		3	4	5	6	7	8	9
					Aircraft characteristics for airport planning		Jane's		Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collectior	Webs
Parameter	Symbol	Units	Chosen value		A	B	Basic	LR							
PAX			149		128-134-149		128-149		149-128			149	149-128		
Landing field length	s_{LFL}	m	1433		1460		1433		1396			1433	1396	1400	
Approach speed	V_{APP}	m/s	69,45				69,45		68,42			69,44		66,877778	
Temperature above ISA (288,15K)	ΔT_L	K	0		0		0		0			0			
Relative density	s														
Take-off field length	s_{TOFL}	m	1940		2980	2225	2286		1939				1939	1600	2300
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0	0	15		0						
Relative density	s														
Range (max payload)	R	km	1464		3550		4204		2922			4204	1464		4204
Cruise Mach number	M_{CR}		0,745				0,745			0,8			0,74	0,745	0,745
Wing area	S_W	m²	105,4				105,4		91,04			105,4	91,04		
Wing span	b_W	m	28,88		28,88-31,22		28,88		28,9			28,88	28,88	28,9	28,88
Aspect ratio	A		7,9				7,9		9,1740993			7,9	9,16		9,11
Maximum take-off mass	m_{MTO}	kg	58967		56472-58967	63276	56470	62820	56470			56470	56473	56470	62820
Payload mass	m_{PL}	kg	16148		16148	15404			16030				16148		
Mass ratio, payload - take-off	m_{PL}/m_{MTO}					0,24344143			0,2838675				0,286		
Maximum landing mass	m_{ML}	kg	51710		51710	52889	51720	52890	51710			51720	51710		51700
Mass ratio, landing - take-off	m_{ML}/m_{MTO}					0,83584613			0,9157075						
Operating empty mass	m_{OE}	kg	31869		31479	32904	32704	33266	31869				31480		32700
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}					0,52000759			0,5643528				0,557		
Wing loading	m_{MTO}/S_W	kg/m²	535,6				535,6	595,8	620,2768				620		
Maximum zero fuel mass	m_{MZF}	kg	47627		47627	49714	47625	49715	47630				47628		48410
Number of engines	n_E		2						2				2	2	2
Engine type	CFM56-3		CFM56-3B1		CFM56-3B1	CFM56-3B2	CFM56-3C-1		CFM56-3-B1	CFM56-3B1			CFM56-3B1	CFM56-3B1	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	88,964			97,7942	89-97,9		89	88,96444			88,964	90	90
Total take-off thrust	T_{TO}	kN													
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,32						0,3213166				0,32		
Bypass ratio	μ		6							6			6		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	1,08E-05							1,0754E-05			1,08E-05		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s	1,89E-05							1,8876E-05			1,89E-05		
Available fuel volume	$V_{fuel,available}$	m³	20,102		20,102	23,827	20,104-23,83		20,105-23,170				20,102		23,17
Cruise speed	V_{CR}	m/s	220,7						220,7-252,6					220,69667	
Cruise altitude	h_{CR}	m	10668				10195		10668-7924,8	10668			10668		
Sweep angle	ϕ_{25}	°	25						25				25		25
Mean aerodynamic chord	c_{MAC}	m	3,73						3,73				3,73		
Position of maximum camber	$x_{(y\_c),max}$	%c	10												10
Camber	$(y_c)_{max}/c$	%c	0,8												0,8
Position of maximum thickness	$x_{t,max}$	%c	29,7												29,7
Relative thickness	t/c	%	12,9						12,89				12,9		12,5
Taper	λ		0,24						3,73				0,24		
Overall pressure ratio	OAPR		22,6							22,6					
Turbine entry temperature	TET	K													

Figure 2. 5 Screenshot-Data collection

2.3.4 Specifications and Reverse Engineering Results

Almost all of the entries that the user has to make are made in this tab. All of the blue fields printed here in bold must be completed by the user. The bold red fields are results that the tool calculates. Values printed in black are calculated values.

Aeroplane Specifications

The section "Airplane Specifications" starts with the subsection "Data to apply reverse engineering". Here the user enters the input parameters in the blue thick printed fields. If the input parameter "Known" appears next to the input field, this means that this input parameter can also be specified as "Unknown".

Aeroplane Specifications

Data to apply reverse engineering					*LL*	*UL*
Landing field length	**Known**	s_{LFL}	**1646**	m		
Approach speed	**Known**	V_{APP}	**72,00**	m/s	72,0	72,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2300**	m	2300	2300
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**1998**	NM		
Cruise Mach number		M_{CR}	**0,785**			
Wing area		S_W	**125**	m²		
Wing span	**Known**	b_W	**34,32**	m²	34,32	34,32
Aspect ratio		A	9,45			
Maximum take-off mass		m_{MTO}	**78245**	kg		
Maximum payload mass		m_{PL}	**20276**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,259			
Maximum landing mass		m_{ML}	**65315**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,835			
Operating empty mass		m_{OE}	**41145**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,526			
Wing loading		m_{MTO}/S_W	628,0	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**106,757**	kN		
Total take-off thrust		T_{TO}	213,514	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,278			
Bypass ratio		μ	**5,3**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Figure 2. 6 Screenshot: Reverse Engineering.xlsm – _Specs + RE – _Data to apply reverse engineering

In the next subsection "Data to optimize V/Vmd" values for the cruise speed and the cruise altitude are entered. The values for these input parameters are used by the solver in Excel in order to minimize the square sum of the differences in reverse engineering. This is done by optimizing the ratio between speed and speed with minimum resistance V / Vmd. This ratio has a value between 1 and 1.316, which corresponds to the speed at minimum resistance or the maximum cruise speed.

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	233	m/s		
Cruise altitude	h_{CR}	11887	m		
Speed ratio	V/V_{md}	1,000	-	1	1,316

Figure 2. 7 Screenshot: Reverse Engineering.xlsm – _Specs + RE – _Data to optimize V/Vmd

The last subsection is called "Data to execute the verification". Some of the input parameters that are required for the verification of the maximum lift coefficient for take-off and landing are entered here. Further input parameters for the verification must be entered in the "Verification" tab.

Data to execute the verification

					Range	
Sweep angle		φ_{25}	25	°		
Mean aerodynamic chord		c_{MAC}	4,17	m		
Position of maximum camber		$x_{(y\_c),max}$	30	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	4	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	30	%c	30 - 45	%c
Relative thickness	Known	t/c	12,5	%		
Taper		λ	0,219			

Figure 2. 8 Screenshot: Reverse Engineering.xlsm – _Specs + RE – _Data to execute the verification

Reverse Engineering

First there is the subsection "Reverse engineering & optimization of V/Vmd". Here you can see the deviations between the value entered by the user ("Original Value") and the value calculated by the tool ("RE Value") for the following parameters: safety take-off and landing distance, approach speed, span, and cruising speed and altitude.

In the second subsection, "Results reverse engineering", the results of the secret parameters maximum lift coefficient for take-off and landing, maximum glide ratio and specific fuel consumption are listed. In addition, here is the button which the user presses after the input parameters have been entered in order to run the tool.

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1646	1646	m	0,00%
Approach speed	V_{APP}	72,00	72,0	m/s	0,00%
Take-off field length	s_{TOFL}	2300	2300	m	0,00%
Span	b_W	34,32	34,32	m	0,00%
Aspect ratio	A	9,45	9,45		0,00%
Cruise speed	V_{CR}	232,5	232	m/s	-0,36%
Cruise altitude	h_{CR}	11887	11679	m	-1,75%
Squared Sum					**3,20E-04**
Absolute maximum deviation					1,8%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,98**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,30**	
Maximum aerodynamic efficiency	E_{max}	**18,17**	
Specific fuel consumption	SFC	**1,54E-05**	kg/N/s

Reverse Engineering

Figure 2. 9 Screenshot: Reverse Engineering.xlsm – _Specs + RE – _Reverse Engineering

2.3.5 Maximum Lift Coefficient

The maximum lift coefficient for take-off and landing is calculated in this tab. In addition, individual parameters are calculated for the flight phases take-off, landing, 2nd segment and go-around maneuver, just as they are calculated in the dimensioning of passenger aircraft. With these sizes it is possible to create a design diagram. The draft diagram and the associated table can be found in the tabs “5a) Matching Chart and “5b) Matching Chart-points.

The only input the user has here is the choice of certification basis. Using FAR Part 25 will take the drag of the landing gear into account. JAR-25/CS-25 does the calculations with retracted landing gear and thus no additional drag.

1) Maximum Lift Coefficient for Landing and Take-off

Landing			
Landing field length	s_{LFL}	1646	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	72,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,83	
Wing loading at maximum take-off mass	m_{MTO}/S_W	628,0	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,98**	

Take-off			
Take-off field length	s_{TOFL}	2300	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,278	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,30**	

2nd Segment		
Aspect ratio	A	9,453
Lift coefficient, take-off	$C_{L,TO}$	1,60
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,025
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,045
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	9,54
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,258

Missed approach		
Lift coefficient, landing	$C_{L,L}$	1,76
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,033
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,068
Glide ratio in landing configuration	E_L	8,11
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,241

Figure 2. 10 Screenshot: Reverse Engineering.xlsm – _1) C_Lmax

2.3.6 Maximum Aerodynamic Efficiency

The maximum aerodynamic efficiency is calculated in this tab. At the top of the subsection "Constant parameters" there are constant parameters that are required for the calculation. There is also a subsection of this type in the "3) SFC" tab. The maximum aerodynamic efficiency can not be calculated directly but has to be solved using a numerical iteration. Therefore, the Newton-Raphson method is applied. In the Excel file, there are ten iterations executed to calculate the maximum aerodynamic efficiency. The iteration converges quickly, thus it is impossible that the amount of iterations is not sufficient. The iteration is found on the bottom of this tab. The eventual value for the maximum aerodynamic efficiency is shown in the red field, represented on the picture below.

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	
Specifications			
Mach number, cruise	M_{CR}	0,785	
Aspect ratio	A	9,45	
Bypass ratio	μ	5,30	
Wing loading	m_{MTO}/S_W	628	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,278	
Variables			
	V/V_{md}	**1,0**	
Calculations			
Zero-lift drag coefficient	$C_{D,0}$	0,019	
Lift coefficient at E_{max}	$C_{L,md}$	0,69	
Ratio, lift coefficient	$C_L/C_{L,md}$	1,000	
Lift coefficient, cruise	C_L	0,695	
Actual aerodynamic efficiency, cruise	E	18,17	
Max. glide ratio, cruise	E_{max}	**18,17**	

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,23	-0,01	0,00
f'(x)	-0,10	-0,11	-0,11
E_{max}	16	18,26	18,17

Figure 2. 11 Screenshot: Reverse Engineering.xlsm – _2) E_max

2.3.7 Specific Fuel Comsumption

The specific fuel consumption is calculated in this tab. In the “Mission fuel fraction” subsection, the user must select the type of aircraft and the type of flight. For the aircraft type, the user can choose between “Transport Jet” and “Business Jet”. The "Transport Jet" is a passenger aircraft. A “business jet” is a jet that carries a small number of passengers. According to the type of jet, the fuel fractions will modify automatically. It is also possible to fill out own values for a specific mission. Besides this, the user has to give up if it is a domestic flight or an international flight. According to the choice made here, the amount of reserve fuel will modify. To calculate the specific fuel consumption, the payload mass and operating empty mass must be ‘known’ in the tab ‘Specs+RE’. It is important that the payload mass matches with its range. If the maximum range is used to calculate the specific fuel consumption, there is also another way to calculate this using the available fuel volume of the aeroplane.

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³
Specifications			
Range	R	1998	NM
Mach number, cruise	M_{CR}	0,785	
Bypass ratio	μ	5,30	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,278	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	78245	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,259	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,526	
Calculated values			
Actual aerodynamic efficiency, cruise	E	18,17	
Cruise altitude	h_{CR}	11679	m
Cruise speed	V_{CR}	232	m/s
Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	
Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,215	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,785	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,244	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,771	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,54E-05**	kg/N/s

Figure 2. 12 Screenshot: Reverse Engineering.xlsm – _3) SFC

2.3.8 Verification

The verification is independent of the actual reverse engineering. It serves only as a theoretical check of the reverse engineering results. This provides the user with a verification value and the option to confirm the reverse engineering result. The deviations between the verification values and the reverse engineering results are displayed directly below the results.

Maximum Lift Coefficient for Landing and Take-off

Some of the values required for verification for the maximum lift coefficient for take-off and landing have already been entered in the "Spec + Re" tab in the "Data to execute the verification" subsection. In the subsection "Maximum lift coefficients" the user has to select the profile type in order to calculate the maximum lift coefficient of the wing. After calculating the maximum lift coefficient of the wing, the influence of the high lift systems on the leading and trailing edge on the lift coefficient is calculated. The user has to indicate how many different types of flaps the aircraft has and select the flap types. Furthermore, the span or area of these flaps must be specified. The sweep angle of the hinge line must also be specified for the flaps on the front edge. Finally, the results of the maximum lift coefficient for take-off and landing from the verification and from the reverse engineering are shown below.

Calculations increase of lift coefficient due to flaps		**2 flap types**	
Correction factor, sweep	K_φ	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,42	
Use flapped span	b_W,fA	**6,846**	m
Percentage of flaps allong the wing		18%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,22	
• Flap group B			
Double-slotted flap	$\Delta c_{L,max,fB}$	1,42	
Use flapped span	b_W,fB	**11,84**	m
Percentage of flaps allong the wing		31%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,39	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,61	
Calculations increase of lift coefficient due to slats		**2 slat types**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**26**	°
• Slat group A			
0,1c Kruger flap	$\Delta c_{L,max,sA}$	0,66	
Use slatted span	b_W,sA	**4,46**	m
Percentage of slats allong the wing		12%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,07	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**25,4**	m
Percentage of slats allong the wing		67%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,54	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,61	
Wing			
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,64**	
RE value maximum lift coefficient, landing		2,98	
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,04**	
RE value maximum lift coefficient, take-off		2,30	
-11%			

Figure 2. 13 Screenshot: Reverse Engineering.xlsm – _4) Verification – Maximum lift coefficient

Aerodynamic Efficiency

For the verification of the maximum aerodynamic efficiency, the user must select the winglet type. If the aircraft does not have any winglets, the user can select this accordingly. In addition to the winglet type, the winglet height must be specified. The last entry here is the value for the ratio of wetted surface and wing area S_{wet}/S_W.

Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,11	
Span	b_W	34,32	m
Winglet height	h	**2,49**	m
Aspect ratio	A	9,45	
Effective aspect ratio	A_{eff}	10,45	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**19,4**	
RE value maximum aerodynamic efficiency		18,17	
7%			

Figure 2. 14 Screenshot: Reverse Engineering.xlsm – _4) Verification – Maximum aerodynamic efficiency

Specific Fuel Comsumption

The verification value of the specific fuel consumption is calculated in this tab. The user does not have to enter anything here. However, it is advisable to enter values for the turbine inlet temperature TET and the overall pressure ratio OAPR in order to obtain more reliable and more real values.

Nevertheless, this verification turns out to be inefficient when the value for the input parameter “Take-off thrust for one engine” is below 60 kN.

Specific fuel consumption (Herrmann 2010)			
Cruise Mach number	M_{CR}	0,785	
Cruise altitude	h_{CR}	11887	m
By Pass Ratio	μ	5,30	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	106,76	kN
Overall Pressure ratio	OAPR	**26,00**	
Turbine entry temperature	TET	**1445,06**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,86	
Compressor efficiency	$\eta_{compresor}$	0,86	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,98	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,67	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,73	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,15	
Verification value specific fuel consumption	SFC	0,60	kg/daN/h
Verification value specific fuel consumption	SFC	**1,68E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,54E-05	kg/N/s
9%			

Figure 2. 15 Screenshot: Reverse Engineering.xlsm – _4) Verification – _Specific fuel consumption

2.3.9 Matching Chart

This tab shows the design diagram for the aircraft under studied. Using the dimensioning method, either the wing loading, the thrust-to-weight ratio or the thrust-to-weight ratio is calculated as a function of the wing loading for each flight phase. The results are plotted on the design diagram. The design point indicates the lowest possible thrust / weight ratio with the greatest possible wing loading. However, this design point is not marked in the tool. By looking at the diagram, the user can determine whether everything is correct. Unusual curves are an indication that an error has crept in. The respective points that are shown in this diagram are located in the “5b) Matching Chart_points” tab.

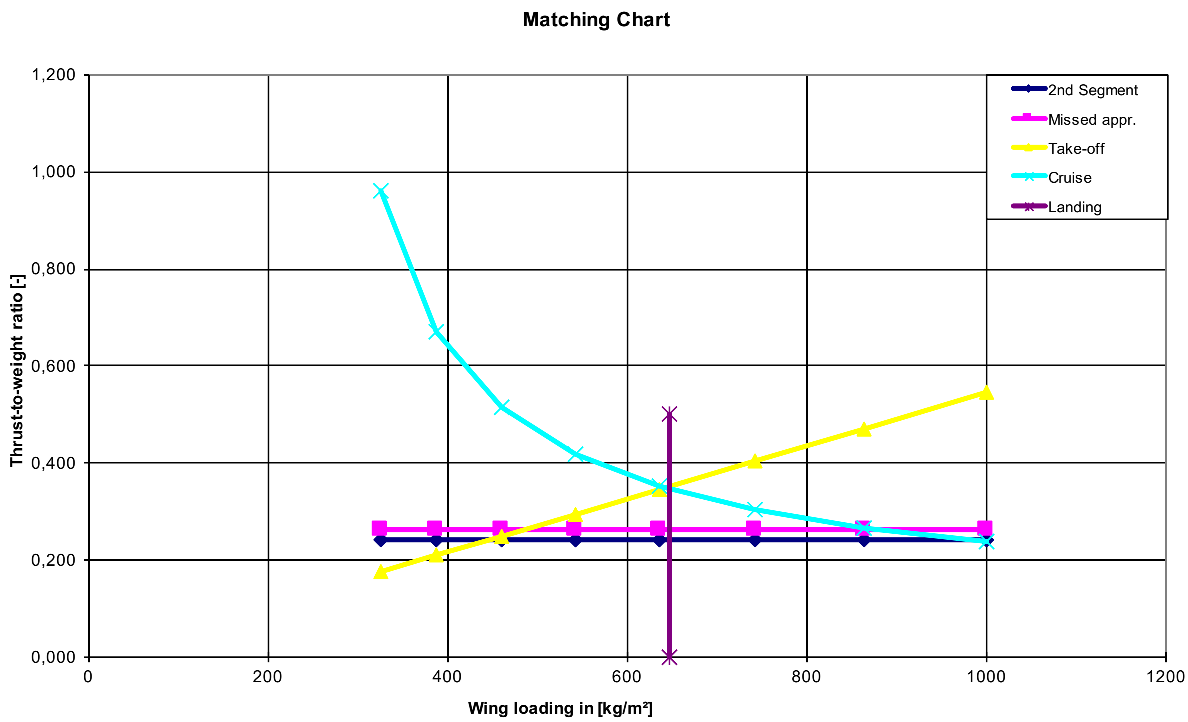


Figure 2. 16 Screenshot: Reverse Engineering.xlsm – _5a) Matching Chart

2.3.10 Instructions for Using the Tool

In this paragraph, the user is told how to work with the program. A brief version of the operating instructions can be found in the Excel file under the tab "Instructions". In order to be user friendly, the program is build-up using colour code and drop down menus. In a few cells, where it is not obvious what to do, additional information is shown when the cell is selected.
In general, the bold blue values represent input. These cells should be filled out by the user. There is no possibility one can make the program unusable by changing these values. Cells with another layout should not be touched unless the user is aware of the consequences and knows how to handle this. Blue values (not bold) are parameters based on experience. Black values are calculated interim or repeated values. The bold red values are the actual results which interest the user. The final colour is light grey, these values can be either parameters that do not apply or upper and lower limits.

Execute the Reverse Engineering

To start the reverse engineering, the user goes to the tab "Specs + RE" and does the necessary research about the aeroplane that has to be reverse engineered. The aeroplane specifications need to be filled out, starting with changing the status of a few parameters to "Known" or "Unknown". If the case occurs that the take-off field length or the wing span is unknown or if both the landing field length and the approach speed are unknown, the user goes to the tab "Data –

SKYbrary" where the aircraft category is filled out, using the drop down menus. Extra attention is required when the numerical classification of the category ICAO Aerodrome Reference Code equals four. When this occurs, the user has to give an upper limit for the take-off field length. The range status should also be adapted. The user gets a drop down menu with the following options for the range: range for maximum payload, range for maximum PAX (number of passengers), maximum range and the possibility to use another range according to the payload range diagram of the aeroplane. The available volume of fuel is only to be filled out when the maximum range is used. Now that every parameter has a status, the user fills out all the values.

Next is the data to optimize V/V_{md}. The actual cruise speed and cruise altitude of the aeroplane is filled out. When one of these parameters is unknown, the user has to fill out an upper and lower limit for this. If necessary, the upper and lower limits for V/V_{md} can be adapted. Initial it is set in a way that the lower limit is the minimum drag speed and the upper limit is the maximum range speed.

The next step is to choose a certification basis in the tab "1) C_Lmax" under the section "Missed Approach". Choosing FAR Part 25 will add profile drag due to the extended landing gear. The other certification basis, JAR-25 or CS -25, does not integrate an additional drag caused by the landing gear.

As a final step, the user goes to the tab "3) SFC". In the section "Mission fuel fraction" there is a drop down menu for the user where one can select if the aeroplane is a transport jet or a bussines jet. According to this choice, the mission fuel fraction will be modified. Since the mission is not standard or the same for every plane, the user can adapt these values without causing any problems in the program. The last input for the user is to assign the type of flight to the aeroplane, wether it is a domestic or international flight. According to this input, the fuel reserves will modify, complying with FAR Part-121-Reserves.

Eventually, the user returns to the tab "Specs + RE" and pushes the "Reverse Engineering" button. The solver in Excel will start and the reverse engineering calculations are made. The results are displayed next to the button.

Execute the Verification

The program is initially not created to perform a verification on the reverse engineering values. It is interesting for the keen user to verify the trustworthiness of the reverse engineering calculations. The reliability of the verification values stands or falls with the accuracy of the aeroplane information.

Start on the tab "Specs + RE" and go to the section "Data to execute the verification". Fill out the bold blue values. If the relative thickness is unknown, Excel will simply calculate the mean relative thickness using an equation which only depends on the cruise Mach number, detailed explained in **De Grave 2017**.

From here on, everything happens in the tab “4) Verification”. In the section “Maximum lift coefficients” the user selects the type of airfoil. If the type is not a standard NACA profile or the user owns more detailed data, it is possible to select “Use own type & values”. When this is the case, the user fills out the required information in the tab “Data” section “Airfoil”. Once this is done, the amount of flap and slat types are slected. Also the types itself are selected. For the selection of the flap and slat type, the user should consult **Jane’s 2008**. Next, the user choses whether the flapped span or flapped area is used to calculate the contribution of the flaps and slats. The area gives a more accurate result but is more time consuming then using the span. When using the span, measure the length of the flaps or slats along the wing (not perpendicular to the symmetric plane). The flapped or slatted span or area is than filled out. For the slats, the sweep angle of the hinge line must be inserted. Besides that, the deviation with the reverse engineering results is calculated and shown graphically directly under the verification values for the maximum lift coefficients.

In the section “Maximum aerodynamic efficiency”, the user starts by chosing the type of winglets. For the selection of the winglet type and height, the user should consult **Winglets 1999**, **Winglets 2008** and **Aviation Partners 2020**. Note, if the winglet is an endplate, the user should also fill out the winglet height. Next, the relative wetted area must be filled out. For the calculations of the maximum aerodynamic efficiency, a value is chosen using Figure 2.17. If the aeroplane is not on the picture, a typical value for jet powered passenger aeroplanes is a value between 6,0 and 6,2 or an own estimation can be made too. These inputs result in a verification value for the maximum aerodynamic efficiency which is compared with the value gained with the reverse engineering.

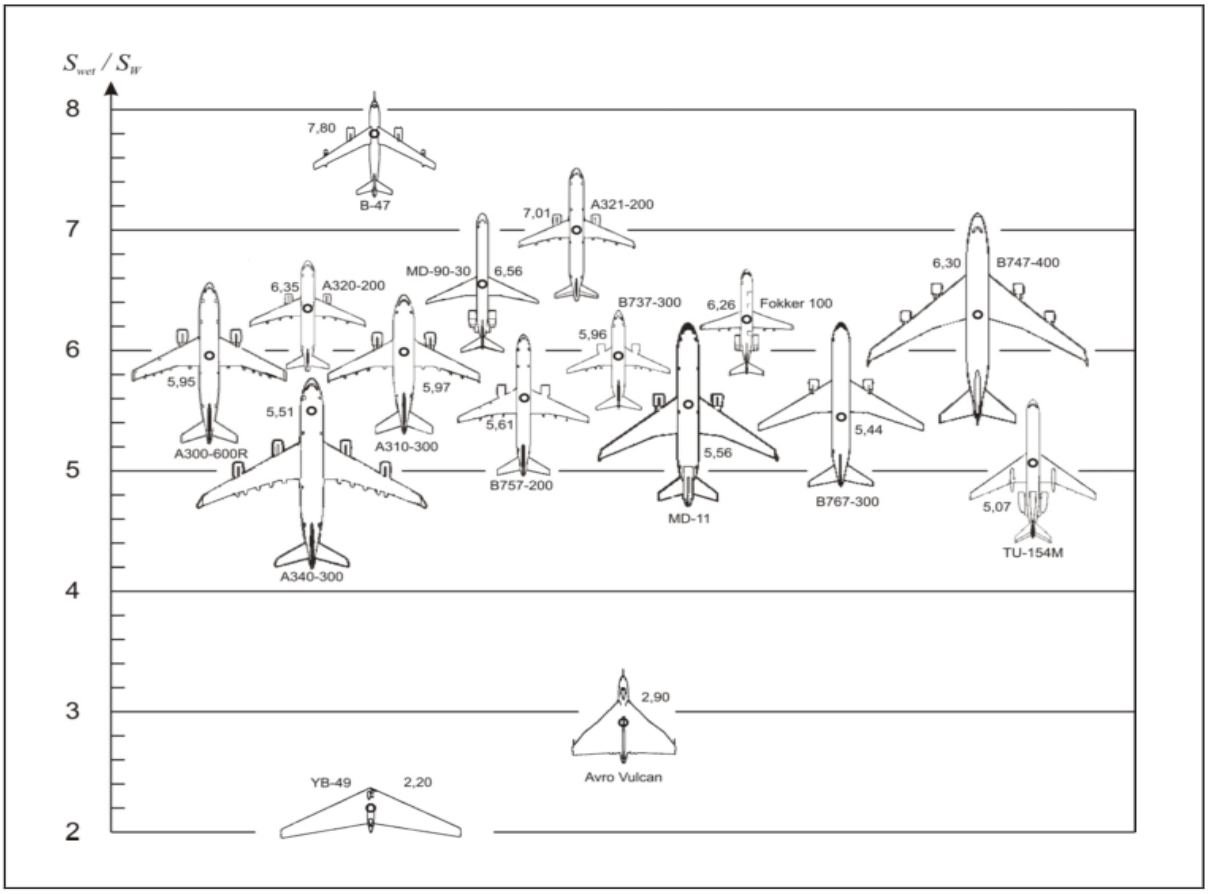


Figure 2. 17 Aircraft plan forms and their relative wetted area S_{wet}/S_w (Raymer 1989)

Finally, the specific fuel consumption is verified. This does not require any input from the operator. Pay attention that the overall pressure ratio (OAPR) or the turbine entry temperature (TET) can deviate a lot from the practical values. They have a big influence on the result of the specific fuel consumption. This can be an explanation if the deviation between the reverse engineered value and the verification value of the specific fuel consumption is big.

3 Data Research

The data research represents a great part of the invested time while doing the Master's thesis. This time might not be reflected in the final result but it is of vital importance if one is to provide with reliability to the final conclusions.

In order to use the tool successfully, it is important to collect reliable input parameters of the aircraft. Searching for the input parameters can be very complex and time-consuming. By narrowing down to reliable sources, the search for the input parameters can be considerably simplified. This section is made to be helpful for the user. It describes how to find a big amount of useful information in a quick and accurate way. The tips and tricks are based on own experience and provide a good basic and support for the user.

To begin, several sources and platforms are mentioned and described using pros and cons concerning accuracy, reliability and integrality. A single source is rarely enough to collect all the information needed to use the tool. It is recommended to look through all of the sources listed below and to write down the respective input parameters. In the end, an overview is shown of a comparison between the different sources.

3.1 Jane's All the World's Aircraft

It is an annual that contains information about all the airships over the years. It was founded by John Fredrick Thomas Jane (1865 – 1916) in 1909. Since then, it has been compiled and edited by many different authors. The aircraft data are detailed, complete and reliable. Because of this, its purchase is very expensive. A disadvantage is that not every airvehicle is contained in one book. The data for older aeroplanes can be found in the old editions but are left out in the new editions, unlike a dictionary. The books contain useful aircraft specifications (regarding the Excel file) such as:

Table 3. 1 Source of information (**Jane's 2007** and **Jane's 2008**) catalogue

Performance	Cruising Mach number
	Take-off field length
	Landing field length
	Range
	Cruise speed
	Cruise altitude
	Approach speed
Weights and loadings	Maximum payload
	Operating empty weight
	Maximum take-off weight

	Maximum landing weight
Dimensions	3 view sketch
Power plant	Thrust
	Usable fuel capacity
Wing	Wing span
	Wing area
Flying controls	Leading edge devices
	Trailing edge devices

3.2 Élodie Roux

The first book of Élodie Roux, Avions civils à réaction: plan 3 vues et données caractéristiques (**Roux 2007a**), the user will find the data of nearly 270 civilian airplanes equipped with single or double flow reactors. These are civil transport planes, cargo planes, business planes, etc. Each aircraft is displayed on two pages presenting: a 3-view plan and characteristic data of geometry, mass, propulsion and performance with the Payload/Range diagram. It is a well organized source of information with the only inconvenient that is just written in French.

Table 3. 2 Source of information (**Roux 2007a**) catalogue

Performance	Cruising Mach number
	Cruising altitude
	Take-off field length
	Landing field length
	Payload-Range diagram
Weights and loadings	Maximum payload
	Operating empty weight
	Maximum take-off weight
	Maximum landing weight
	Maximum zero fuel weight
	Weight ratios
Dimensions	3 view sketch
Power plant	Engine type
	Number of engines
	Thrust
	Usable fuel capacity
	Specific fuel consumption, cruise
	Specific fuel consumption, dry
	Bypass ratio
Wing	Wing span
	Wing area
	Aspect ratio
	Taper ratio
	Root chord
	Mean aerodynamic chord

	Sweep angle at 25% chrod
	Dihedral angle
	Relative thickness
Flying controls	Trailing edge devices

The second book, Turbofan and Turbojet Engines: database handbook (**Roux 2007b**), is a collection of the characteristics of about 1500 turbofan and turbojet engines, with or without afterburner. These engines are implanted on many kinds of aircraft: airliners, freighters, business aircraft, fighters, experimental aircraft, gnopters... In order to facilitate the use of this book, engine characteristics are shown in the same synthetic way: thrust, specific fuel consumption, engine weight, bypass-ratio, overall pressure ratio, turbine entry temperature...

Table 3. 3 Source of information (**Roux 2007b**) catalogue

Power plant	Engine type
	Turbine Entry Temperature at static sea level
	Cruise thrust (at M_{cr} and h_{cr})
	Static sea level thrust with/without afterburner
	Bypass ratio
	Overall pressure ratio at static sea level
	Overall pressure ratio in cruise
	Specific fuel consumption at static sea level
	Specific fuel consumption in cruise
	Cruise Mach number

3.3 Jenkinson

The third reference is a website on the book 'Civil Jet Aircraft Design' by L. Jenkinson, P. Simkin and D. Rhodes (**Jenkinson 2017**). The site contains more than only some details about the book, it contains aircraft industry data. This site can be used for both aircraft (**Jenkinson 2017a**) and engine (**Jenkinson 2017b**) specifications. The listing of the engine specifications is divided into three stages; take-off, climb and cruise. They are very comprehensive, accurate, user friendly and free. A few disadvantages are that some engine parameters are not expressed in SI-units and thus they need to be converted before one is able to use the values for the program. Besides, the list of different aircraft types is not large. The last disadvantage is that there is no 3 view drawing available, which makes it impossible to scale measure some parameters. The following specifications can be found with this source:

Table 3. 4 Source of information (**Jenkinson 2017a**) catalogue

Performance	Cruise Mach number
	Cruise altitude
	Cruise speed
	Approach speed

	Take-off field length
	Landing field length
	Payload-Range diagram
Weights and loadings	Maximum payload
	Operating empty weight
	Maximum take-off weight
	Maximum landing weight
	Maximum zero fuel weight
	Weight ratios
Power plant	Engine type
	Number of engines
	Static thrust
	Fuel capacity (Standard or optional)
	Specific fuel consumption
Wing	Wing span
	Wing area
	Aspect ratio
	Taper ratio
	Root chord
	Mean aerodynamic chord
	25% sweep angle
	Relative thickness
	Maximum lift coefficient, landing
	Maximum lift coefficient, take-off
Flying controls	Leading edge devices
	Trailing edge devices

Engine specifications (**Jenkinson 2017b**)

Table 3. 5 Source of information (**Jenkinson 2017b**) catalogue

Take-off	Thrust
	Bypass ratio
	Overall pressure ratio
	Specific fuel consumption
Climb	Maximum thrust
Cruise	Altitude
	Mach number
	Thrust
	Specific fuel consumption

3.4 Airport Planning

The next source worthy to consult is the airport planning (**Boeing 2020**, **Airbus 2020**, **Bombardier 2020**, **Embraer 2020** and **ATR 2020**). This is information provided by the aircraft manufacturer and can be found on their own website. It gives a description about every detail from the aeroplane such as general dimensions, aircraft performance, servicing operations and maintenance preparation. The data provided by this source is integral, quite complete, reliable and for free. The only disadvantage is that the documents contain lots of unnecessary data so that it takes some time to discover the required information. Data that are needed to perform the reverse engineering and that can be found using this source are:

Table 3. 6 Source of information (**Airport planning**) catalogue

Performance	Take-off field length
	Landing field length
	Payload-Range diagram
	Approach speed
Weights and loadings	Maximum payload
	Operating empty weight
	Maximum take-off weight
	Maximum landing weight
Dimensions	3 view drawing (detailed)
Power plant	Engine type
	Usable fuel capacity

3.5 Engine

Engine 2005 is a presentation of technical information of Civil Turbojet/Turbofan Specifications, sorted by engine manufacturer. It is narrowed to engines information, therefore, it is a reliable site to check the engine options of every aircraft.

Table 3. 7 Source of information (**Engine 2005**) catalogue

Power plant	Engine type
	Thrust (dry)
	Thrust (cruise)
	Bypass ratio
	Overall pressure ratio
	Specific fuel consumption (dry)
	Specific fuel consumption (cruise)
	Mach number
	Cruise altitude

3.6 Data Collection

The last interesting and free source is **SKYbrary 2017a** which contains data of 554 aeroplanes. This source provides data which are not comprehensive in comparison with the required inputs for the program. When it is consultet by the user for the first time, it is possible that the display of the information is not clear. The following, usefull information, is listed below:

Table 3. 8 Source of information (**SKYbrary 2017a**) catalogue

Performance	Cruise Mach number
	Cruise speed
	Approach speed
	Take-off field length
	Landing field length
	Range
Weights and loadings	Maximum take-off weight
Dimensions	3 view sketch
Power plant	Engine type
	Number of engines
	Thrust
Wing	Span

3.7 Paul Müller

For the verification of the parameters search, it has been also taken into account the Diplomarbeit from Paul Müller, **Müller 1999,** *Anpassung von Statistik-Gleichungen des Flugzeugentwurfs an neue Flugzeugtypen*. In the *Appendix C Verwendete Flugzeugtypen* there is a compilation of several aircraft that provides a fairly wide range of parameters that are useful for the user, belonging to several aircraft types. However, when studying the values more carefully the user realices that these paremeters might be selected from one of the sources explained above.

Table 3. 9 Source of information (**Müller 1999**) catalogue

Performance	Landing field length
	Approach speed
	Range (maximum Payload)
Weights and loadings	Maximum take-off weight
	Maximum landing weight
Dimensions	3 view sketch
Wing	Span
	Area
	Aspect ratio

The sources mentioned above are only to help the user. If all these sources are consulted and there are still a few parameters missing, that does not mean that they can not be found in another way. It is recommended to take a look on the manufactures platform. This contains lots of thrustworthy information. If by then, the user still has unknown parameters, the last option is to invoke SKYbrary. This source is free and already integrated in the Excel file. A big disadvantage is that it uses intervals and thus the final value for a certain parameter depends on the solver in Excel and the accuracy from the other specifications. SKYbrary is only an option if the take-off field length, the wing span or when both the landing field length and the approach speed is unknown. Using this method is inadvisable and serves as a last possible solution to perform the reverse engineering.

Table 3. 10 Every source of information features

	Jane's	Roux	Jenkinson	Airport	Engine	SKYbrary
Performance						
Cruise Mach number	x	x	x	x	x	x
Take-off field length	x	x	x	x		x
Landing field length	x	x	x	x		x
Range	x		x			x
Payload-Range diagram		x		x		
Cruise speed	x		x			x
Cruise altitude	x	x	x		x	
Approach speed	x		x	x		x
Weights and loadings						
Maximum take-off weight	x	x	x	x		x
Maximum payload	x	x	x	x		
Maximum landing weight	x	x	x	x		
Operating empty weight	x	x	x	x		
Maximum zero fuel weight	x	x	x	x		
Weight ratios		x	x			
Power plant						
Number of engines	x	x	x	x		x
Thrust	x	x	x		x	x
Bypass ratio	x	x			x	
Overall pressure ratio		x			x	
Fuel capacity	x	x	x	x		
Specific fuel consumption		x			x	
Wing						
Span	x	x	x	x		x
Area	x	x	x			
Aspect ratio	x	x	x			
Taper ratio		x	x			
Root chord	x	x				
Mean aerodynamic chord		x	x			
Sweep angle at 25% chrod	x	x	x			
Dihedral angle	x	x				
Relative thickness		x	x			
Flying controls						
Leading edge devices	x		x			
Trailing edge devices	x	x	x			

Below is shown a table that rates every source of information from 1 to 5 in terms of comprehensiveness of the aircraft/engine types (the source offer a wide range of aircraft/engine types), comprehensiveness of the parameters (the source offers all the parameters that the user is searching), accuracy (the parameter values are accurate enough), reliability (the parameter values are consistent and match the specifications of the other sources) and its access (the source can be found quickly and for free on the web or, on the contrary, must be searched in a library).

Table 3. 11 Ranking of the sources

	Jane's	Roux	Jenkinson	Airport	Engine	SKYbrary
Comprehensiveness aircraft/engine types	5	4	2	4	4	3
Comprehensiveness parameters	4	5	4	3	2	1
Accuracy	5	4	5	5	5	2
Reliability	4	4	3	5	5	2
Free	No	No	Yes	Yes	Yes	Yes

4 Aviation Market

The aviation market is segmented by Type (Commercial Aircraft, Military Aircraft, General Aviation), and Geography. The aviation market is anticipated to show the next behaviors during the forecast period, according to **Aviation Market 2020**:

- Increasing defense expenditure, mostly from the developing countries, may drive the procurement of military aircraft, thereby propelling the growth of the aviation market in the coming years.
- Lower air fares, growing living standards, and a growing middle-class in large, emerging markets, like China and India, are the hmajor contributors to increased air travel. This has made the airlines operating in the regions to establish new routes and serve more passengers, by procuring new aircraft, thereby adding more seats.
- Replacement of aging commercial aircraft and the procurement of new generation commercial aircraft are the main factors driving the growth of the market.

4.1 Key Market Trends

The commercial aircraft segment dominates the aviation market, accounting for more than half of the market revenues, as of 2019. The commercial segment is expected to continue to dominate the market during the forecast period, due to the rising demand for new aircraft to cater to the increasing air travel. Additionally, several airlines are replacing their ageing fleet with newer generation fuel-efficient aircraft. The military aircraft segment is anticipated to grow, however, slower than the commercial aircraft segment, as most of the new aircraft order finalizations for the military take few years before getting the final approval for the procurement. The declining military expenditures from some countries also hampered the growth of the military aircraft segment, to some extent.

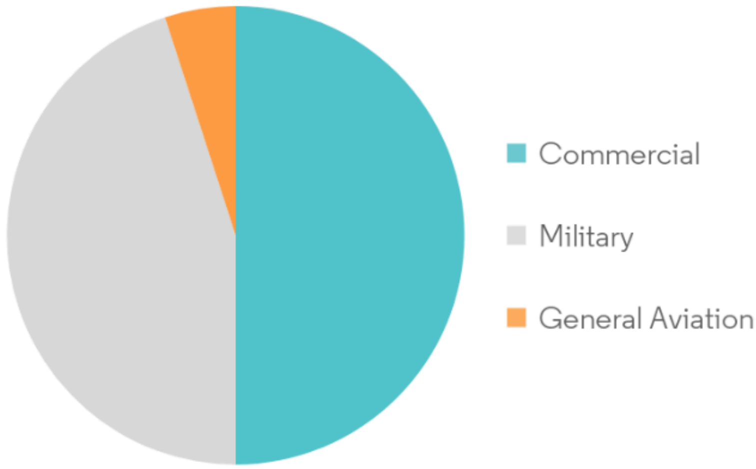


Figure 4. 1 Aviation Market: Revenue (%), by type, Global, 2019 (**Aviation Market 2020**)

Where is the largest and fastest growing market for the commercial aircraft? North America was the largest region in the global commercial aircraft market, accounting for 60% of the market in 2019. Asia Pacific was the second largest region accounting for 15% of the global commercial aircraft market. Eastern Europe was the smallest region in the global commercial aircraft market.

The market in the Asia-Pacific Region is expected to grow during the Forecast Period (2020-2025). In 2019, North America accounted for the highest market share across all the regions in the world. The revenues from the region are predominantly due to the United States, which has the highest aircraft fleet in the world. North America was followed closely by Asia-Pacifc, in terms of revenue share, in 2019. Revenues from Asia-Pacific are projected to grow with a high growth rate, during the foecast period, as the emerging economies in the region, like India and China, are experiencing a huge surge in their respective aviation markets, due to an increased demand for air travel in the countries.

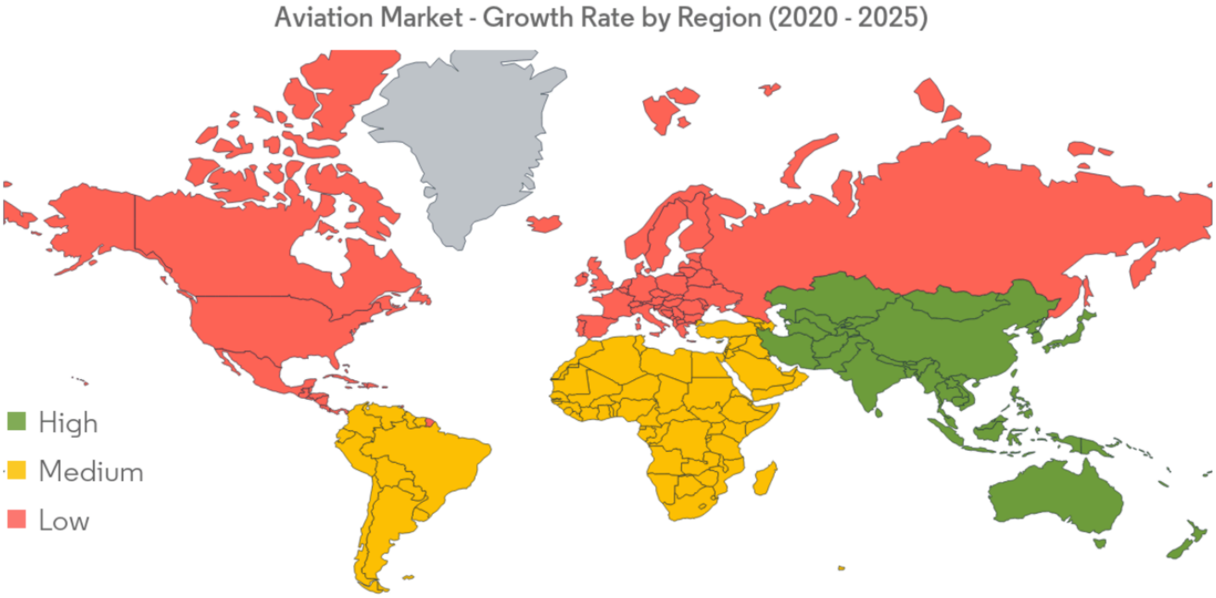


Figure 4. 2 Aviation Market – Growth rate by region (2020-2025) (**Aviation Market 2020**)

4.2 Commertial Aircraft Market

Commercial aircraft transport passengers and cargo from one location to another. Commercial aviation involves general aviation and scheduled airline services. The world commercial aircraft market is divided by aircraft size, end user, and geographical region. The aircraft sizes could be wide-body, narrow-body, regional, and others (single aisle, feederliner, and short haul). Considering the end users, the market is bifurcated into public and private sector. Based on geography, the market is analyzed across four major regions namely, North America, Europe, Asia-Pacific, and LAMEA.

The forecast for the commercial aircraft market can be summarized as follows, according to **Aviation Market 2020**:

- Increase in number of air passengers: This factor is expected to have high impact on the market growth throughout the forecast. Key players in the market have anticipated significant growth in the number of air passengers by the end of 2034; by then, they aim to enhance their overall air transport services.
- Improvement in commercial aviation network: Increase in passenger security concerns may encourage prominent players to invest significant amount on passenger security enhancement solutions and services, thus, projecting high impact of this factor by the end of 2022.
- Increasing tourism and economic development: It is anticipated that; the global tourism industry will witness significant hike during the forecast period. This is projected to have a high impact on the overall commercial aircraft market by 2022.

- Environment-friendly and fuel-efficient aircraft: To meet the environment compliance by the governments, businesses have started consuming and offering eco-friendly products and services. By 2022, the overall impact of this factor is expected to remain high due to increasing environmental concerns.
- Lack of security and terrorism threats: Significant increase in aviation terrorism has created a negative impact on commercial aircraft market growth. Currently, this factor has high impact in the market and is expected to remain high throughout the forecast period. Major issues include air traffic control error, cabin fire, explosive devices, flight hijacks, lightning, and incompetent pilots.
- Congestion and delay: Currently, congestion and delay have high impact on the market growth. However, introduction of several initiatives by government and aviation service providers to manage air-traffic effectively may reduce the overall impact on the market growth by 2022.

Aircraft fleets in mature markets around the world are aging rapidly and with growing demand from airlines and fleet operators for fuel-efficient aircrafts, manufacturing companies are offering advanced aircrafts for passenger transportation. These advanced aircrafts are equipped with advanced avionics, superior cabin designs and noise reduction capabilities that increase the fuel efficiency and performance of aircrafts. Higher hydraulic operating pressure (5000 psi) systems, variable frequency power generators, Brake to Vacate technology and high-efficiency air filters are new technologies being integrated in aircrafts. Some of the new aircraft offerings include Airbus A320 neo, A330 neo, Boeing's 787, 737 MAX, 777X and Bombardier's C-series.

4.3 Commercial Aircraft Sales

Table 4.1 shows the exact number of sold and delivered in service aircraft according to a model classification, taking into account the backlog for each model as well.

Table 4. 1 Commercial aircraft sales (**DVB 2018**)

	Manufacturer	Aircraft type	Total		Manufacturer	Aircraft type	Total
1	Boeing	737-800	4984	51	Boeing	737-400	142
2	Airbus	A320-200	4279	52	Irkut	MS-21-300	142
3	Airbus	A320-200 Neo	3671	53	Sukhoi	SSJ100-95	127
4	Boeing	737-8	2065	54	Boeing	737-400SF	124
5	Airbus	A321-200	1686	55	Boeing	737-9	119
6	Airbus	A321-200 Neo	1355	56	Bombardier	CS100	113
7	Airbus	A319-100	1341	57	Fokker	100	111
8	Boeing	737-700	1026	58	Boeing	737-300SF	109
9	Boeing	777-300ER	813	59	Airbus	A340-300	103
10	Airbus	A330-300	735	60	Airbus	A300-600F	103
11	Boeing	787-9	678	61	Embraer	195-E2	102
12	Airbus	A350-900	625	62	Embraer	175-E2	100
13	Airbus	A330-200	553	63	Boeing	747-8F	88
14	Embraer	190	536	64	McDonnel D.	MD-11BCF	85
15	Embraer	175	529	65	Embraer	190-E2	83
16	ATR	ATR 72-600	527	66	Boeing	757-200PF	79
17	Boeing	737-900ER	508	67	Airbus	A321-200NX	74
18	Bombardier	CRJ100/200/440	499	68	Airbus	A300-600F	68
19	Boeing	767-300/300ER	452	69	Bombardier	CRJ1000NextGe	67
20	Bombardier	CRJ900	438	70	Boeing	737-7	65
21	Embraer	ERJ-145	417	71	McDonnel D.	MD-90-30	64
22	Boeing	787-8	401	72	Boeing	777-200	62
23	Boeing	777-200ER	348	73	Airbus	A340-600	62
24	McDonnel D.	MD-81/82/83/88	345	74	Boeing	767-200SF	59
25	Boeing	757-200	333	75	Boeing	767-300(ER)BCF/SF	56
26	Airbus	A380-800	316	76	Boeing	757-300	55
27	Bombardier	Dash-8 Q400NextGen	301	77	Boeing	777-200LR	54
28	Bombardier	CRJ700	300	78	Airbus	A321-100	54
29	Comac	C919	287	79	Boeing	737-900	52
30	ATR	ATR 72-500	286	80	Boeing	777-8	53
31	Boeing	777-9	263	81	Boeing	737-600	48
32	Boeing	737-10	256	82	Boeing	777-300	48
33	Mitsubishi	MRJ90	233	83	Airbus	A319-100 Neo	47
34	Bombardier	Dash-8 Q400	225	84	Airbus	A318-100	44
35	Boeing	737-300	218	85	Boeing	747-400BCF	43
36	Airbus	A350-1000	212	86	Airbus	A330-200F	41
37	Boeing	737-8-200	210	87	Embraer	ERJ-135	40
38	Boeing	757-200SF	205	88	Boeing	747-8I	37
39	Airbus	A330-900 Neo	204	89	Boeing	767-400ER	37
40	Bombardier	CS300	200	90	McDonnel D.	MD-11F	34
41	Boeing	767-300F	190	91	Irkut	MS-21-200	33
42	Comac	ARJ21-700	180	92	Boeing	737-300QC	29
43	Boeing	787-10	168	93	Airbus	A310-200	26
44	Boeing	747-400	165	94	Airbus	A310-300	26
45	Boeing	737-500	162	95	Fokker	70	25
46	Boeing	777 Freighter	160	96	Airbus	A300-600(R)	22
47	Embraer	195	157	97	Boeing	767-200	16
48	Boeing	717-200	154	98	Airbus	A310-200F	16
49	Embraer	170	152	99	Boeing	747-400M Combi	13
50	Boeing	747-400(ER)F	143	100	Bombardier	CRJ100/200PF/SF	10

In order to carry out the research, it has been taken into account the maximum number of manufacturers, aircraft models and types. The objective is to cover the whole commertial market spectrum. To do so, both passenger aircraft and freighters have been included, as well as every engine option, either turbofan or turboprop. Although the Reverse Engineering Excel-based tool PJRE is not design to study turboprop engines, they have been also taken into account so as to increase the research reliability and accuracy.

The following manufacturers take part in the research: Airbus, Boeing, Bombardier, Embraer, McDonnel Douglas, Fokker, Mitsubishi, Sukhoi, Irkut, Comac and ATR. In total, 118 aircraft models have been studied, of which 91 were passenger aircraft and 26 were freighters. In addition, the vast majority had turbofan as engine option and only 4 out of 118 had turboprop as engine option.

If we add up all the sold aircraft, a total of 37753 is given. The aircrafts of the table have already been ranked by their number of sales, being the Boeing 737-800 the most used commertial aircraft, with 4984 aircraft in service, and the Airbus A320-200 the second most used commertial aircraft, with 4279 sold and delivered aircraft. Only these two aircraft models already cover the 25% of the commertial market spectrum.

How many more aircraft models must be taken into account in order to cover the 90% of the market?

The following figure shows the cummulative sum of the most used commercial aircraft, with which a visual interpolation can be carried out in order to unravel the number of aircraft models that will be the object of study. Thank to the graph’s shape, one can realize that only less than half of the aircraft models are needed to cover almost all of the commercial market spectrum.

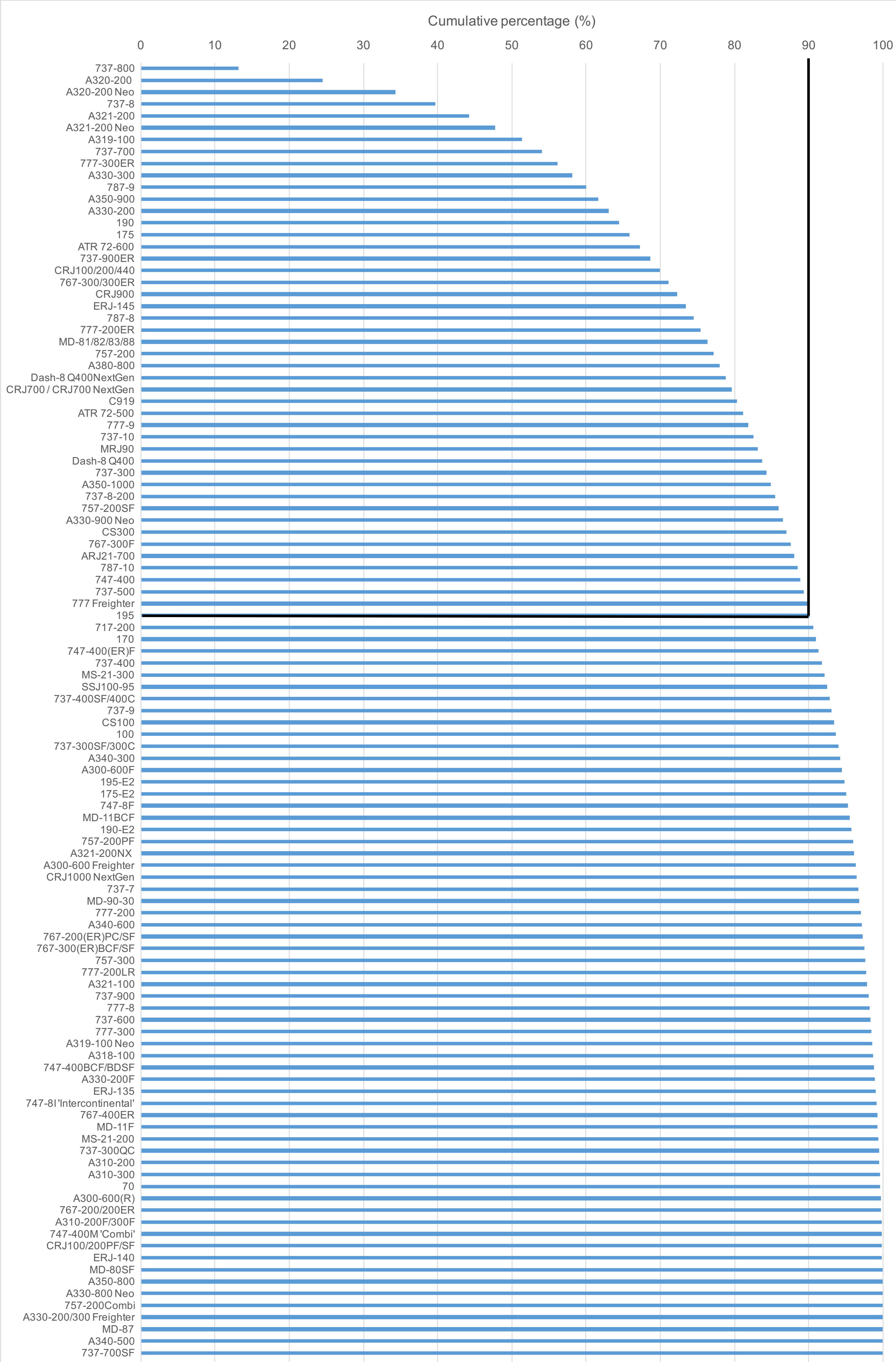


Figure 4. 3 Cummulative sum of most used passenger aircraft

Figure 4.4 shows the most used passenger aircraft. These values include both aircraft in service and in backlog. Now that the sales of every aircraft are displayed, it becomes clearer that sales are concentrated in the first aircraft models. These are the Boeing 737-800 and the Airbus A320-200, closely followed by the Airbus A320-200Neo and Boeing 737-8, which are the modern and more efficient versions of the first two aircrafts.

Based on aircraft size, the market is segmented into wide-body, narrow-body, and regional jets. From the ranking, it is evident that the narrow-body segment has the maximum market share aircraft, as they are fuel-efficient and help in reducing the overall cost. This is one of the crucial factors that have increased the adoption of narrow-body aircraft globally. However, the wide-body segment is expected to grow at a rapid rate during the forecast period due to an increase in the number of aircraft delivery via wide-body aircraft, especially in Asia-Pacific.

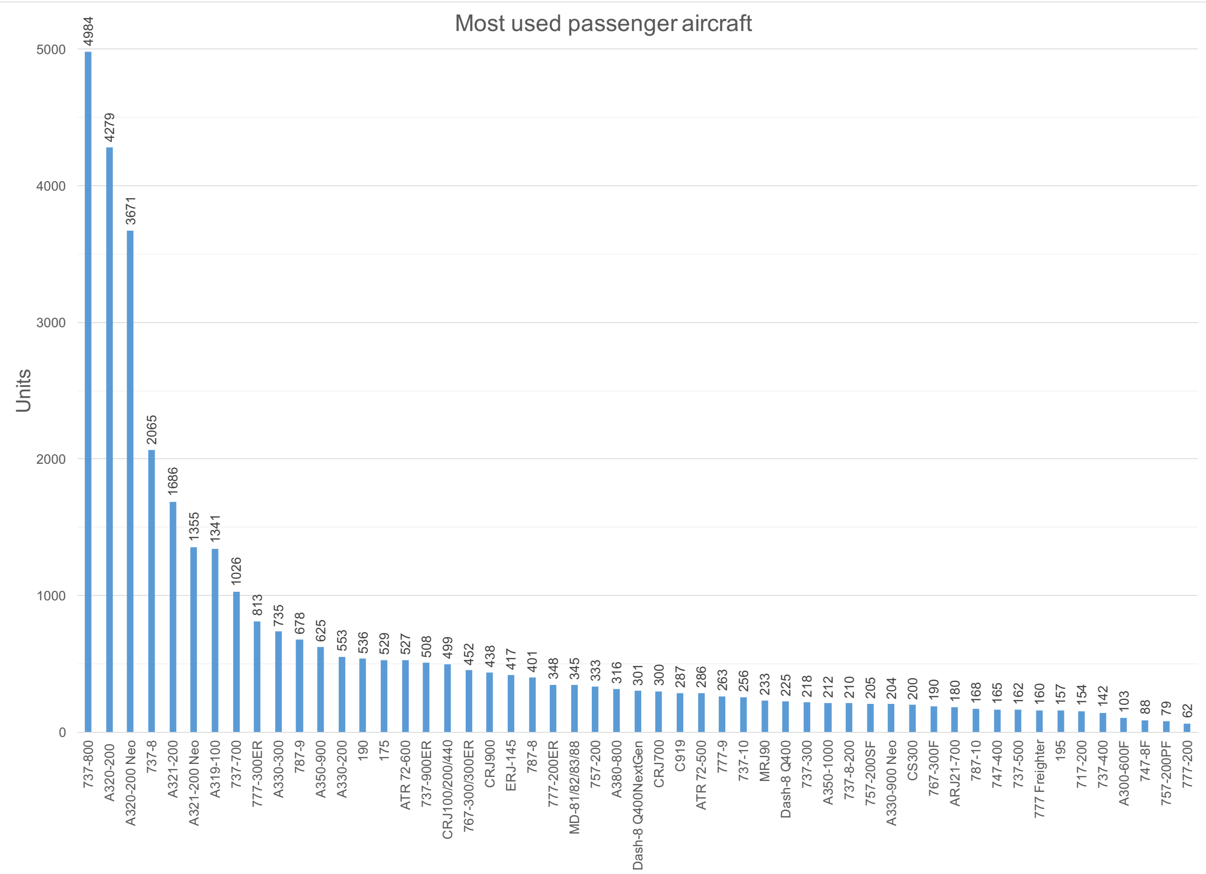


Figure 4. 4 Most used passenger aircraft total sales

5 Aircraft Analysis

5.1 Boeing 737-800

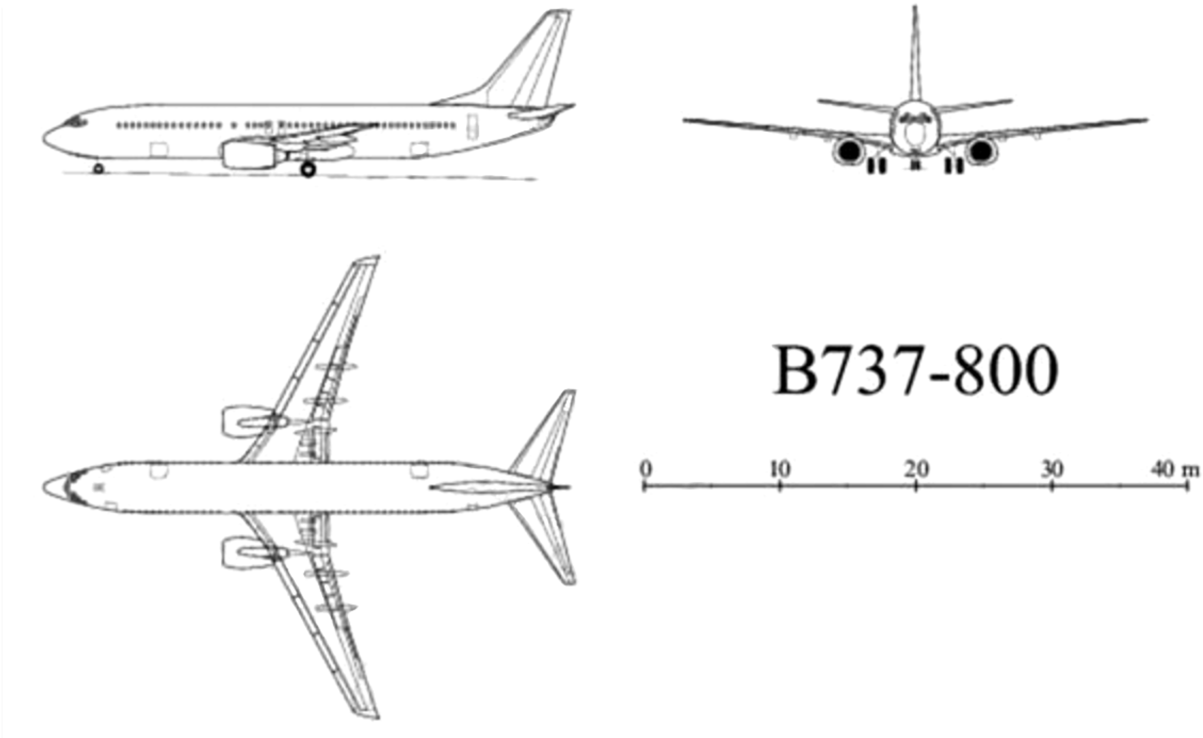


Figure 5. 1 3 view drawing of the Boeing 737-800 (**Roux 2007a**)

The 737-800 is a medium narrow-bodied jet with capacity for a maximum seating of 189 passengers whose first flight took place on July 31, 1997. It is considered the most liquid commercial aircraft in the market today due to its more than 4450 aircraft in active service, over 500 on order backlog and almost 200 operators. It belongs to the 737NG (Next Generation) family (737-700, 737-800 and 737-900ER). Among the aircraft family, the 737-800 represents the optimum model. It has a slightly longer fuselage than its 737-400 predecessor, increasing the seating capacity and overtaking by two seat-rows the A320, its main competitor, giving it a potential revenue advantage and lower seat-mile costs. Besides, the fact that there is only one engine option (CFM56-7B) generates no engine split as in the A320 market. In order to stimulate sales on the 737, Boeing offered performance upgrades consisting of an improved engine, the CFM56-7BE 'Evolution' engine, aerodynamic refinements, weight schedule improvements, the new Sky Interior, longer maintenance intervals, new space-saving lavatories and/or aggressive pricing, as well as standardize the use of winglets in order to improve in 3-5% the fuel burn. With more than 500 aircraft on order and the introduction of the 737 MAX, Boeing will increase the production of the 737 from 44 aircraft per month to 57 aircraft per month in 2019.

Boeing and Aeronautical Engineers (AEI) also offer freight conversions: AEI launched its 737-800SF (Special Freighter) program on 4 March 2014 while Boeing's 737-800BCF (Boeing

Converted Freighter) program was launched on 24 February 2016, being able to carry up to 23,9t of cargo in up to 6,5 cubic feet on routes of up to 3700km.

Table 5. 1 Input values of the Boeing 737-800

Parameter	Symbol	Units	Chosen value
PAX			189
Landing field length (ISA)	s_{LFL}	m	1646
Approach speed	V_{APP}	m/s	72
Take-off field length (ISA)	s_{TOFL}	m	2300
Range (max payload)	R	km	3700
Cruise Mach number	M_{CR}		0,785
Cruise speed	V_{CR}	m/s	232,5
Cruise altitude	h_{CR}	m	11887
Wing area	S_W	m²	124,6
Wing span	b_W	m	34,32
Aspect ratio	A		9,45
Maximum take-off mass	m_{MTO}	kg	78245
Payload mass	m_{PL}	kg	20276
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,259
Maximum landing mass	m_{ML}	kg	65315
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,835
Operating empty mass	m_{OE}	kg	41145
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,526
Maximum zero fuel mass	m_{MZF}	kg	61690
Wing loading	m_{MTO}/S_W	kg/m²	564,3
Number of engines	n_E		2
Engine type			CFM56-7B24
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	106,757
Total take-off thrust	T_{TO}	kN	213,514
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,31
Bypass ratio	μ		5,3
Overall pressure ratio	OAPR		26
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	1,05E-05
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	1,78E-05
Available fuel volume	$V_{fuel,available}$	m³	26,022
Sweep angle	ϕ_{25}	°	25
Mean aerodynamic chord	c_{MAC}	m	4,17
Position of maximum camber	$x_{(y\_c),max}$	%c	30
Camber	$(y_c)_{max}/c$	%c	4
Position of maximum thickness	$x_{t,max}$	%c	30
Relative thickness	t/c	%	12,5
Taper	λ		0,219

Table 5. 2 Reverse engineering results of the Boeing 737-800

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,98**	-11
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,30**	
Maximum aerodynamic efficiency	E_{max}	-	**18,17**	7
Specific fuel consumption	SFC	kg/N/s	**1,54E-05**	9

5.2 Airbus A320-200

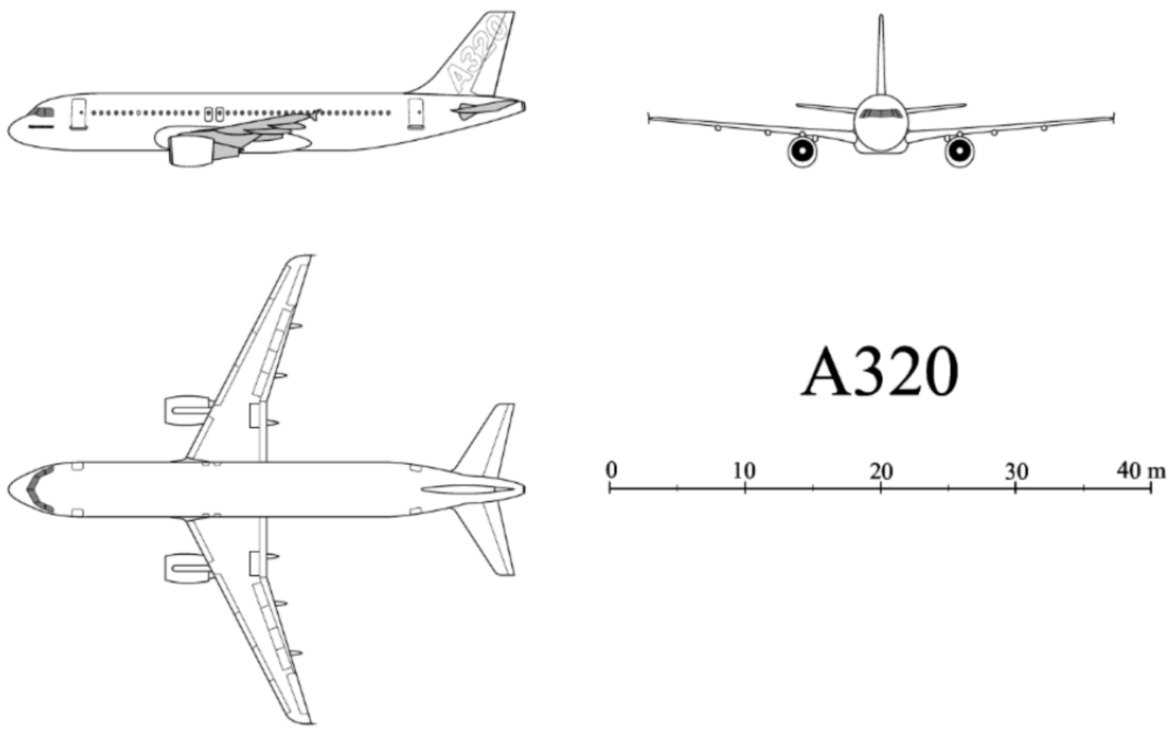


Figure 5. 2 3 view drawing of the Airbus A320-200 **(Roux 2007a)**

The A320-200 is a medium narrow-bodied jet with capacity for a maximum seating of 180 passengers whose first flight took place on June 27, 1988. It is the reference aircraft of narrow-bodied aircraft family from Airbus and is one of the most successful aircraft regarding sales volume. It had a successful entrance in the low cost market thank to the selection of the A320 by JetBlue in 1999 and was followed by more low cost airline orders, particularly from Asia, which led to a current value of 4048 airplanes in service, 231 on order and 266 operators around the world.

It was originally conceived as a longer range of its A320-100 predecessor, featuring wigtip fences and an increased fuel capacity. Early versions of the A320s were powered by the old V2500-A1 or CFM56-5A, that needed substantially more maintenance which made them much less attractive. However, modern versions are equipped with either CFM56-5B or IAE V2500-A5. Having split engine options is an advantage for operators during purchase operations and could be a disadvantage to the manufacturer since in theory two sub-fleets could limit remarketing options. Nevertheless, in case of the A320 the two sub-fleets each have enough critical mass to ensure market liquidity. In 2012 Airbus launched the so-called Sharklets (Airbus marketing name for winglets) which has resulted in an improvement of approximately 4% in fuel consumption which in turn improves operational flexibility, that is, an increase of 500kg of payload and 280km of additional range.

Table 5. 3 Input values of the Airbus 320-200

Parameter	Symbol	Units	Chosen value
PAX			180
Landing field length (ISA)	s_{LFL}	m	1490
Approach speed	V_{APP}	m/s	70
Take-off field length (ISA)	s_{TOFL}	m	2180
Range (max payload)	R	km	2870
Cruise Mach number	M_{CR}		0,78
Cruise speed	V_{CR}	m/s	230
Cruise altitude	h_{CR}	m	11278
Wing area	S_W	m²	122,4
Wing span	b_W	m	34,1
Aspect ratio	A		9,4
Maximum take-off mass	m_{MTO}	kg	77000
Payload mass	m_{PL}	kg	19000
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,247
Maximum landing mass	m_{ML}	kg	64500
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,838
Operating empty mass	m_{OE}	kg	42100
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,547
Maximum zero fuel mass	m_{MZF}	kg	61000
Wing loading	m_{MTO}/S_W	kg/m²	600
Number of engines	n_E		2
Engine type			CFM56-5B4
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	111,2
Total take-off thrust	T_{TO}	kN	222,4
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,32
Bypass ratio	μ		6
Overall pressure ratio	OAPR		29,1
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	9,62E-06
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	1,54E-05
Available fuel volume	$V_{fuel,available}$	m³	23,86
Sweep angle	ϕ_{25}	°	24,967
Mean aerodynamic chord	c_{MAC}	m	4,2
Position of maximum camber	$x_{(y\_c),max}$	%c	15
Camber	$(y_c)_{max}/c$	%c	1,8
Position of maximum thickness	$x_{t,max}$	%c	30
Relative thickness	t/c	%	15,2
Taper	λ		0,24

Table 5. 4 Reverse engineering results of the Airbus 320-200

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,31**	-6
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,29**	
Maximum aerodynamic efficiency	E_{max}	-	**16,80**	13
Specific fuel consumption	SFC	kg/N/s	**1,60E-05**	1

5.3 Airbus A320-200Neo

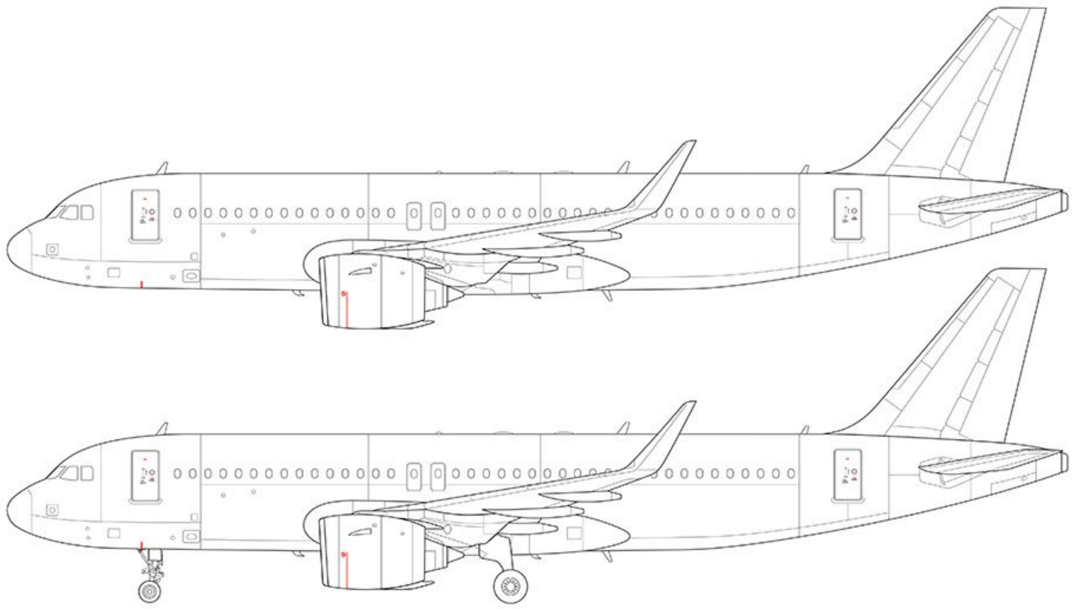


Figure 5. 3 3 view drawing of the Airbus A320-200Neo (**Norebbo 2020**)

The A320-200Neo is a medium narrow-bodied jet with capacity for a maximum seating of 189 passengers whose first flight took place on September 25, 2014. In December 2010, Airbus launched the 'New Engine Option' (or “NEO”) for the A320 family. Lufthansa was the first airline to be delivered the A320-200Neo and it was followed by more than 4000 aircraft in backlog. This new aircraft type results in an efficiency gain of 10-15% when compared to the standard A320-200. The gain is based on two new features: the new engine option and some aerodynamic and structural adjustments together with new winglets ('Sharklets'). The engine option consists of either the Pratt & Whitney's PW1100G-JM ('Geared Turbo Fan') engines or CFM's new Leap-1A engines, whose larger diameter (higher BPR and heavier) offers a 15% fuel burn advantage.

Table 5. 5 Input values of the Airbus 320-200Neo

Parameter	Symbol	Units	Chosen value
PAX			180
Landing field length (ISA)	s_{LFL}	m	1440
Approach speed	V_{APP}	m/s	69
Take-off field length (ISA)	s_{TOFL}	m	1880
Range (max payload)	R	km	4500
Cruise Mach number	M_{CR}		0,78
Cruise speed	V_{CR}	m/s	230
Cruise altitude	h_{CR}	m	11000
Wing area	S_W	m²	
Wing span	b_W	m	35,8
Aspect ratio	A		
Maximum take-off mass	m_{MTO}	kg	79000
Payload mass	m_{PL}	kg	19250
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,244
Maximum landing mass	m_{ML}	kg	67400
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,853
Operating empty mass	m_{OE}	kg	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		
Maximum zero fuel mass	m_{MZF}	kg	64300
Wing loading	m_{MTO}/S_W	kg/m²	
Number of engines	n_E		2
Engine type			CFM LEAP-1A
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	136,5
Total take-off thrust	T_{TO}	kN	273
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	
Bypass ratio	μ		
Overall pressure ratio	OAPR		40
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	26,73
Sweep angle	ϕ_{25}	°	24,967
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	15
Camber	$(y_c)_{max}/c$	%c	1,8
Position of maximum thickness	$x_{t,max}$	%c	30
Relative thickness	t/c	%	15
Taper	λ		

Table 5. 6 Reverse engineering results of the Airbus 320-200Neo

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,57**	-13
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,28**	
Maximum aerodynamic efficiency	E_{max}	-	**18,01**	13
Specific fuel consumption	SFC	kg/N/s	**1,36E-05**	8

5.4 Boeing 737-8

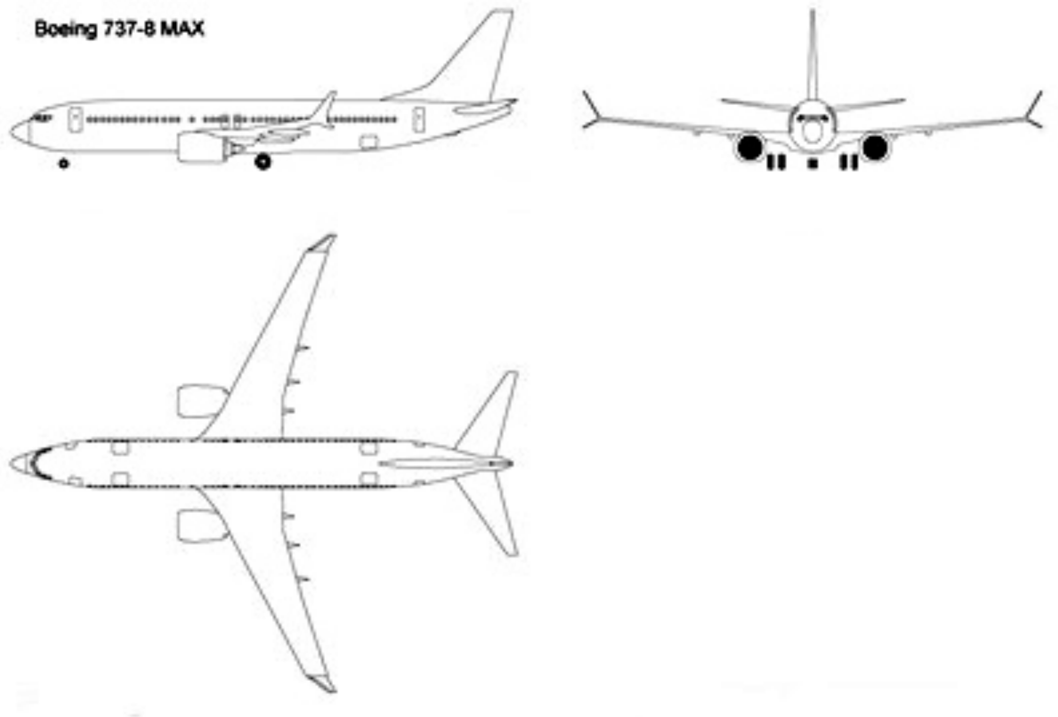


Figure 5. 4 3 view drawing of the Boeing 737-8 (**Blueprints 2020**)

The 737-8 is a medium narrow-bodied jet with capacity for a maximum seating of 189 passengers whose first flight took place on January 29, 2016. It was Boeing's respond to the introduction of the A320Neo family by Airbus. The 737-8 directly competes against the A320Neo with the 2056 orders that have been placed among 63 operators, making it the most popular 737 MAX variant. There are however many open orders for which the customer has not yet decided for the specific 737 MAX variant. The name "MAX" is used as a marketing term to name the whole family (737-7, 737-8, 737-8-200, 737-9 and 737-10), which was presented in August 2011 as a quick reaction to A320Neo's efficient specifications and high sales figures. Initially Boeing did not change the fuselage length and door configurations of the 737 MAX so the 737-7, 737-8 and 737-9 corresponded to those of the -700, -800 and 900ER members of the 737NG family.

The most important new feature of the 737 MAX was the introduction of the new CFM International LEAP-1B engine which are mounted higher and further forward relative to the 737NG's CFM56 engines and whose new larger fan diameter improves the fuel burn by a claimed 12-14%. The new engine also has external nacelle chevrons similar to those on the 787 and 747-8 which reduce engine noise. The new Leap-1B engine is smaller than either the Leap-1A or the PW1100G engine options available to operators of the new A320neo family. Fuel efficiency is also improved by some aerodynamic modifications on the fuselage (a new tail cone) of the 737 MAX and the introduction of a new winglet design, called the Boeing Advanced Technology ("AT") winglet. Therefore, the range of the 737 MAX has increased by 740-1000km compared to the 737NG.

Table 5. 7 Input values of the Boeing 737-8

Parameter	Symbol	Units	Chosen value
PAX			189
Landing field length (ISA)	s_{LFL}	m	1650
Approach speed	V_{APP}	m/s	
Take-off field length (ISA)	s_{TOFL}	m	2540
Range (max payload)	R	km	4630
Cruise Mach number	M_{CR}		0,79
Cruise speed	V_{CR}	m/s	233,89
Cruise altitude	h_{CR}	m	
Wing area	S_W	m²	124,6
Wing span	b_W	m	35,92
Aspect ratio	A		
Maximum take-off mass	m_{MTO}	kg	82190
Payload mass	m_{PL}	kg	
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		
Maximum landing mass	m_{ML}	kg	69308
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,843
Operating empty mass	m_{OE}	kg	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		
Maximum zero fuel mass	m_{MZF}	kg	65952
Wing loading	m_{MTO}/S_W	kg/m²	
Number of engines	n_E		2
Engine type			LEAP-1B25
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	130
Total take-off thrust	T_{TO}	kN	260
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	
Bypass ratio	μ		
Overall pressure ratio	OAPR		40
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	25,817
Sweep angle	ϕ_{25}	°	25
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	20,4
Camber	$(y_c)_{max}/c$	%c	1,5
Position of maximum thickness	$x_{t,max}$	%c	39,9
Relative thickness	t/c	%	10
Taper	λ		

Table 5. 8 Reverse engineering results of the Boeing 737-8

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,15**	-8
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**1,88**	
Maximum aerodynamic efficiency	E_{max}	-	**17,45**	17
Specific fuel consumption	SFC	kg/N/s	**1,77E-05**	-13

5.5 Airbus A321-200

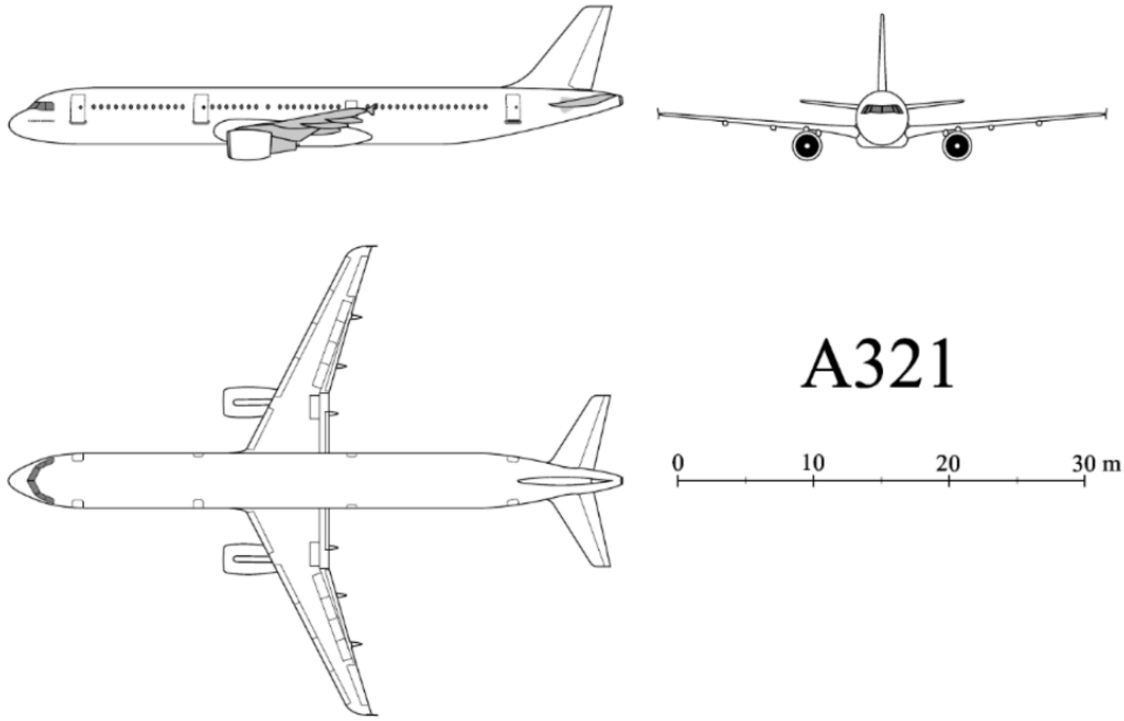


Figure 5. 5 3 view drawing of the Airbus A321-200 (**Roux 2007a**)

The A321-200 is a large narrow-bodied jet with capacity for a maximum seating of 220 passengers whose first flight took place on March 15, 1997. It is the first direct competitor to the Boeing 757-200. Although A321-200's range is not as high as the 757-200, the A321-200 become a strong competitor on medium routes, such as the US coast-to-coast, taking over the US domestic routes and leaving the 757 only for long distance single aisle routes. With 1443 aircraft in service and 243 on order, in the recent years the A321 sales figures have been rising resulting since 2010 in the outsold of the 319 and the outsold of the A320 in the past two years, making it the second most popular aircraft in the A320 family. With more than 100 operators, the A321-200 has become popular among low-cost carriers (Frontier, Vueling, WizzAir, VietJet, etc).

The A321-200 features structural reinforcements, a higher weight schedule and a provision for two ACTs which gives it its 5560km range when compared to its A321-100 predecesor. From mid-2013 'Sharklets' have been available for new A321s resulting in a fuel burn improvement of approximately 4% and 2550kg more payload which further enhances operational flexibility. Also, Airbus has developed increased cabin enhancements (“ICE”) to raise the A320 family's seating capacity through changes to cabin configuration (new rear galley configuration and lavatory design) and the use of slim-line seats. In 2014, the Aviation Authorities reassessed the A320 family exit limit to increase its exit capability, which also contributes to a higher seating capacity on A320 family aircraft. For the A321-200, all these initiatives, in combination with reduced seat pitches, improved the seat count by up to ten additional seats, resulting in a much lower fuel burn per seat.

Table 5. 9 Input values of the Airbus 321-200

Parameter	Symbol	Units	Chosen value
PAX			185
Landing field length (ISA)	s_{LFL}	m	1580
Approach speed	V_{APP}	m/s	72
Take-off field length (ISA)	s_{TOFL}	m	2200
Range (max payload)	R	km	3700
Cruise Mach number	M_{CR}		0,78
Cruise speed	V_{CR}	m/s	231
Cruise altitude	h_{CR}	m	11278
Wing area	S_W	m²	122,4
Wing span	b_W	m	34,09
Aspect ratio	A		9,4
Maximum take-off mass	m_{MTO}	kg	93500
Payload mass	m_{PL}	kg	23000
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,246
Maximum landing mass	m_{ML}	kg	77800
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,832
Operating empty mass	m_{OE}	kg	49200
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,526
Maximum zero fuel mass	m_{MZF}	kg	73800
Wing loading	m_{MTO}/S_W	kg/m²	762,6
Number of engines	n_E		2
Engine type			CFM56-5B3/P
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	142,342
Total take-off thrust	T_{TO}	kN	284,684
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,33
Bypass ratio	μ		5,4
Overall pressure ratio	OAPR		33,7
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	0,0000102
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	26,6
Sweep angle	ϕ_{25}	°	24,967
Mean aerodynamic chord	c_{MAC}	m	4,3
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		0,24

Table 5. 10 Reverse engineering results of the Airbus 321-200

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,76**	-18
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,62**	
Maximum aerodynamic efficiency	E_{max}	-	**15,35**	18
Specific fuel consumption	SFC	kg/N/s	**1,44E-05**	9

5.6 Airbus A321-200Neo

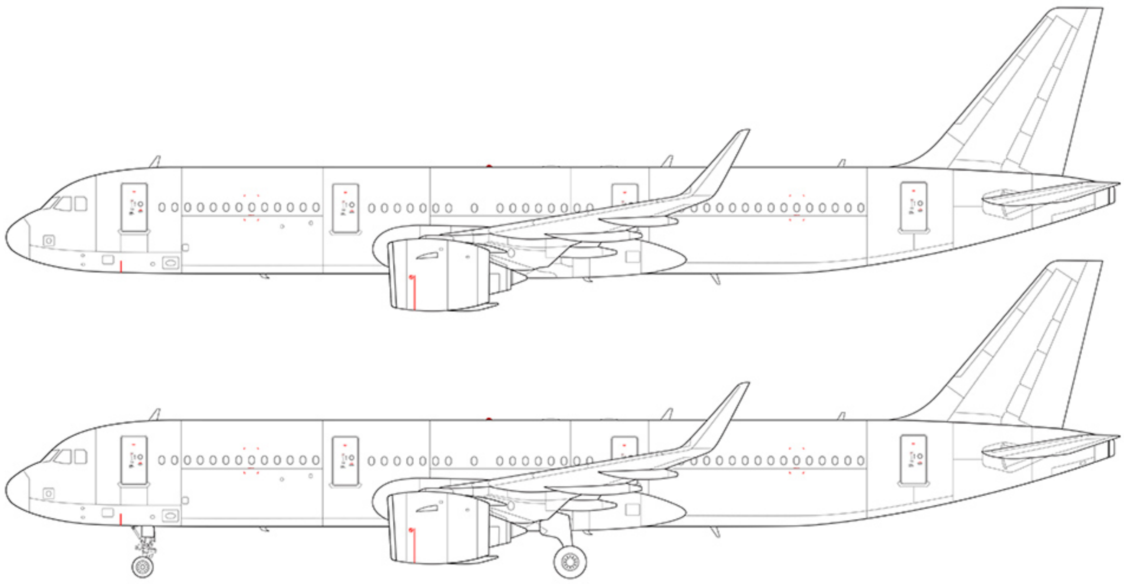


Figure 5. 6 3 view drawing of the Airbus A321-200Neo (**Norebbo 2020**)

The A321-200Neo is a large narrow-bodied jet with capacity for a maximum seating of 230 passengers whose first flight took place on February 9, 2016. The base-line A320-200Neo entered service in 2016 and the longer A321-200Neo followed in May 2017. The first A321-200N was delivered to Virgin America. With a backlog of more than 1300 aircraft, the A321-200Neo is a very successful programme for Airbus. Boeing tried hard to catch up with the 737-9 and the 737-10, but even if we combine the sales of these Boeing types, Airbus has still sold almost a thousand more A321-200Neo.

Like the A320-200Neo, the A321-200N will either have Pratt & Whitney's PW1100GJM ('Geared Turbo Fan') engines or CFM's new LEAP-1A engines. The larger (higher bypass ratio) and slightly heavier engines reportedly will offer ~15% fuel burn advantage. Together with some aerodynamic and structural adjustments and the new 'Sharklets' winglets, the anticipated efficiency gain is expected to be 10-15% compared to the preceding A321-200s.

Table 5. 11 Input values of the Airbus 321-200Neo

Parameter	Symbol	Units	Chosen value
PAX			202
Landing field length (ISA)	s_{LFL}	m	1700
Approach speed	V_{APP}	m/s	70
Take-off field length (ISA)	s_{TOFL}	m	2300
Range (max payload)	R	km	5600
Cruise Mach number	M_{CR}		0,79
Cruise speed	V_{CR}	m/s	231,5
Cruise altitude	h_{CR}	m	12000
Wing area	S_W	m²	
Wing span	b_W	m	35,8
Aspect ratio	A		
Maximum take-off mass	m_{MTO}	kg	97000
Payload mass	m_{PL}	kg	24000
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,247
Maximum landing mass	m_{ML}	kg	79200
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,816
Operating empty mass	m_{OE}	kg	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		
Maximum zero fuel mass	m_{MZF}	kg	75600
Wing loading	m_{MTO}/S_W	kg/m²	
Number of engines	n_E		2
Engine type			PW1133G-JM
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	147
Total take-off thrust	T_{TO}	kN	294
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	
Bypass ratio	μ		12,5
Overall pressure ratio	OAPR		
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	29,474
Sweep angle	ϕ_{25}	°	24,967
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		

Table 5. 12 Reverse engineering results of the Airbus 321-200Neo

Secret parameter	Symbol	Units	RE Value	Verification deviation[%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,46**	-10
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,42**	
Maximum aerodynamic efficiency	E_{max}	-	**20,10**	3
Specific fuel consumption	SFC	kg/N/s	**1,25E-05**	17

5.7 Airbus A319-100

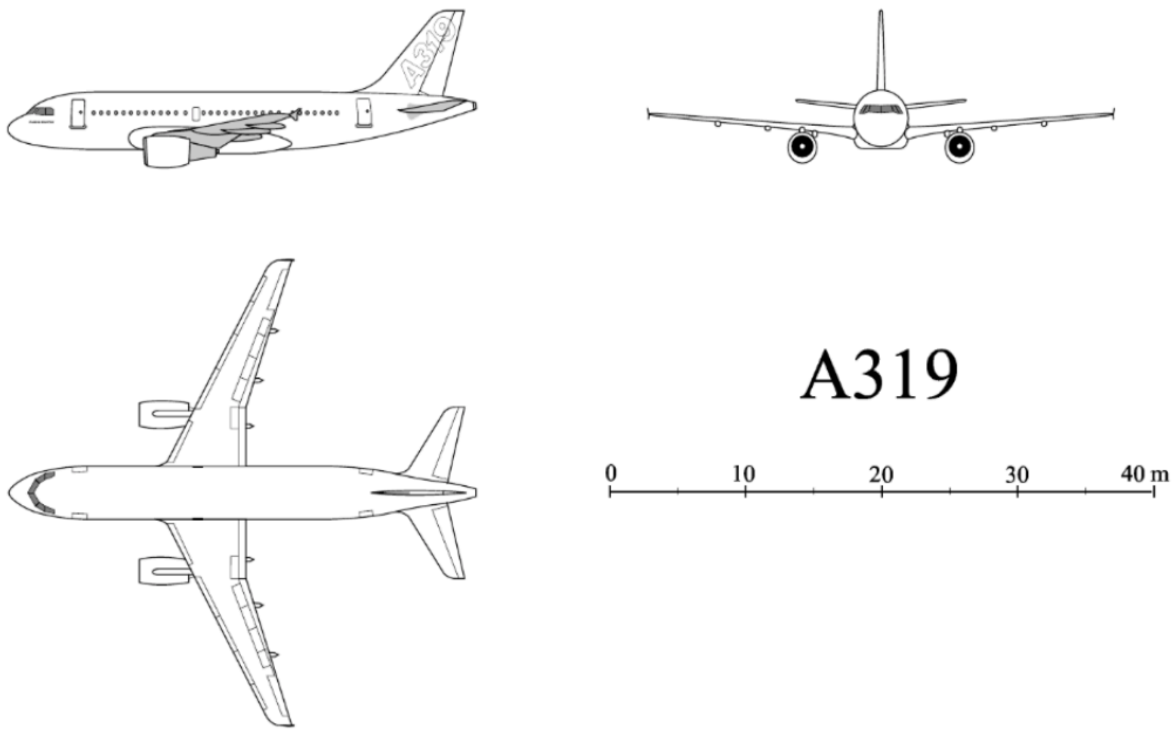


Figure 5. 7 3 view drawing of the Airbus A319-100 (**Roux 2007a**)

The A319-100 is a moderate size narrow-bodied jet with capacity for a maximum seating of 156 passengers whose first flight took place on August 29, 1995. For a long time, the A319 was the second most popular member of the A320 family, with over 1300 in service aircraft, but, based on the current trend in orders, it has lost this position to the A321. Due to the few on order aircraft (just 25), A319-100's sales have been lagging behind the larger A320 and A321 which have lower seat-mile costs due to their larger seating capacity. The outlook for the A319 is rather unclear. The biggest operator, easyJet has started to gradually phase out the A319 but, on the other hand, low cost carriers such as Allegiant and Volotea are looking for second hand A319s as they transition their fleets from the MD-80 / Boeing 717 to a fleet of Airbus narrow-bodied aircraf.

The A319 is a simple shrink of the baseline A320. Like its main competitor, the 737-700, it is used by a wide range of operators, specifically 131 operators. The
increased MTOW options combined with up to two additional fuel tanks give the A319 a relatively long range by single aisle standards. Since 2013 “Sharklets” have been available for the A319s, replacing the original wingtip fences for in-service A320 Family aircraft, resulting in 4.0% fuel burn improvement and 500kg more payload. The Airbus developement of “ICE” (increased cabin enhancements) along with the Aviation Authorities reassessment of the A320 family exit limit to increase the A320 exit capability meant the improvement of the seat count by up to 15 additional seats resulting in lower operating cost per seat. Airbus developed a second over-wing emergency exit option, initially for easyJet, allowing an increase from 145 to 156 passengers.

The A319 is also offered in a low-density long range version for (high) premium services and as an intercontinental corporate jet with up to six additional fuel tanks. There are 65 A319s in service as corporate/private jet/VIP/Head of State aircraft (called the ACJ319).

Table 5. 13 Input values of the Airbus 319-100

Parameter	**Symbol**	**Units**	**Chosen value**
PAX			156
Landing field length (ISA)	s_{LFL}	m	1400
Approach speed	V_{APP}	m/s	67
Take-off field length (ISA)	s_{TOFL}	m	1750
Range (max payload)	R	km	4630
Cruise Mach number	M_{CR}		0,78
Cruise speed	V_{CR}	m/s	230
Cruise altitude	h_{CR}	m	11278
Wing area	S_W	m²	122,4
Wing span	b_W	m	34,09
Aspect ratio	A		9,4
Maximum take-off mass	m_{MTO}	kg	75500
Payload mass	m_{PL}	kg	17900
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,237
Maximum landing mass	m_{ML}	kg	62500
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,828
Operating empty mass	m_{OE}	kg	41200
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,546
Maximum zero fuel mass	m_{MZF}	kg	58500
Wing loading	m_{MTO}/S_W	kg/m²	616,8
Number of engines	n_E		2
Engine type			CFM56-5B6
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	104,5
Total take-off thrust	T_{TO}	kN	209
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,32
Bypass ratio	μ		6,2
Overall pressure ratio	OAPR		24,1
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	9,06E-06
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	23,859
Sweep angle	ϕ_{25}	°	24,967
Mean aerodynamic chord	c_{MAC}	m	4,2
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	11,8
Taper	λ		0,24

Table 5. 14 Reverse engineering results of the Airbus 319-100

Secret parameter	Symbol	Units	RE Value	Verification deviation[%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,26**	-5
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,33**	
Maximum aerodynamic efficiency	E_{max}	-	**17,65**	7
Specific fuel consumption	SFC	kg/N/s	**1,62E-05**	2

5.8 Boeing 737-700

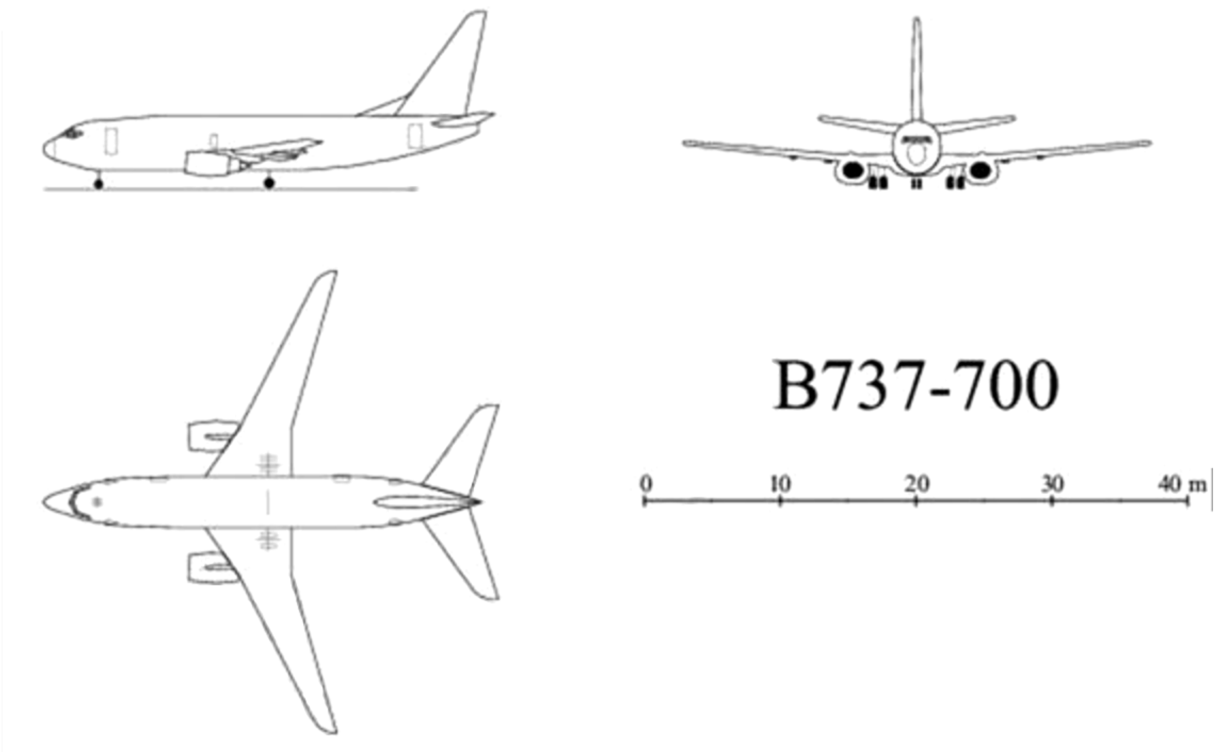


Figure 5. 8 3 view drawing of the Boeing 737-700 (**Roux 2007a**)

The 737-700 is a moderate size narrow-bodied jet with capacity for a maximum seating of 149 passengers whose first flight took place on February 9, 1997. As stated before, the 737-700 is part of the 737 New Generation family and it is the successor of the 737-300. This means it offers the new features of the New Generation family keeping the same old fuselage. It had a decent commercial success, with more than 1000 in service aircrafts and a broad operator base consisting of more than 100 operators, with a large fleet, concentrated at large large North American airlines. Besides, Southwest has added in recent years more than 65 737-700s, previously operated by other airlines, to its fleet and 12 more used 737-700s are due to enter the active Southwest fleet in the near future. Its main competitor, the Airbus A319, is similarly popular and both aircraft seem to have perfectly split the 130-seat market for years.

The 737-700 has benefitted from performance upgrades like the CFM56-7BE 'Evolution' engines, aerodynamic refinements, weight schedule improvements, the new Sky Interior and/or aggressive pricing. Blended Winglets (3-5% fuel burn improvement) are becoming more prevalent (915 in service).

Table 5. 15 Input values of the Boeing 737-700

Parameter	Symbol	Units	Chosen value
PAX			149
Landing field length (ISA)	s_{LFL}	m	1400
Approach speed	V_{APP}	m/s	67
Take-off field length (ISA)	s_{TOFL}	m	1800
Range (max payload)	R	km	2852
Cruise Mach number	M_{CR}		0,785
Cruise speed	V_{CR}	m/s	232
Cruise altitude	h_{CR}	m	11887
Wing area	S_W	m²	124,6
Wing span	b_W	m	34,32
Aspect ratio	A		9,45
Maximum take-off mass	m_{MTO}	kg	69400
Payload mass	m_{PL}	kg	17010
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,245
Maximum landing mass	m_{ML}	kg	58060
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,837
Operating empty mass	m_{OE}	kg	38147
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,550
Maximum zero fuel mass	m_{MZF}	kg	54658
Wing loading	m_{MTO}/S_W	kg/m²	484
Number of engines	n_E		2
Engine type			CFM56-7B20
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	91,633
Total take-off thrust	T_{TO}	kN	183,266
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,31
Bypass ratio	μ		5,6
Overall pressure ratio	OAPR		22,7
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	1,02E-05
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	1,79E-05
Available fuel volume	$V_{fuel,available}$	m³	26,022
Sweep angle	ϕ_{25}	°	25
Mean aerodynamic chord	c_{MAC}	m	4,17
Position of maximum camber	$x_{(y\_c),max}$	%c	10
Camber	$(y_c)_{max}/c$	%c	0,8
Position of maximum thickness	$x_{t,max}$	%c	29,7
Relative thickness	t/c	%	12,5
Taper	λ		0,219

Table 5. 16 Reverse engineering results of the Boeing 737-700

Secret parameter	Symbol	Units	RE Value	Verification deviation[%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,11**	-14
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,44**	
Maximum aerodynamic efficiency	E_{max}	-	**17,99**	8
Specific fuel consumption	SFC	kg/N/s	**1,72E-05**	0

5.9 Boeing 777-300ER

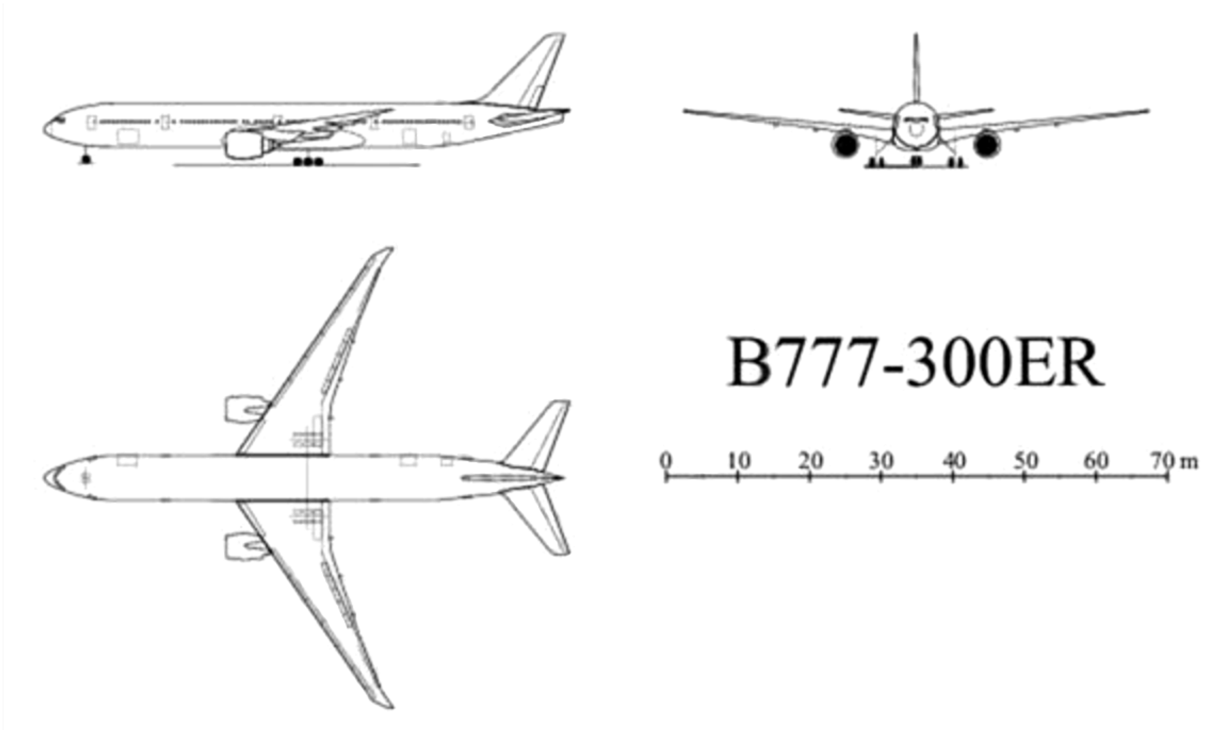


Figure 5. 9 3 view drawing of the Boeing 777-300ER (**Roux 2007a**)

The 777-300ER is a large wide-bodied jet with capacity for a maximum seating of 396 passengers whose first flight took place on February 24, 2003. It basically consists of the stretched 777-300 fuselage with the larger, stronger wing of the 777-200LR and the GE90 engines as only posible option, which simplifies remarketing. With 745 built and delivered aircraft and 68 on order, the 777-300ER has become the must successful Boeing wide-bodied aircraft. The main reason was the successfully replacement of the 747-100/200/300 and even the 747-400, for this was the main purpose the 777-300ER was conceived for. Therefore, the longer term 747 replacement market and limited competition from Airbus' much less efficient four-engined A340- 600 almost gave the 777-300ER a monopoly in its market segment. However, the A350-1000, which entered service in 2017, is to offer a very strong challenge.

To ensure that the current 777-300ER remains competitive in the long range market well after the 777X enters service, Boeing introduced a set of upgrades for the current 777-300ER early 2015. These upgrades include engine and aerodynamic improvements and interior adjustments.

These will result in 2% fuel-burn savings and an increased seating capacity by up to 14 seats that will push the potential fuel-burn savings on a per-seat basis to as much as 5%. Most of the upgrades are retrofitable, and must help Boeing to keep the 777-300ER attractive and pursue new sales of the current generation 777-300ER until the transition to the 777X at the end of this decade. With the coming introduction of the A350-1000 and the 777-9, sales of the 777-300ER have slowed down and its looks like its heydays are over. In the last two years the 777-300ER's backlog has shrunk which has forced Boeing to cut production and with the current order backlog, this new production rate means that Boeing has already sold 90% of the available slots for 2019.

Table 5. 17 Input values of the Boeing 777-300ER

Parameter	Symbol	Units	Chosen value
PAX			370
Landing field length (ISA)	s_{LFL}	m	1844
Approach speed	V_{APP}	m/s	77
Take-off field length (ISA)	s_{TOFL}	m	3050
Range (max payload)	R	km	9275
Cruise Mach number	M_{CR}		0,84
Cruise speed	V_{CR}	m/s	252
Cruise altitude	h_{CR}	m	10668
Wing area	S_W	m²	427,8
Wing span	b_W	m	64,79
Aspect ratio	A		8,7
Maximum take-off mass	m_{MTO}	kg	351535
Payload mass	m_{PL}	kg	69853
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,199
Maximum landing mass	m_{ML}	kg	251290
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,715
Operating empty mass	m_{OE}	kg	167829
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,477
Maximum zero fuel mass	m_{MZF}	kg	237682
Wing loading	m_{MTO}/S_W	kg/m²	615
Number of engines	n_E		2
Engine type			GE90-115B
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	511,5
Total take-off thrust	T_{TO}	kN	1023
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,3
Bypass ratio	μ		7,2
Overall pressure ratio	OAPR		42
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	181,283
Sweep angle	ϕ_{25}	°	31,64
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	30
Camber	$(y_c)_{max}/c$	%c	5,9
Position of maximum thickness	$x_{t,max}$	%c	30
Relative thickness	t/c	%	22
Taper	λ		

Table 5. 18 Reverse engineering results of the Boeing 777-300ER

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,98**	-11
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,13**	
Maximum aerodynamic efficiency	E_{max}	-	**16,25**	27
Specific fuel consumption	SFC	kg/N/s	**1,22E-05**	22

5.10 Airbus A330-300

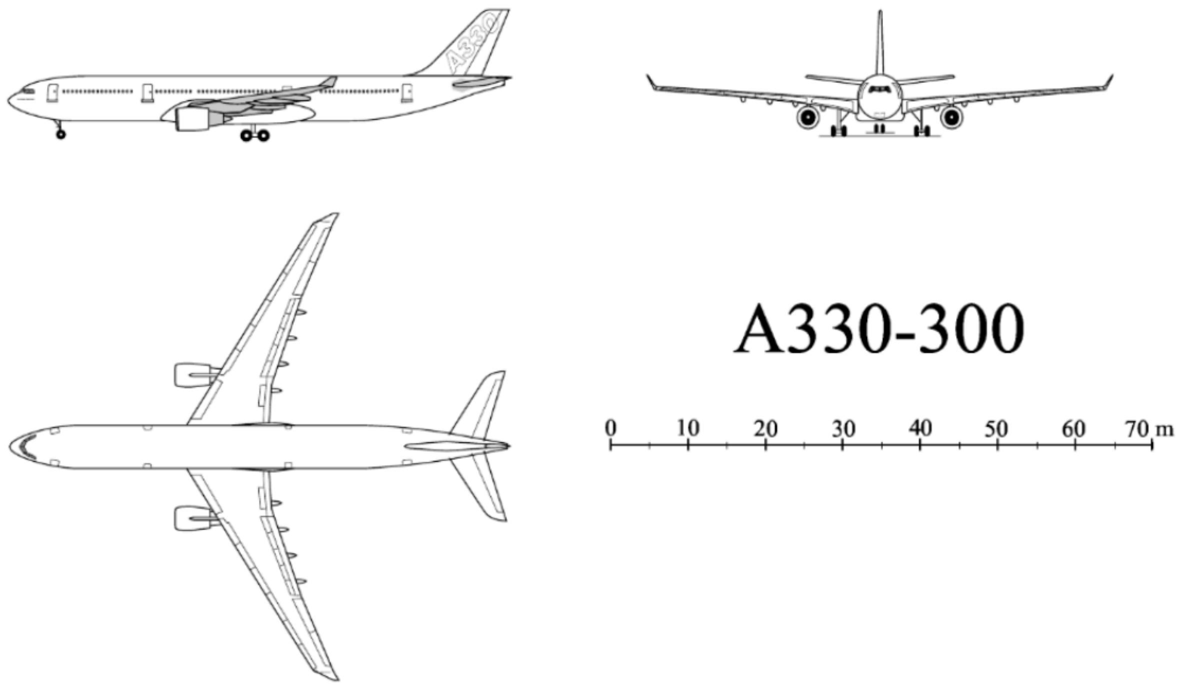


Figure 5. 10 3 view drawing of the Airbus A330-300 (**Roux 2007a**)

The A330-300 is a large wide-bodied jet with capacity for a maximum seating of 440 passengers whose first flight took place on November 2, 1992. The A330-300 is the twin-engined, medium-range sister of the long-range A340-300, with the same fuselage, wing and cockpit. It can be equipped with engines from all three major engine manufacturers. The Airbus A330-300 entered commercial service in 1994 and was optimized for medium range high-density markets, but continuous improvement on the A330-300 means that it has developed into a very capable and efficient medium to long haul aircraft. Prove of that is its 663 in service aircraft and 72 on order. Because of its lower structural weight (higher efficiency) and greater range capability it enjoys considerably more success than the 777-200.

With 20 year's production and the introduction of new generation competitors as the A350XWB and 787, Airbus has been studying ways to extend the life of the A330. In 2013 Airbus launched a new regional version of the A330-300 with a lower 199t MTOW, de-rated engines, a cockpit optimized for high cycle operations and a high density cabin tailored for shorter ranges (less galleys and crew rest rooms). This makes the A330-300 a relatively low-priced short-haul wide bodied people mover. This version is primarily aimed at markets with large populations and fast growing, concentrated air traffic flows (so mainly SO-Asia and China), and is in fact a kind of a return to the originally A330-300 design and intended role.

Table 5. 19 Input values of the Airbus A330-300

Parameter	Symbol	Units	Chosen value
PAX			375
Landing field length (ISA)	s_{LFL}	m	1750
Approach speed	V_{APP}	m/s	70
Take-off field length (ISA)	s_{TOFL}	m	2320
Range (max payload)	R	km	7000
Cruise Mach number	M_{CR}		0,82
Cruise speed	V_{CR}	m/s	
Cruise altitude	h_{CR}	m	11887
Wing area	S_W	m²	361,6
Wing span	b_W	m	60,3
Aspect ratio	A		10,01
Maximum take-off mass	m_{MTO}	kg	242000
Payload mass	m_{PL}	kg	48400
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,200
Maximum landing mass	m_{ML}	kg	185000
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,764
Operating empty mass	m_{OE}	kg	124600
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,515
Maximum zero fuel mass	m_{MZF}	kg	173000
Wing loading	m_{MTO}/S_W	kg/m²	633
Number of engines	n_E		2
Engine type			Trent 772-60
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	316,267
Total take-off thrust	T_{TO}	kN	632,534
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,28
Bypass ratio	μ		4,89
Overall pressure ratio	OAPR		36,8
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	1,60E-05
Available fuel volume	$V_{fuel,available}$	m³	97,53
Sweep angle	ϕ_{25}	°	29,7
Mean aerodynamic chord	c_{MAC}	m	7,28
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	15,3-11,3-10,6
Taper	λ		0,235

Table 5. 20 Reverse engineering results of the Airbus 330-300

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,73**	1
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,53**	
Maximum aerodynamic efficiency	E_{max}	-	**19,19**	10
Specific fuel consumption	SFC	kg/N/s	**1,55E-05**	1

5.11 Boeing 787-9

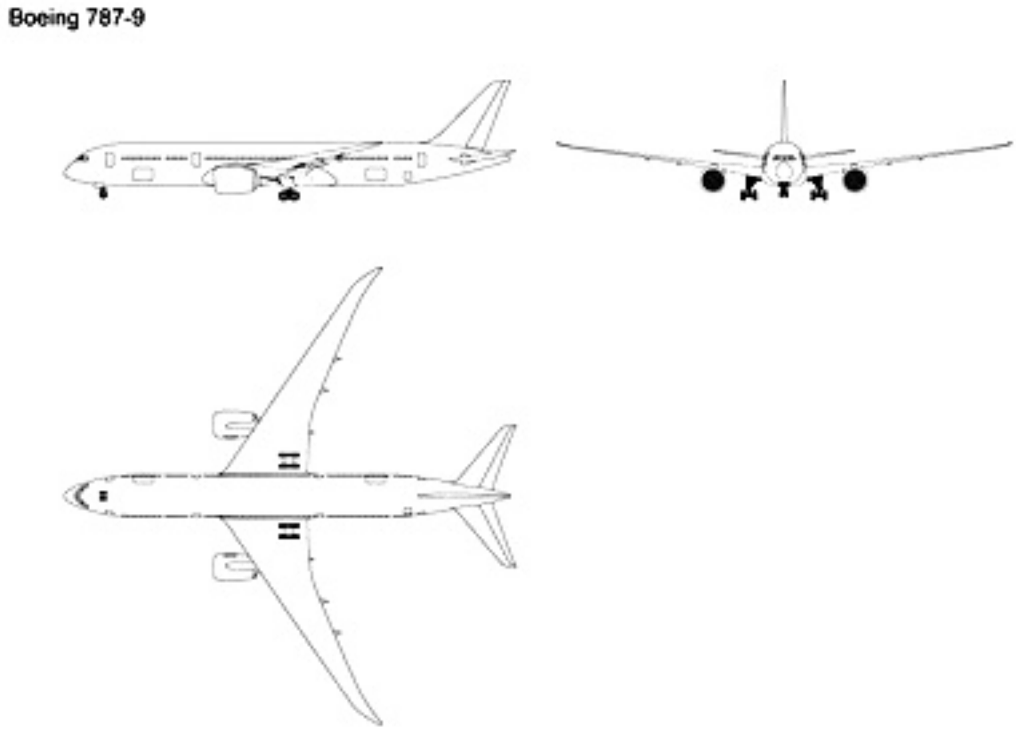


Figure 5. 11 3 view drawing of the Boeing 787-9 (**Blueprints 2020**)

The 787-9 is a medium wide-bodied jet with capacity for a maximum seating of 420 passengers whose first flight took place, after some design and production difficulties which led to serious delays, on September 17, 2013. However, the 787-9 did not suffer from a difficult entry-into-service with operational reliability problems for the airlines as the 787-8 did. For this reason, customers increasingly see the 787-9 as the preferred variant with better performance. As of summer 2017, with 242 787-9s in active service and 436 787-9s on order, the 787-9 has clearly outsold the 787-8.

In general, the 787 family features many new technologies like a full composite structure including wing and barrel shaped fuselage sections (accommodates 9 abreast seating), new up to

15-20% more efficient and relatively quiet engines, improved aerodynamics and many new electric systems instead of pneumatics/hydraulics.

The 787 family is initially designed to replace the 757- and 767 products but the 787-9 variant is closer to the 777-200ER in terms of payload-range. Compared to the baseline 787-8, the 787-9 has more powerful engines and a stretched fuselage which should enable it to carry some 40 more passengers over an additional 550km range. The A350-800 is expected to be a close competitor but the slightly larger A350-900 could offer competing seat-mile economics as well. Compared to the larger 777-200ER, the 787-9 is expected to bring a 20% relative trip cost improvement which is a 10% improvement in seat mile cost.

Table 5. 21 Input values of the Boeing 787-9

Parameter	Symbol	Units	Chosen value
PAX			420
Landing field length (ISA)	s_{LFL}	m	1870
Approach speed	V_{APP}	m/s	
Take-off field length (ISA)	s_{TOFL}	m	3140
Range (max payload)	R	km	9720
Cruise Mach number	M_{CR}		0,85
Cruise speed	V_{CR}	m/s	252
Cruise altitude	h_{CR}	m	
Wing area	S_W	m²	325
Wing span	b_W	m	60,12
Aspect ratio	A		11,1
Maximum take-off mass	m_{MTO}	kg	254011
Payload mass	m_{PL}	kg	
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		
Maximum landing mass	m_{ML}	kg	192776
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,759
Operating empty mass	m_{OE}	kg	115350
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,454
Maximum zero fuel mass	m_{MZF}	kg	181436
Wing loading	m_{MTO}/S_W	kg/m²	
Number of engines	n_E		2
Engine type			GEnx 72A1
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	235,76
Total take-off thrust	T_{TO}	kN	471,52
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	
Bypass ratio	μ		9
Overall pressure ratio	OAPR		46,3
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	126,429
Sweep angle	ϕ_{25}	°	32,2
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		

Table 5. 22 Reverse engineering results of the Boeing 787-9

Secret parameter	Symbol	Units	RE Value	Verification deviation[%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,96**	3
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,20**	
Maximum aerodynamic efficiency	E_{max}	-	**20,08**	27
Specific fuel consumption	SFC	kg/N/s	**1,23E-05**	21

5.12 Airbus A350-900

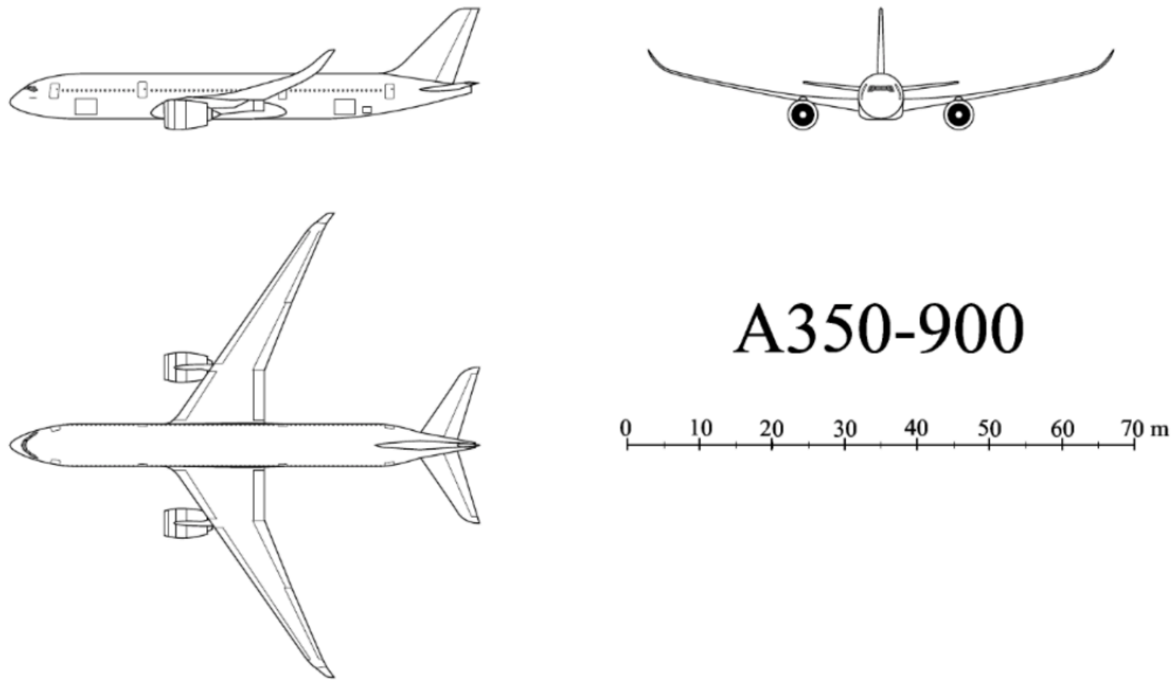


Figure 5. 12 3 view drawing of the Airbus 350-900 (**Roux 2007a**)

The A350-900 is a large wide-bodied jet with capacity for a maximum seating of 315 passengers whose first flight took place on June 14, 2013. The A350 family represents the Airbus' answer to the slightly smaller Boeing 787 family and effectively also competes with the slightly larger Boeing 777 family. It is also considered to be the future twin-engine replacement of the A330/A340 family as well. With 105 A350-900s aircraft in service and 520 on order, it is by far the most popular variant of the A350 family

After its first launch in 2004, the design failed to impress the market and was criticized for being nothing more but an upgraded A330 which wouldn’t be able to compete with the Boeing 787. Airbus responded with the redesigned A350 'XWB' (eXtra Wide Body) which featured a wider fuselage, a new (composite) wing, upgraded A380 based systems and an advanced technology cockpit with 6 large LCD screens. The A350-900 is the first and base line A350 model and features a fuselage which is longer than the A350-800 to accommodate approximately 40 more passengers. In terms of payload-range, the A350-900 is positioned closest to the 777-200ER which has 740km less range and a slightly lower seat capacity. The slightly smaller 787-9 and stretched 787-10 are competitors as well.

Currently around 105 A350-900s have been delivered to various customers and most airlines note that the reliability of the A350 is “over and beyond” expectations. So the entry into service of this new design seems to be without any problems. Something which cannot be said from its production process.

In October 2015 Airbus introduced a new long range version of the A350-900. The A350-900ULR (Ultra Long Range) will feature a higher 278/280t MTOW, a 17% higher usable fuel capacity as well as aerodynamic tweaks to stretch its range to 18000km.

Table 5. 23 Input values of the Airbus 350-900

Parameter	Symbol	Units	Chosen value
PAX			315
Landing field length (ISA)	s_{LFL}	m	1960
Approach speed	V_{APP}	m/s	72
Take-off field length (ISA)	s_{TOFL}	m	2830
Range (max payload)	R	km	10000
Cruise Mach number	M_{CR}		0,85
Cruise speed	V_{CR}	m/s	250,5
Cruise altitude	h_{CR}	m	13100
Wing area	S_W	m²	443
Wing span	b_W	m	64,75
Aspect ratio	A		9,25
Maximum take-off mass	m_{MTO}	kg	265000
Payload mass	m_{PL}	kg	49800
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,188
Maximum landing mass	m_{ML}	kg	202500
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,764
Operating empty mass	m_{OE}	kg	130700
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,493
Maximum zero fuel mass	m_{MZF}	kg	189500
Wing loading	m_{MTO}/S_W	kg/m²	598
Number of engines	n_E		2
Engine type			Trent XWB-74
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	329
Total take-off thrust	T_{TO}	kN	658
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,25
Bypass ratio	μ		8,9
Overall pressure ratio	OAPR		
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	138
Sweep angle	ϕ_{25}	°	35
Mean aerodynamic chord	c_{MAC}	m	8,35
Position of maximum camber	$x_{(y\_c),max}$	%c	15
Camber	$(y_c)_{max}/c$	%c	1,8
Position of maximum thickness	$x_{t,max}$	%c	30
Relative thickness	t/c	%	15
Taper	λ		0,113

Table 5. 24 Reverse engineering results of the Airbus 350-900

Secret parameter	Symbol	Units	RE Value	Verification deviation[%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,23**	-4
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**1,74**	
Maximum aerodynamic efficiency	E_{max}	-	**22,02**	7
Specific fuel consumption	SFC	kg/N/s	**1,54E-05**	0

5.13 Airbus A330-200

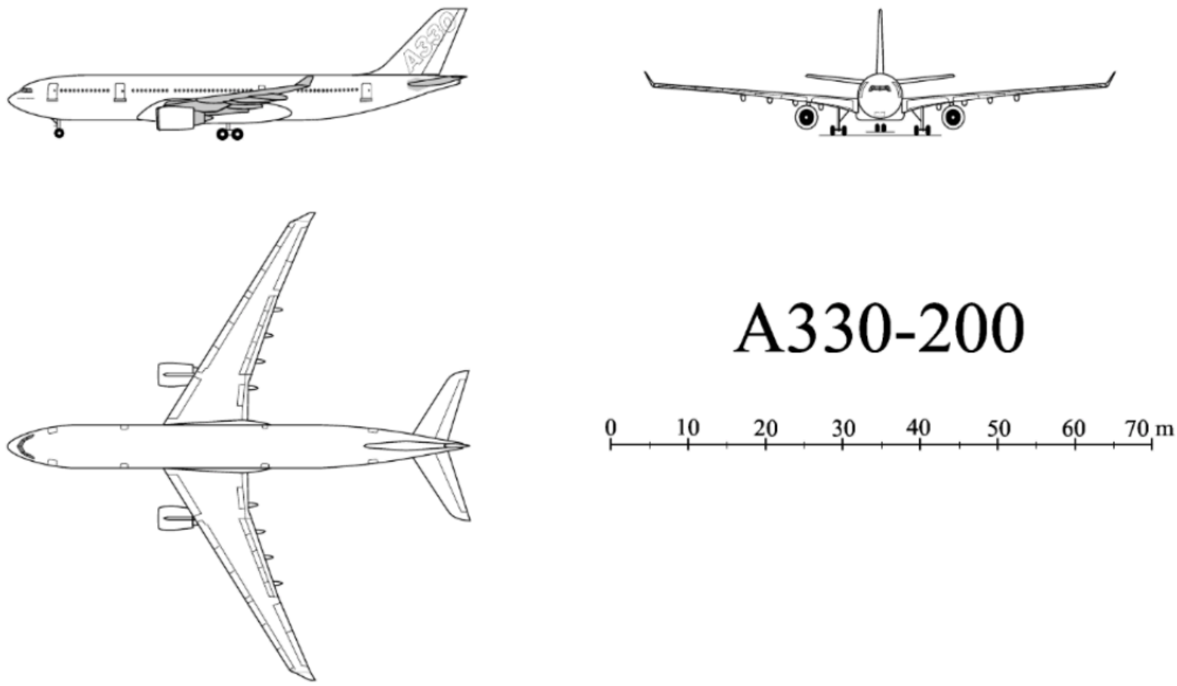


Figure 5. 13 3 view drawing of the Airbus 330-200 (**Roux 2007a)**

The A330-200 is a medium wide-bodied jet with capacity for a maximum seating of 406 passengers whose first flight took place on August 13, 1997. Iberia and Aerolíneas Argentinas are the first operators of 242t MTOW A330-200s. The 242t MTOW option makes the A330-200 an interesting aircraft for airlines who need the extra performance for hot-and-high operations or who need a suitable aircraft for long range, relatively low demand routes.

The A330-200 is the longer range, shorter fuselage development of the A330-300. Airbus positioned the A330-200 as an efficient, more capable and more comfortable alternative to the Boeing 767-300ER. Due to the initial sales success of the A330-200, with 528 aircraft built and delivered, supported by significant interest from leasing companies, Boeing decided to launch the stretched 767-400ER in 1997. The A330-200s newer technology, superior range capability and crew commonality with the A320 and A340 families made the A330-200 the preferred choice in its category. The coinciding demise of the 767 drove Boeing to the development of the Sonic Cruiser concept and later the 787 (originally 7E7) which initially claimed performance should be 20-30% more efficient (787-8) than the A330-200. However, the 787's troublesome entry into service (delays) caused strong (interim) demand for the A330 is now also offered at an upgraded 242t MTOW for more payload/range to better compete with the 787.

The continuous improvement to the A330 programme and especially the A330-300 means that the A330-300 has now almost the same range to offer as the A330-200 with far more passenger load. This makes the A330-300 a more efficient aircraft. Since 2009 annual sales of the A330-200 have been less than the A330-300 and by 2013 the A330-200 was finally outsold by the A330-300. The A330-200 backlog is currently 25 aircraft.

Table 5. 25 Input values of the Airbus 330-200

Parameter	Symbol	Units	Chosen value
PAX			375
Landing field length (ISA)	s_{LFL}	m	1750
Approach speed	V_{APP}	m/s	70
Take-off field length (ISA)	s_{TOFL}	m	2500
Range (max payload)	R	km	7400
Cruise Mach number	M_{CR}		0,82
Cruise speed	V_{CR}	m/s	241,79
Cruise altitude	h_{CR}	m	11887
Wing area	S_W	m²	361,6
Wing span	b_W	m	60,3
Aspect ratio	A		10,01
Maximum take-off mass	m_{MTO}	kg	242000
Payload mass	m_{PL}	kg	47400
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,196
Maximum landing mass	m_{ML}	kg	180000
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,744
Operating empty mass	m_{OE}	kg	120600
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,498
Maximum zero fuel mass	m_{MZF}	kg	168000
Wing loading	m_{MTO}/S_W	kg/m²	633
Number of engines	n_E		2
Engine type			Trent 772B-60
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	316,279
Total take-off thrust	T_{TO}	kN	632,558
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,28
Bypass ratio	μ		4,89
Overall pressure ratio	OAPR		36,8
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	1,60E-05
Available fuel volume	$V_{fuel,available}$	m³	139,09
Sweep angle	ϕ_{25}	°	29,7
Mean aerodynamic chord	c_{MAC}	m	7,28
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	15,3-11,3-10,6
Taper	λ		0,235

Table 5. 26 Reverse engineering results of the Airbus 330-200

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,66**	0
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,35**	
Maximum aerodynamic efficiency	E_{max}	-	**19,19**	10
Specific fuel consumption	SFC	kg/N/s	**1,64E-05**	-4

5.14 Embraer 190

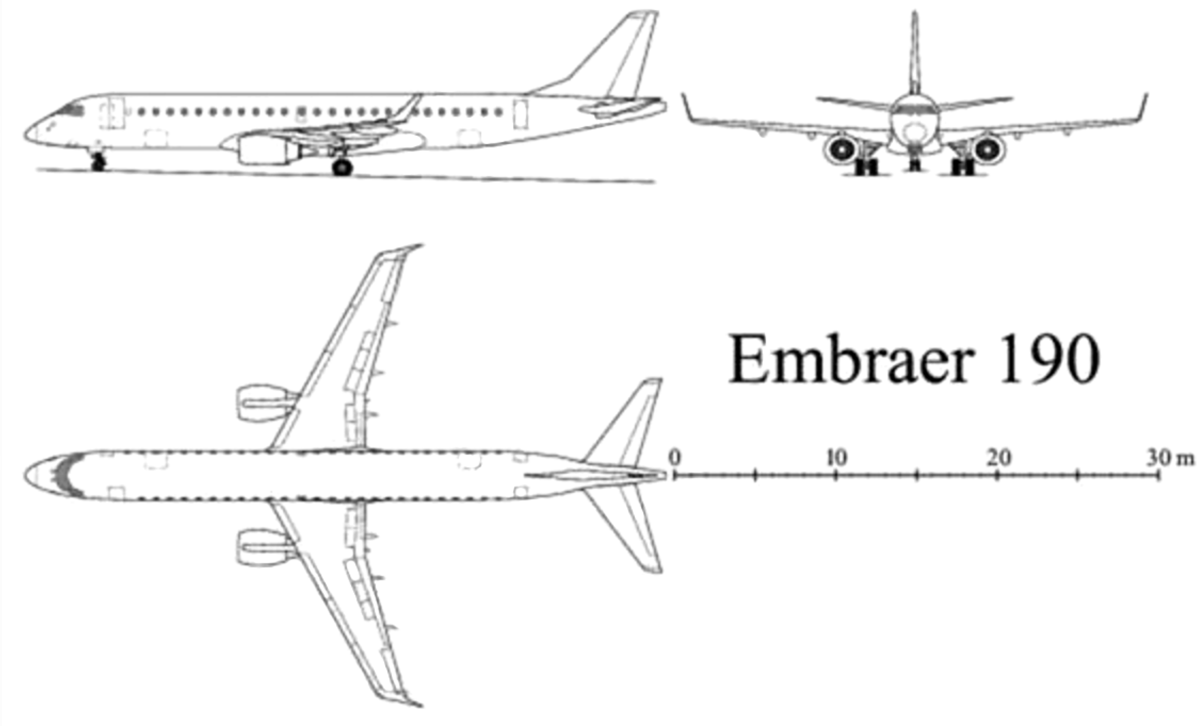


Figure 5. 14 3 view drawing of the Embraer 190 (**Roux 2007a**)

The Embraer 190 is a large regional jet with capacity for a maximum seating of 114 passengers whose first flight took place on March 12, 2004. It is currently offered in a standard, long and advanced range (STD/LR/AR) variant of which the -AR has become the production standard. The E190 is a stretch of the E170 and has a larger wing and more powerful engines with FADEC technology. It got certified for steep approaches in 2010 and enjoys a reasonable sound operator base (up to 44).

The Embraer 190 was launched by successful US low-cost carrier JetBlue Airways, which meant a significant victory for Embraer, indicating the viability of an E-jet as a low density route and market development aircraft. Apart from the North American market including Air

Canada (45 orders, from which 25 still in service) and American (20, inherited after the US Airways merger) as important customers, significant orders were taken from Latin America, Europe and Asia. There are currently 484 built and delivered aircraft and 52 more on order.

The E190's main competitor is the more efficient but narrower CRJ900/1000 and it is a replacement for the older Fokker F100, BAe146-300 and Avro RJ100. Also, for network operators, the E190 is an alternative for the smallest members of the 737 and A320 families. These offer fleet commonality benefits but are also significantly heavier, have much higher trip costs and are more difficult to fill in low density market. Going forward, the success of the E190 will be challenged by new competitors of which the slightly larger CS100 and slightly smaller MRJ90 will be equipped with considerably more efficient engines. Consequently, Embraer was forced to revamp its E-jet family. Early 2013 Embraer announced an enhanced version of the "1st" generation E-Jet, featuring a redesigned wingtip and two packages of aerodynamic, structural and systems improvements to the wing and the fuselage. The new E190 will not feature the new wingtip, designed exclusively for the E175. All these adjustments will lead to a reduction of fuel consumption by 1 – 2% on the E190.

Table 5. 27 Input values of the Embraer 190

Parameter	Symbol	Units	Chosen value
PAX			106
Landing field length (ISA)	s_{LFL}	m	1323
Approach speed	V_{APP}	m/s	
Take-off field length (ISA)	s_{TOFL}	m	2076
Range (max payload)	R	km	1852
Cruise Mach number	M_{CR}		0,78
Cruise speed	V_{CR}	m/s	236
Cruise altitude	h_{CR}	m	10669
Wing area	S_W	m²	92,53
Wing span	b_W	m	28,72
Aspect ratio	A		8,92
Maximum take-off mass	m_{MTO}	kg	51800
Payload mass	m_{PL}	kg	12900
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,249
Maximum landing mass	m_{ML}	kg	43000
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,830
Operating empty mass	m_{OE}	kg	27900
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,539
Maximum zero fuel mass	m_{MZF}	kg	40800
Wing loading	m_{MTO}/S_W	kg/m²	516,5
Number of engines	n_E		2
Engine type			CF34-10E5
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	82,292
Total take-off thrust	T_{TO}	kN	164,584
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,35
Bypass ratio	μ		5
Overall pressure ratio	OAPR		29
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	1,08E-05
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	16,029
Sweep angle	ϕ_{25}	°	
Mean aerodynamic chord	c_{MAC}	m	3,68
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	15,3-11,3-10,6
Taper	λ		

Table 5. 28 Reverse engineering results of the Embraer 190

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,28**	-12
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**1,95**	
Maximum aerodynamic efficiency	E_{max}	-	**14,41**	29
Specific fuel consumption	SFC	kg/N/s	**1,80E-05**	-4

5.15 Embraer 175

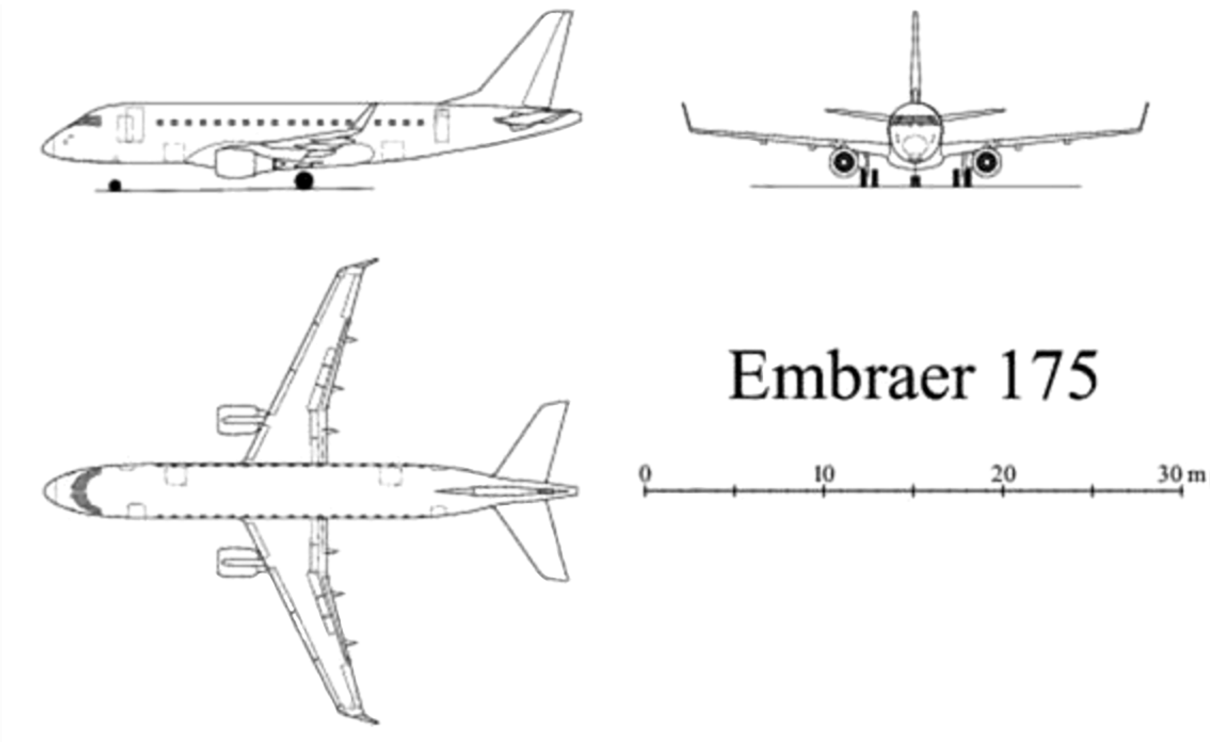


Figure 5. 15 3 view drawing of the Embraer 175 (**Roux 2007a**)

The Embraer 175 is a medium regional jet with capacity for a maximum seating of 88 passengers whose first flight took place on June 15, 2003. Like the E170, the E175 is offered in a basic, mid and high gross weight version (STD/LR/AR) with increasing range. The Embraer 175 is a two seat row stretch of the E170, resulting in an increased payload (8 more seats) at the cost of reduced range capability. Contrary to the E170 or the E190, the E175 is not certified for steep approaches which exclude it from certain airports like London City.

The scope clause optimized E175 is especially popular in the US and this has resulted in a huge concentration of E175s (80,3%) in the US at Republic Airlines (126 in service / 5 on order), Skywest Airlines (103 in service / 2 on order), Mesa Airlines (54 in service), Compass Airlines

(56 in service), Envoy Air (40 in service / 4 on order), Horizon Air (10 in service / 23 on order). As can be seen from this list, the E175 still has a healthy order backlog.

Like the E170, the main competition comes from the lighter but narrower CRJ700 but also the more efficient 70 seat turboprops (ATR72-500 and Q400) have become increasingly popular due to lower fuel burn, lower noise and fewer emissions. The arrival of a new regional jets such as the Superjet SSJ100, the Bombardier CS100 and Mitsubishi's MRJ70/90, the last two featuring significantly more efficient ultra-high bypass ratio engines, forced Embraer to revamp its E-jet family, announcing an enhanced version of the "1st" generation E-Jet, featuring a redesigned wingtip and two packages of aerodynamic, structural and systems improvements to the wing and the fuselage which led to a reduction of fuel consumption by 5% for the E175. The E175 is the only member of the E-jet family that features the full package of modifications, because: i) it believes the performance improvements will be most pronounced on this variant; ii) the E175 will be the last version of the "E1" family to be replaced by the "E2" and; iii) to strengthen the E175's position as the preferred scope optimized regional jet in North America.

Table 5. 29 Input values of the Embraer 175

Parameter	Symbol	Units	Chosen value
PAX			86
Landing field length (ISA)	s_{LFL}	m	1294
Approach speed	V_{APP}	m/s	
Take-off field length (ISA)	s_{TOFL}	m	1714
Range (max payload)	R	km	1815
Cruise Mach number	M_{CR}		0,78
Cruise speed	V_{CR}	m/s	221,4
Cruise altitude	h_{CR}	m	10668
Wing area	S_W	m²	72,72
Wing span	b_W	m	26
Aspect ratio	A		9,3
Maximum take-off mass	m_{MTO}	kg	40370
Payload mass	m_{PL}	kg	10200
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,253
Maximum landing mass	m_{ML}	kg	34100
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,845
Operating empty mass	m_{OE}	kg	21500
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,533
Maximum zero fuel mass	m_{MZF}	kg	31700
Wing loading	m_{MTO}/S_W	kg/m²	515,7
Number of engines	n_E		2
Engine type			CF34-8E2
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	62,275
Total take-off thrust	T_{TO}	kN	124,55
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,34
Bypass ratio	μ		5
Overall pressure ratio	OAPR		28,5
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	1,11E-05
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	11,625
Sweep angle	ϕ_{25}	°	
Mean aerodynamic chord	c_{MAC}	m	3,195
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		

Table 5. 30 Reverse engineering results of the Embraer 175

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,39**	-15
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,41**	
Maximum aerodynamic efficiency	E_{max}	-	**15,02**	27
Specific fuel consumption	SFC	kg/N/s	**1,94E-05**	-6

5.16 Boeing 737-900ER

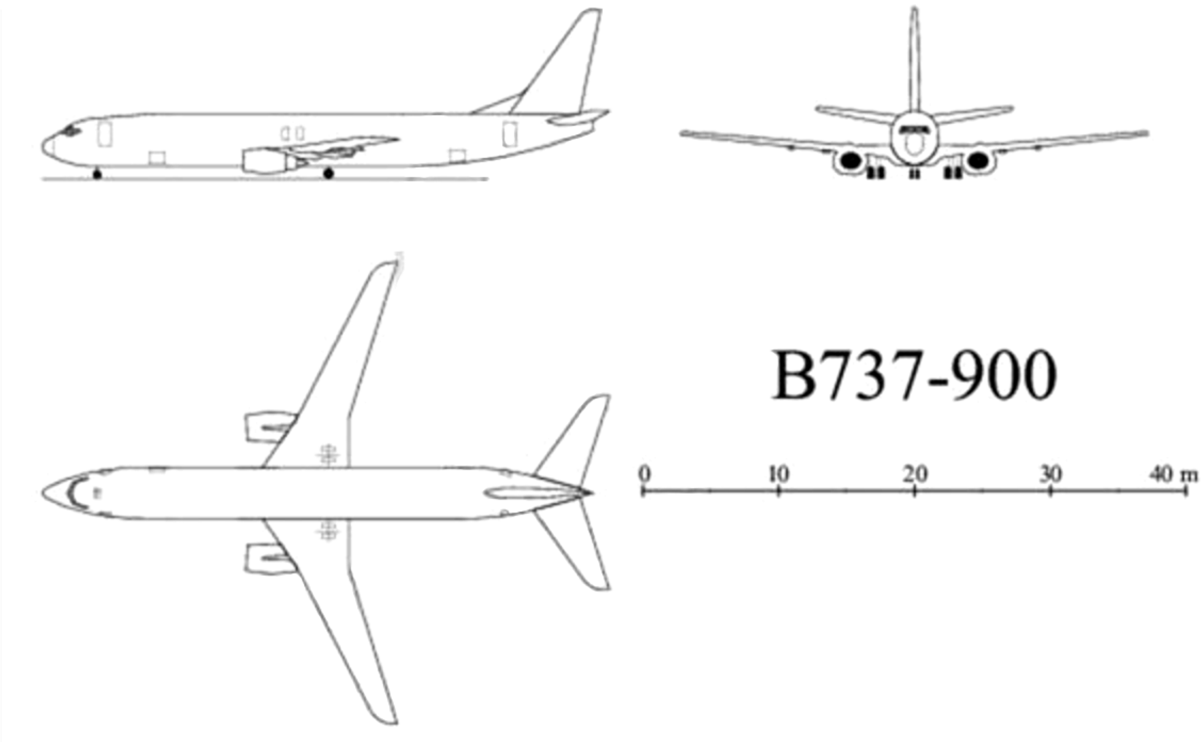


Figure 5. 16 3 view drawing of the Boeing 737-900ER (**Roux 2007a**)

The 737-900ER is a large narrow-bodied jet with capacity for a maximum seating of 215 passengers whose first flight took place on September 5, 2006. It was developed by Boeing as a solution to the bad outcome that had the 737-900, which was not able to compete effectively with the A321. The 737-900ER offers longer range and more seats. Technically, it features a flat rear pressure bulkhead which enlarges the usable cabin space, a pair of additional "mid-exit" doors to increase the maximum seat capacity to 215, structural and aerodynamic changes and two optional additional fuel tanks which increase the range to enable it to fly 'coast-to-coast' in the US domestic market

In the first years of service, the 737-900ER fleet was highly concentrated with Lion Air and this somehow contributed to its stigma as a not very liquid, difficult-to-finance asset. Since

2011, things have improved, especially thanks to big orders from United and Delta Air Lines, who saw the aircraft as a more-able replacement for their domestic 757- 200s than the smaller 737-800. With 136 aircraft (all in service), United is the biggest operator of the type, followed by Delta with a fleet of 120 aircraft (83 aircraft in service and 37 on order).

With only 21 operators and its high fleet concentration in North America and Indonesia, it is clear that the 737-900ER does not have the market appeal of its fiercest competitor, the A321-200. On paper, the 737-900ER matches some of the A321-200's key capabilities but, a combination of a late introduction compared to the rest of the 737NG family and a poor field performance in hot/high take-off conditions meant that the aircraft failed to match the A321 for sales volume and particularly for growth of the operator base.

Table 5. 31 Input values of the Boeing 737-900

Parameter	**Symbol**	**Units**	**Chosen value**
PAX			215
Landing field length (ISA)	s_{LFL}	m	1660
Approach speed	V_{APP}	m/s	72
Take-off field length (ISA)	s_{TOFL}	m	2600
Range (max payload)	R	km	3120
Cruise Mach number	M_{CR}		0,785
Cruise speed	V_{CR}	m/s	228,61
Cruise altitude	h_{CR}	m	11215
Wing area	S_W	m²	125
Wing span	b_W	m	34,32
Aspect ratio	A		9,4
Maximum take-off mass	m_{MTO}	kg	79015
Payload mass	m_{PL}	kg	17830
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,226
Maximum landing mass	m_{ML}	kg	66360
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,840
Operating empty mass	m_{OE}	kg	42493
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,538
Maximum zero fuel mass	m_{MZF}	kg	62730
Wing loading	m_{MTO}/S_W	kg/m²	595,1
Number of engines	n_E		2
Engine type			CFM56-7B26
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	117,433
Total take-off thrust	T_{TO}	kN	234,866
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,32
Bypass ratio	μ		5,6
Overall pressure ratio	OAPR		27,9
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	1,08E-05
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	29,663
Sweep angle	ϕ_{25}	°	25,02
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	10
Camber	$(y_c)_{max}/c$	%c	0,8
Position of maximum thickness	$x_{t,max}$	%c	29,7
Relative thickness	t/c	%	12,5
Taper	λ		0,219

Table 5. 32 Reverse engineering results of the Boeing 737-900

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,99**	-12
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**1,88**	
Maximum aerodynamic efficiency	E_{max}	-	**16,00**	15
Specific fuel consumption	SFC	kg/N/s	**1,77E-05**	-8

5.17 Bombardier CRJ200

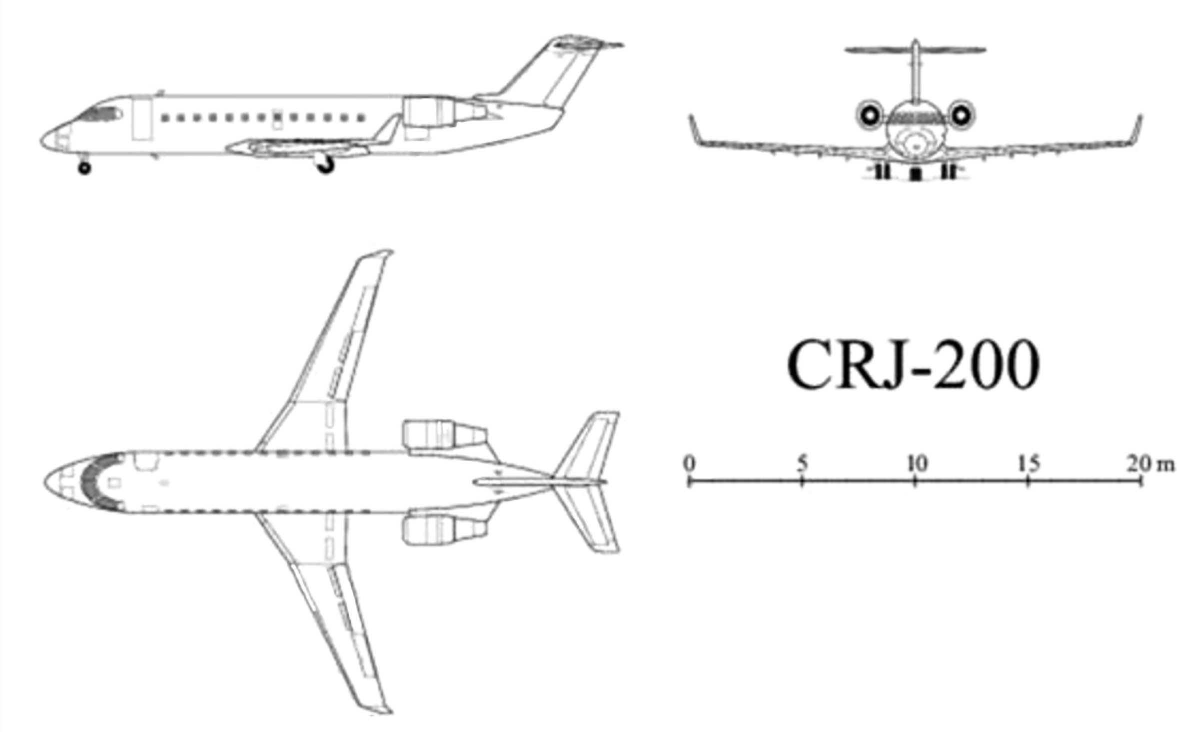


Figure 5. 17 3 view drawing of the Bombardier CRJ200 (**Roux 2007a**)

The CRJ100 is a small regional jet with capacity for a maximum seating of 50 passengers whose first flight took place on May 10, 1991. The CRJ200 is basically a CRJ100 with improved engines and also exists in -ER and -LR version. It is effectively a stretch of the Bombardier CL-601 Challenger corporate jet.

In the nineties, the 'Canadair Regional Jet' replaced a part of the more fuel-efficient but slower turboprop fleets in hub-spoke networks, but also supplemented mainline narrowbody operations during off-peak hours and developed new thin point-to point routes taking away traffic from competitors ("hub raiding"). Vis-a-vis Embraer's 50 seater jets (ERJs), the Bombardier products had a head start as they were available a couple of years earlier. US mainline pilot unions, who considered the regional jet a threat, forced limitations (via so-called scope clauses) on the number and size of regional jets to be operated by the US Major carriers via their regional partners. By virtually excluding the use of regional jets larger than 50 seats, the unions created a synthetic market for (sub-optimized) 50-seaters. A few years later, relaxation of the scope clauses led to an oversupply of 50-seaters as airlines switched to the more economical 70-seater regional jets. Many CRJ100/200 ended up in the famous storage areas in the Southwestern US deserts. The CRJ100/200s had some success as a (converted) Corporate/VIP-jet (101 in service / 13 stored), though large concentrations of the passenger fleet remain in the North American regional market.

Table 5. 33 Input values of the Bombardier CRJ200

Parameter	Symbol	Units	Chosen value
PAX			50
Landing field length (ISA)	s_{LFL}	m	1478
Approach speed	V_{APP}	m/s	70
Take-off field length (ISA)	s_{TOFL}	m	1768
Range (max payload)	R	km	1064,9
Cruise Mach number	M_{CR}		0,74
Cruise speed	V_{CR}	m/s	225
Cruise altitude	h_{CR}	m	11278
Wing area	S_W	m²	57,07
Wing span	b_W	m	21,21
Aspect ratio	A		7,88
Maximum take-off mass	m_{MTO}	kg	24041
Payload mass	m_{PL}	kg	6125
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,255
Maximum landing mass	m_{ML}	kg	21320
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,887
Operating empty mass	m_{OE}	kg	13835
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,575
Maximum zero fuel mass	m_{MZF}	kg	19960
Wing loading	m_{MTO}/S_W	kg/m²	424
Number of engines	n_E		2
Engine type			CF34-3B1
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	41,012
Total take-off thrust	T_{TO}	kN	82,024
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,39
Bypass ratio	μ		6,3
Overall pressure ratio	OAPR		21
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	9,80E-06
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	8,081
Sweep angle	ϕ_{25}	°	24,9
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		0,248

Table 5. 34 Reverse engineering results of the Bombarider CRJ200

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,36**	-11
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**1,60**	
Maximum aerodynamic efficiency	E_{max}	-	**15,17**	16
Specific fuel consumption	SFC	kg/N/s	**1,77E-05**	11

5.18 Boeing 767-300

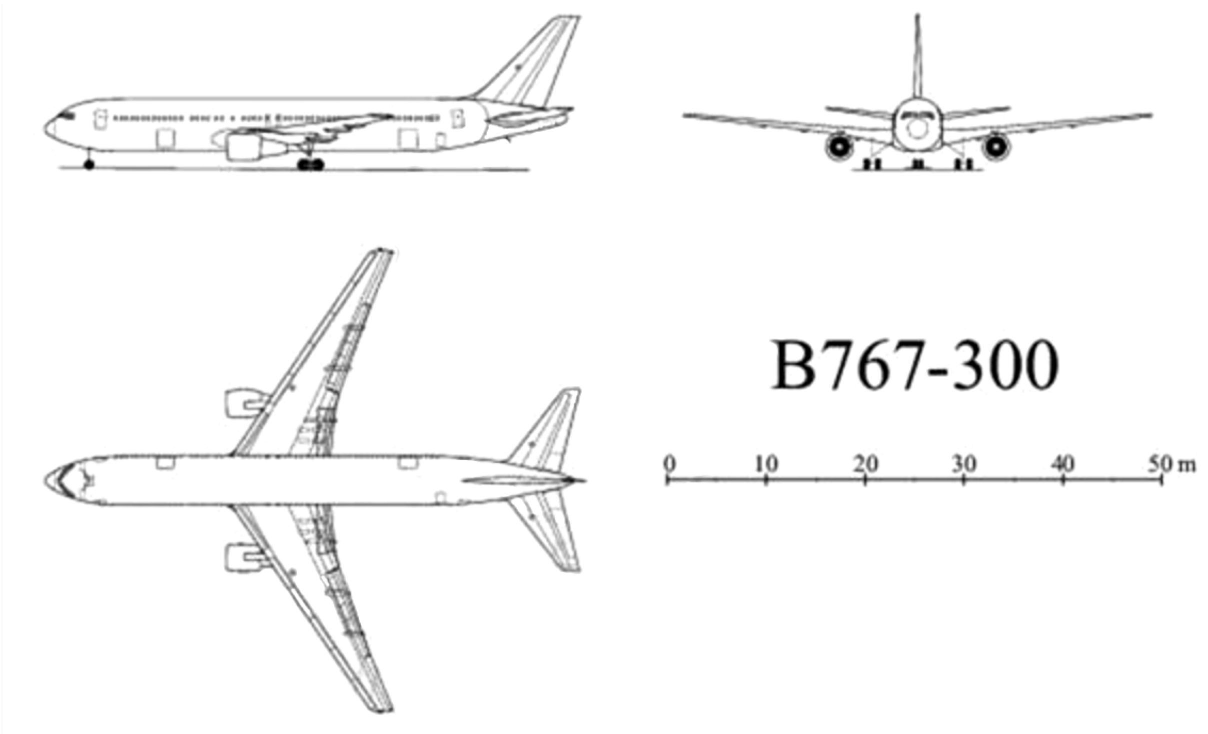


Figure 5. 18 3 view drawing of the Boeing 767-300 (**Roux 2007a**)

The 767-300 is a medium wide-bodied jet with capacity for a maximum seating of 229 passengers whose first flight took place on January 30, 1986. The basic 767-300 is essentially a 45 seat stretch of the 767-200. Boeing almost simultaneously developed the higher gross weight 767-300ER which has up to 3700km of additional range, a standard lower deck large cargo door and is mostly used on inter-continental routes. The 767-300ER is the most successful member of the 767 family, selling over 500.

However, like the 757, the 767 is technically outdated, a problem that became obvious after the introduction of the A330-200 which is more efficient and more capable. Many airlines therefore replaced their 767-300ERs with the new Airbus products (among others KLM, Air Europa, SAS, and Air France). Although still on offer by Boeing, sales of the 767-300ER have dried up. The A330-200 still records moderate sales and has already outsold the 767- 300ER. It is possible to upgrade the 767-300ER with winglets (4-5% fuel burn improvement) which has been done to 270 aircraft, mostly by the US majors which still operate the majority of the 767-300(ER) fleet. Boeing's 787 will replace a large part of all 767s in the near future. However, the economics of 767-300ER with relative low capital costs but a higher fuel burn work better than those of a fuel efficient, but expensive to acquire 787-8, especially in a low fuel price environment.

Table 5. 35 Input values of the Boeing 767-300

Parameter	Symbol	Units	Chosen value
PAX			290
Landing field length (ISA)	s_{LFL}	m	1646
Approach speed	V_{APP}	m/s	74,6
Take-off field length (ISA)	s_{TOFL}	m	2545
Range (max payload)	R	km	3873
Cruise Mach number	M_{CR}		0,8
Cruise speed	V_{CR}	m/s	236,5
Cruise altitude	h_{CR}	m	11887
Wing area	S_W	m²	283,3
Wing span	b_W	m	47,57
Aspect ratio	A		7,99
Maximum take-off mass	m_{MTO}	kg	158758
Payload mass	m_{PL}	kg	39140
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,247
Maximum landing mass	m_{ML}	kg	136078
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,857
Operating empty mass	m_{OE}	kg	84541
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,533
Maximum zero fuel mass	m_{MZF}	kg	126099
Wing loading	m_{MTO}/S_W	kg/m²	552
Number of engines	n_E		2
Engine type			CF6-80C2B2F
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	231,351
Total take-off thrust	T_{TO}	kN	462,702
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,3
Bypass ratio	μ		5,3
Overall pressure ratio	OAPR		30,4
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	9,00E-06
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	1,63E-05
Available fuel volume	$V_{fuel,available}$	m³	63,216
Sweep angle	ϕ_{25}	°	31,5
Mean aerodynamic chord	c_{MAC}	m	6,98
Position of maximum camber	$x_{(y\_c),max}$	%c	20
Camber	$(y_c)_{max}/c$	%c	1,5
Position of maximum thickness	$x_{t,max}$	%c	20
Relative thickness	t/c	%	11,5
Taper	λ		0,207

Table 5. 36 Reverse engineering results of the Boeing 767-300

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,73**	1
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**1,73**	
Maximum aerodynamic efficiency	E_{max}	-	**17,44**	11
Specific fuel consumption	SFC	kg/N/s	**1,52E-05**	4

5.19 Bombardier CRJ900

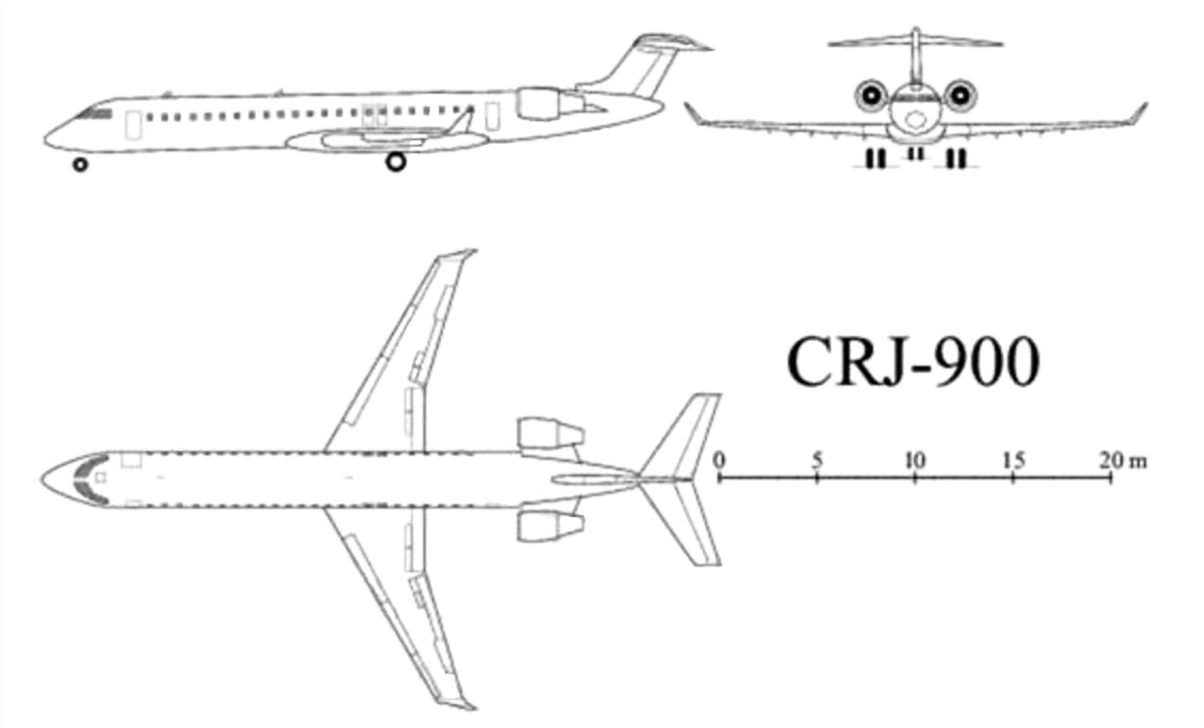


Figure 5. 19 3 view drawing of the Bombardier CRJ900 (**Roux 2007a**)

The CRJ900 is a large regional jet with capacity for a maximum seating of 90 passengers whose first flight took place on February 21, 2001. The CRJ900 is a further stretch of the already stretched CRJ700 (almost twice the length of the original CL-601 Challenger) with more powerful engines. The aircraft is offered in a standard and high gross weight -ER version, this last one offering 430km additional range. In April 2016 Bombardier introduced an improved cabin for the CRJ900, with larger bins, larger forward toilet and bigger entrance area. These improvements are also available as retrofit for older CRJ900s.

The main competition for the CRJ900 comes from the smaller 78-seat Embraer 175 but primarily the slightly larger 98-seat Embraer 190. In general, the CRJ is slightly more efficient, partly due to the E-Jets’ larger cabin crosssection offering more comfort, which is however appreciated by the passengers, especially on longer routes. Looking forward, Mitsubishi's all new MRJ90 could turn out to be a very efficient, modern technology, competitor as well.

Initially, there was only very limited airline interest, though (in anticipation of) further relaxation of scope clauses, ordering eventually took off. The CRJ900 now also 'benefits' from scope clauses, prohibiting some operators to scale up to larger RJs or even mainline narrowbodies on some routes. The CRJ900(ER) offers the advantage of commonality with the existing fleet of CRJ's. Although not many, the CRJ900 still gets some orders.

Table 5. 37 Input values of the Bombardier CRJ900

Parameter	Symbol	Units	Chosen value
PAX			86
Landing field length (ISA)	s_{LFL}	m	1596
Approach speed	V_{APP}	m/s	71,5
Take-off field length (ISA)	s_{TOFL}	m	1878
Range (max payload)	R	km	1828
Cruise Mach number	M_{CR}		0,78
Cruise speed	V_{CR}	m/s	244
Cruise altitude	h_{CR}	m	
Wing area	S_W	m²	68,63
Wing span	b_W	m	23,24
Aspect ratio	A		7,87
Maximum take-off mass	m_{MTO}	kg	38329
Payload mass	m_{PL}	kg	10205
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,266
Maximum landing mass	m_{ML}	kg	33340
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,870
Operating empty mass	m_{OE}	kg	21432
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,559
Maximum zero fuel mass	m_{MZF}	kg	31751
Wing loading	m_{MTO}/S_W	kg/m²	532
Number of engines	n_E		2
Engine type			CF34-8C5
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	64,499
Total take-off thrust	T_{TO}	kN	128,998
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,36
Bypass ratio	μ		4,9
Overall pressure ratio	OAPR		28,5
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	1,11E-05
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	10,989
Sweep angle	ϕ_{25}	°	
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		

Table 5. 38 Reverse engineering results of the Bombardier CRJ900

Secret parameter	Symbol	Units	RE Value	Verification deviation[%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,84**	-3
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,24**	
Maximum aerodynamic efficiency	E_{max}	-	**15,17**	16
Specific fuel consumption	SFC	kg/N/s	**1,47E-05**	25

5.20 Embraer ERJ-145

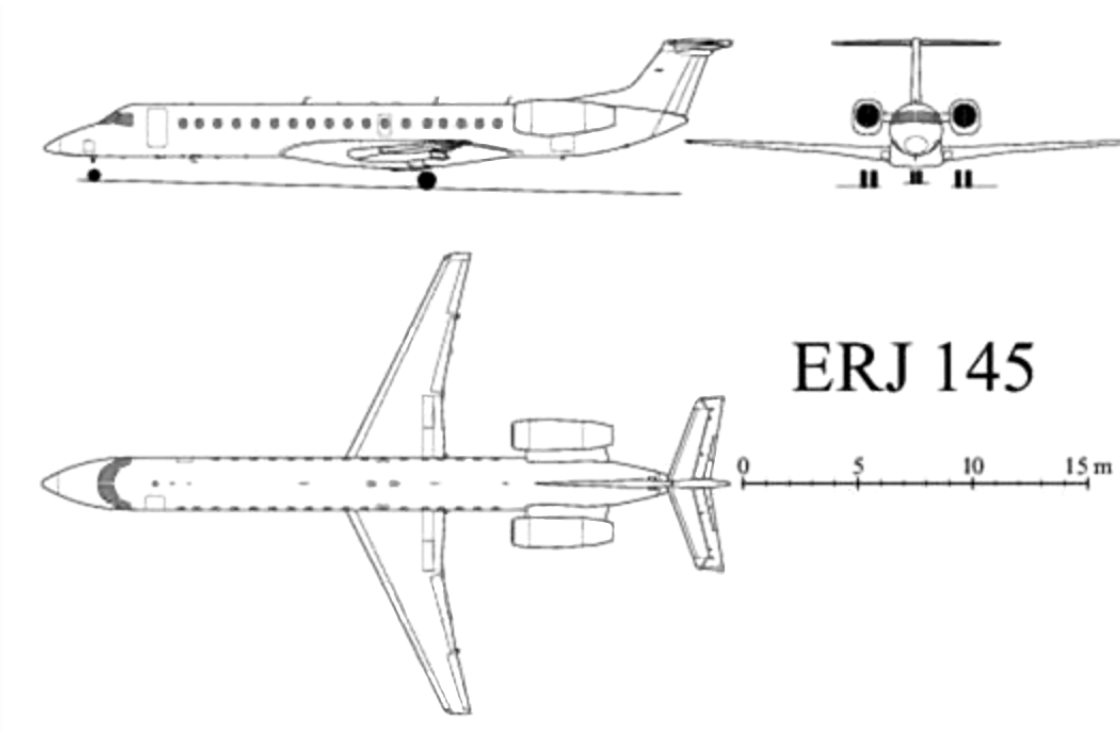


Figure 5. 20 3 view drawing of the Embraer ERJ-145 (**Roux 2007a**)

The Embraer ERJ-145 is a small regional jet with capacity for a maximum seating of 50 passengers whose first flight took place on August 11, 1995. The ERJ-145 was offered in seven different variants (excluding military and business jets), each tailored to match different range and MTOW requirements for different operators. Embraer has developed the –EU and –EP version of the ERJ-145ER and the LU variant of the ERJ-145LR for (European) airlines which prefer aircraft that fall in lower MTOW fee scales for airports and ATC. For airlines that did need the MTOW capabilities of the –LR, but didn't have a long-range capability requirement, Embraer developed the –MP. Furthermore, it developed the extra-long range –XR for Continental's ExpressJet. The –LR version is by far the preferred variant of the ERJ-145 with 37 operators, a fleet of 226 aircraft in service and 117 aircraft in storage.

The combination of high fleet concentration in the US and the scope clause relaxations to 70+ seats resulted the phase-out of many ERJ-145's. In the secondary market, there is strong competition from the surplus of similar sized CRJ100/200 jets. Although a high level of commonality remains among the different ERJ-145 versions, it turned out that all these different variants further complicate remarketing efforts.

Table 5. 39 Input values of the Embraer ERJ 145

Parameter	**Symbol**	**Units**	**Chosen value**
PAX			50
Landing field length (ISA)	s_{LFL}	m	1400
Approach speed	V_{APP}	m/s	65
Take-off field length (ISA)	s_{TOFL}	m	2270
Range (max payload)	R	km	1759
Cruise Mach number	M_{CR}		0,78
Cruise speed	V_{CR}	m/s	231,5
Cruise altitude	h_{CR}	m	11278
Wing area	S_W	m²	51,18
Wing span	b_W	m	20,04
Aspect ratio	A		7,85
Maximum take-off mass	m_{MTO}	kg	22000
Payload mass	m_{PL}	kg	5153
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,234
Maximum landing mass	m_{ML}	kg	18700
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,850
Operating empty mass	m_{OE}	kg	11947
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,543
Maximum zero fuel mass	m_{MZF}	kg	17100
Wing loading	m_{MTO}/S_W	kg/m²	402,5
Number of engines	n_E		2
Engine type			AE3007A1/1
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	33,717
Total take-off thrust	T_{TO}	kN	67,434
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,33
Bypass ratio	μ		5,3
Overall pressure ratio	OAPR		23
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	5,146
Sweep angle	ϕ_{25}	°	22,7
Mean aerodynamic chord	c_{MAC}	m	3,13
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	11
Taper	λ		0,254

Table 5. 40 Reverse engineering results of the Embraer ERJ-145

Secret parameter	Symbol	Units	RE Value	Verification deviation[%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,44**	-9
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**1,34**	
Maximum aerodynamic efficiency	E_{max}	-	**16,55**	2
Specific fuel consumption	SFC	kg/N/s	**1,47E-05**	66

5.21 Boeing 787-8

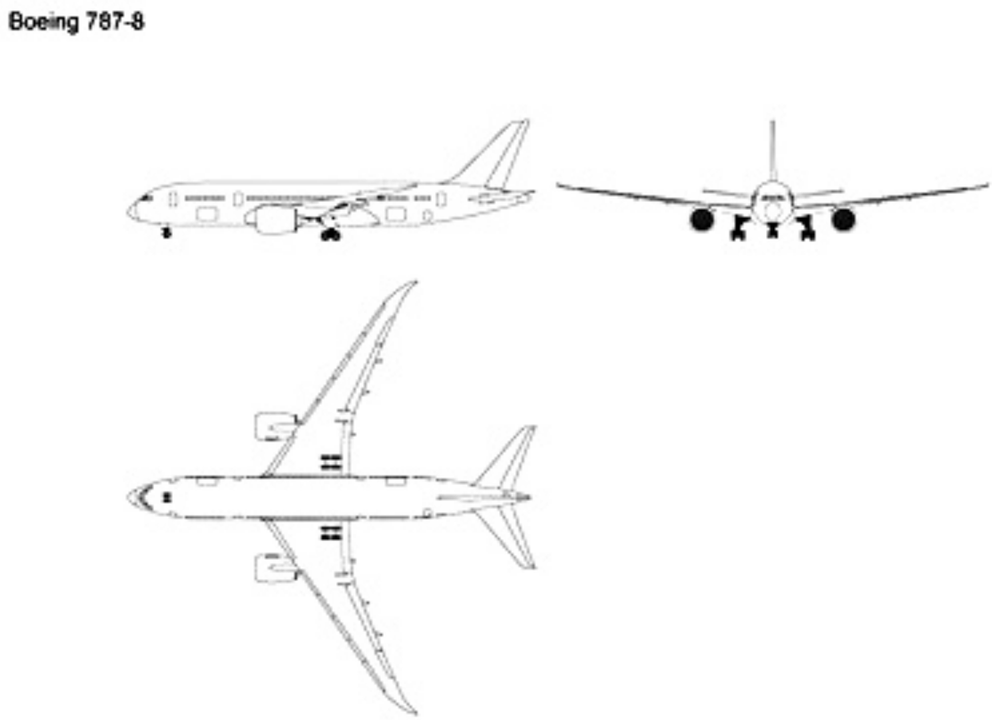


Figure 5. 21 3 view drawing of the Boeing 787-8 (**Blueprints 2020**)

The 787-8 is a medium wide-bodied jet with capacity for a maximum seating of 440 passengers whose first flight took place on December 15, 2009. The 787 family is initially designed to replace the 757- and 767 products and is the most successful wide-bodied aircraft design ever in terms of aircraft ordered prior to its entry into service. The 787 family features many new technologies like a full composite structure including wing and barrel shaped fuselage sections (accommodates 9 abreast seating), new up to 15-20% more efficient and relatively quiet engines, improved aerodynamics and many new electric systems instead of pneumatics/ hydraulics.

The 787-8 is the 'baseline model' and is optimized for the long-range medium-density markets and would serve as such as a replacement for the 767-300ER and be a new threat to the successful A330-200. Furthermore, its ultra-long-range capability enables it as well to develop new point-to-point routes, as airlines may use it as “pathfinder” to develop routes between city-pairs at long range that have insufficient traffic density to (yet) justify the larger long range aircraft types. Design and production difficulties lead to multiple serious delays of the first delivery. As of summer 2017, more than 330 787-8s have been built and delivered to more than 40 operators.

Table 5. 41 Input values of the Boeing 787-8

Parameter	Symbol	Units	Chosen value
PAX			440
Landing field length (ISA)	s_{LFL}	m	1520
Approach speed	V_{APP}	m/s	72
Take-off field length (ISA)	s_{TOFL}	m	3100
Range (max payload)	R	km	10180
Cruise Mach number	M_{CR}		0,85
Cruise speed	V_{CR}	m/s	252
Cruise altitude	h_{CR}	m	
Wing area	S_W	m²	325
Wing span	b_W	m	60,12
Aspect ratio	A		11,1
Maximum take-off mass	m_{MTO}	kg	227930
Payload mass	m_{PL}	kg	45359
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,199
Maximum landing mass	m_{ML}	kg	167825
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,736
Operating empty mass	m_{OE}	kg	117480
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,515
Maximum zero fuel mass	m_{MZF}	kg	161025
Wing loading	m_{MTO}/S_W	kg/m²	
Number of engines	n_E		2
Engine type			GEnx 72A1
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	235,76
Total take-off thrust	T_{TO}	kN	471,52
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	
Bypass ratio	μ		9
Overall pressure ratio	OAPR		43,8
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	126,917
Sweep angle	ϕ_{25}	°	32,2
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		

Table 5. 42 Reverse engineering results of the Boeing 787-8

Secret parameter	Symbol	Units	RE Value	Verification deviation[%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,96**	0
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**1,91**	
Maximum aerodynamic efficiency	E_{max}	-	**19,73**	29
Specific fuel consumption	SFC	kg/N/s	**1,16E-05**	30

5.22 Boeing 777-200ER

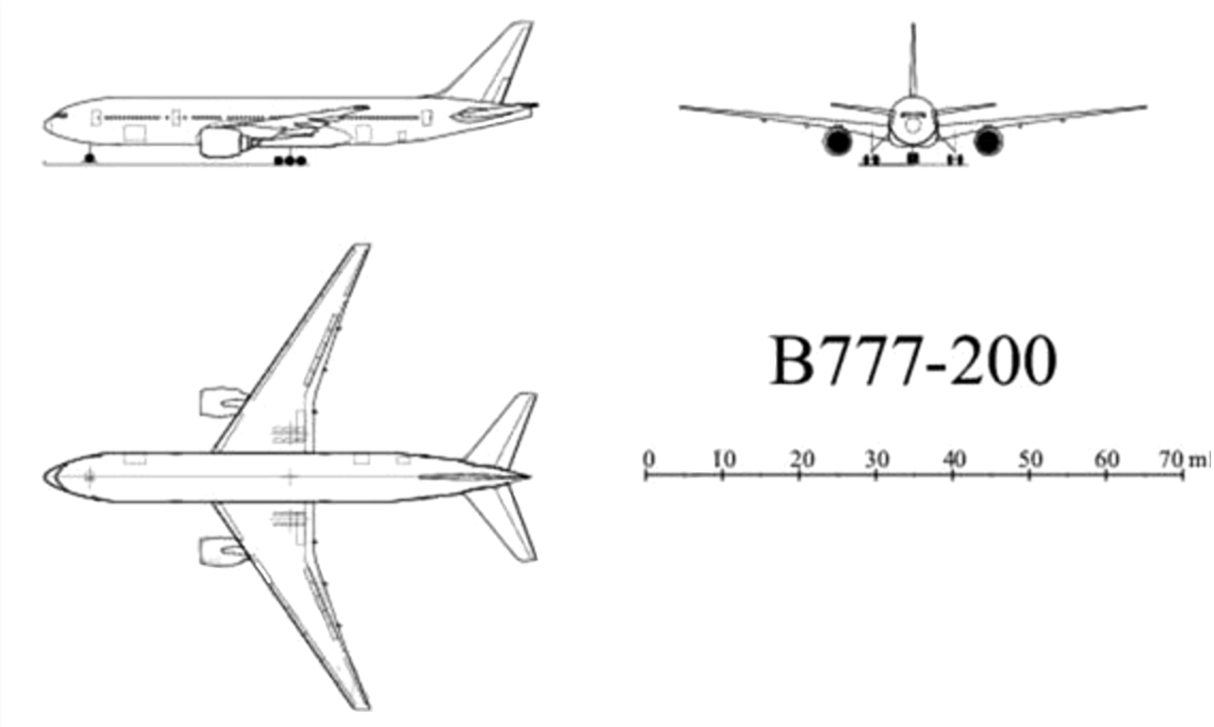


Figure 5. 22 3 view drawing of the Boeing 777-200ER (**Roux 2007a**)

The 777-200ER is a large wide-bodied jet with capacity for a maximum seating of 440 passengers whose first flight took place on October 7, 1996. The Boeing 777-family was developed to fill the capacity gap between the 767 and 747-400 and to replace older wide bodies as DC-10 and L 1011 Tristar. Especifically, the 777-200ER, also referred to as the 777-200IGW (increased gross weight) or 777B, was developed to replace the DC-10 and L1011 tri-jets on long-haul routes and compete with the four engine A340-300 and the MD-11 tri-jet. The 777-200ER is offered in six different gross weight variants. Its payload/range performance combined with the efficiency of twin-engines made the 777-200ER the fastest selling wide-bodied until the 787 was launched.

In recent years, sales of the 777-200ER have dried up and although the aircraft is still offered by Boeing there are no 777-200ERs on backlog. The 777-200ER has long been one of the most popular wide-bodied aircraft in the market. But with a new generation aircraft entering service in the coming years and the fact the 777-200ER design is starting to age, many aircraft will be phased out in the coming years. Most 777-200ERs are still in service operated by their original operator. With the new replacement types as the 787-9 and A350-900 now entering service and their deliveries finally getting momentum, it is not expected that market values for 777-200ER aircraft will recover.

Many airlines favour the A330-300 especially the new 240t and 242T MTOW variants or go for the larger 777-300ER variant, which has become the most popular model within the 777-family. In 2013, the 777-200ER was overtaken by the 777-300ER in terms of the number of aircraft produced. It seems that Airbus finally will challenge the 777-200ER's market dominance with the A350-900 design. For operators that don't need the range, the more efficient high gross weight A330-300 (or the future A330-900N) is more attractive.

Table 5. 43 Input values of the Boeing 777-200ER

Parameter	Symbol	Units	Chosen value
PAX			440
Landing field length (ISA)	s_{LFL}	m	1585
Approach speed	V_{APP}	m/s	71
Take-off field length (ISA)	s_{TOFL}	m	2135
Range (max payload)	R	km	4820
Cruise Mach number	M_{CR}		0,84
Cruise speed	V_{CR}	m/s	
Cruise altitude	h_{CR}	m	11155
Wing area	S_W	m²	427,8
Wing span	b_W	m	60,93
Aspect ratio	A		8,68
Maximum take-off mass	m_{MTO}	kg	242670
Payload mass	m_{PL}	kg	54635
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,225
Maximum landing mass	m_{ML}	kg	200050
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,824
Operating empty mass	m_{OE}	kg	135550
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,559
Maximum zero fuel mass	m_{MZF}	kg	190510
Wing loading	m_{MTO}/S_W	kg/m²	567
Number of engines	n_E		2
Engine type			GE90-85B
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	377
Total take-off thrust	T_{TO}	kN	754
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,32
Bypass ratio	μ		8,4
Overall pressure ratio	OAPR		40
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	9,18E-06
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	1,47E-05
Available fuel volume	$V_{fuel,available}$	m³	117,348
Sweep angle	ϕ_{25}	°	31,6
Mean aerodynamic chord	c_{MAC}	m	8,75
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	14,5-11,1-10,4
Taper	λ		0,149

Table 5. 44 Reverse engineering results of the Boeing 777-200

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,76**	-11
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**1,96**	
Maximum aerodynamic efficiency	E_{max}	-	**17,81**	-1
Specific fuel consumption	SFC	kg/N/s	**1,26E-05**	18

5.23 McDonnel Douglas MD-83

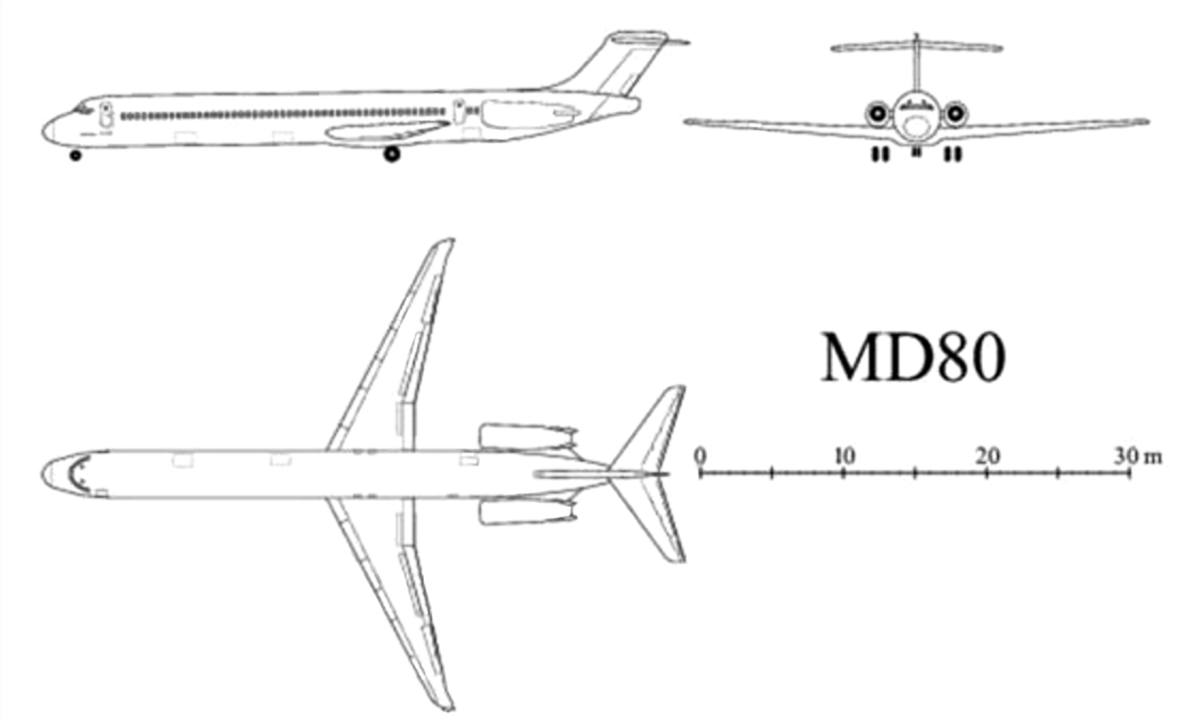


Figure 5. 23 3 view drawing of the McDonnel Douglas MD-83 (**Roux 2007a**)

The MD-80 family is the generic term for a number of development versions of small regional jets (MD-81/82/83/87/88) with capacity for a maximum seating of 172 passengers based on the Douglas DC-9, initially referred to as DC-9 'Super 80', whose first flight took place on October 19, 1979.

The MD-81 differed from the DC-9-50 by a 14ft fuselage stretch, improved more quiet PW JT8D Series 200 engines and extended wing. The increased payload/range MD-82, the most successful MD-80, is equipped with the higher thrust JT8D-217 engines. The MD-83 incorporated the slightly higher trust JT8D-219 engines and additional fuel tanks which increased its payload/range capability. The MD-88 is similar to the MD-83, but is equipped with the more advance EFIS-cockpit.

As the first Stage III noise compliant single aisle mainline jet, initially the MD-80 was a commercial success. Powered by engines derived from the “old” JT8D, the MD-80 had a head-start over the competition. Once the 737 Classic (-300/-400/-500) - powered by the more advanced all new CFM56 engines – reached the market, the end of the MD-80 came in sight. The arrival of the Airbus A320 family (powered by the CFM56 as well as the new V2500 engine) meant the beginning of the end for the once very successful (McDonnell) Douglas single aisle product range.

Table 5. 45 Input values of the McDonnel-Douglas MD-83

Parameter	Symbol	Units	Chosen value
PAX			172
Landing field length (ISA)	s_{LFL}	m	1585
Approach speed	V_{APP}	m/s	71,51
Take-off field length (ISA)	s_{TOFL}	m	2551
Range (max payload)	R	km	3345
Cruise Mach number	M_{CR}		0,76
Cruise speed	V_{CR}	m/s	225
Cruise altitude	h_{CR}	m	10668
Wing area	S_W	m²	112,3
Wing span	b_W	m	32,87
Aspect ratio	A		9,62
Maximum take-off mass	m_{MTO}	kg	72575
Payload mass	m_{PL}	kg	18721
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,258
Maximum landing mass	m_{ML}	kg	63276
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,872
Operating empty mass	m_{OE}	kg	35300
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,486
Maximum zero fuel mass	m_{MZF}	kg	55338
Wing loading	m_{MTO}/S_W	kg/m²	646
Number of engines	n_E		2
Engine type			JT8D-219
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	96,526
Total take-off thrust	T_{TO}	kN	193,052
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,27
Bypass ratio	μ		1,8
Overall pressure ratio	OAPR		20,1
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	1,47E-05
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	2,09E-05
Available fuel volume	$V_{fuel,available}$	m³	26,426
Sweep angle	ϕ_{25}	°	24,5
Mean aerodynamic chord	c_{MAC}	m	4,08
Position of maximum camber	$x_{(y\_c),max}$	%c	82
Camber	$(y_c)_{max}/c$	%c	2,3
Position of maximum thickness	$x_{t,max}$	%c	36
Relative thickness	t/c	%	11
Taper	λ		0,195

Table 5. 46 Reverse engineering results of the McDonnel Douglas MD-83

Secret parameter	Symbol	Units	RE Value	Verification deviation[%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,32**	-17
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,26**	
Maximum aerodynamic efficiency	E_{max}	-	**14,76**	24
Specific fuel consumption	SFC	kg/N/s	**1,67E-05**	23

5.24 Boeing 757-200

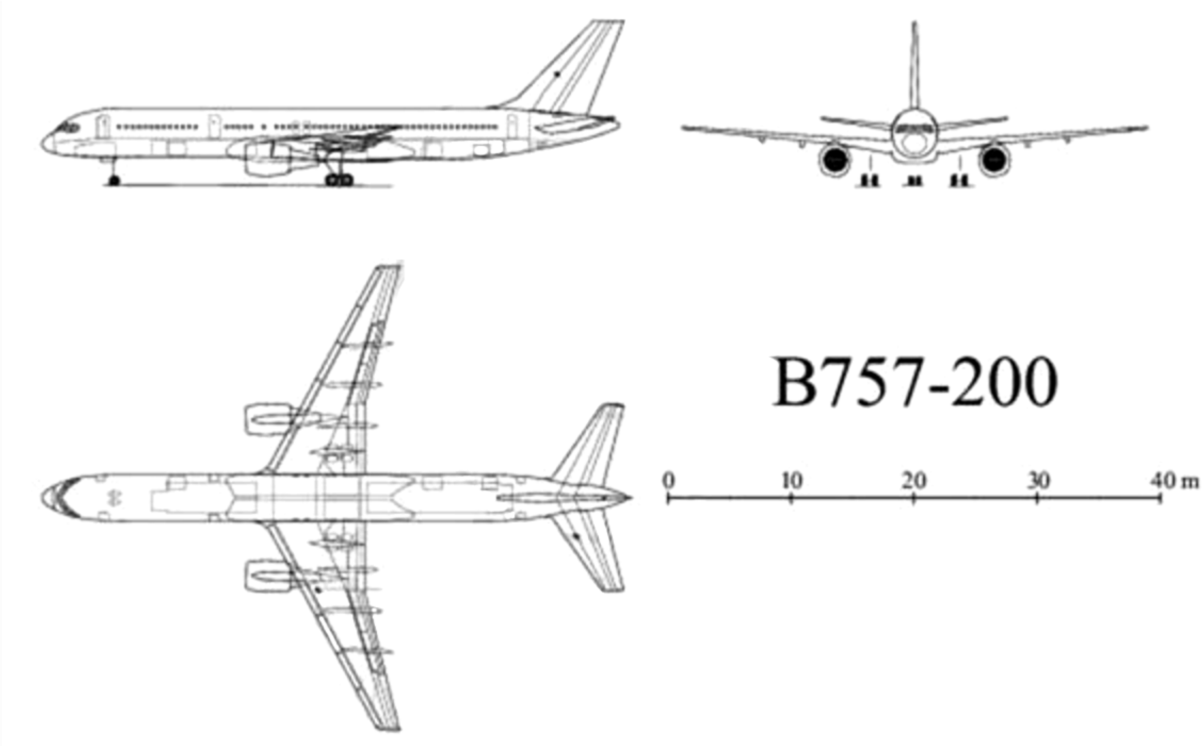


Figure 5. 24 3 view drawing of the Boeing 757-200 (**Roux 2007a**)

The 757-200 is a large narrow-bodied jet with capacity for a maximum seating of 224 passengers whose first flight took place on February 19, 1982. It was developed in conjunction with the wide-bodied 767 programme. As a result, the 757-200 shares some components with the 767 and has a common crew rating. The 757 was designed for trans-continental markets that had outgrown the then-available 727. In its first years of production, the 757 attracted many orders from major carriers and charter airlines alike.

Nevertheless, for the higher frequency mainline operations, legacy carriers and more importantly low cost airlines, mostly selected A320 family or 737NG aircraft, when these aircraft became available on the market. The 757's transcontinental range made the aircraft heavy in comparison to the more modern A320 family and 737NG. The newer A321-200 was lighter, more fuel efficient and also able to fly US coast-to-coast routes. When retrofitted with winglets

(73,3% of pax fleet), the 757-200 became 4-5% more fuel-efficient which opened up a whole new role in low density medium haul (transatlantic) operations. In 2016, Aviation Partners Boeing (APB) introduced the Scimitar Blended Winglets (SBW) for the Boeing 757-200 aircraft which delivered one percent reduction of fuel burn, so were only attractive for aircraft that would remain in service for a longer period of time.

Boeing decided to end the 757 production in 2004. Although the partout phase had already started for older 757s, large fleets of younger 757s remained in passenger service, particularly at some US majors. About 21 percent of the 757-200 fleet is stored today. Some will be converted to freighter, but many will not return to the skies again. With the introduction of even more efficient aircraft with the same seating, payload and range specifications as the 757-200 in the form of the A321Neo and 737-9, the days of the 757-200 as a transcontinental workhorse of the US majors are numbered.

Table 5. 47 Input values of the Boeing 757-200

Parameter	Symbol	Units	Chosen value
PAX			224
Landing field length (ISA)	s_{LFL}	m	1550
Approach speed	V_{APP}	m/s	68
Take-off field length (ISA)	s_{TOFL}	m	2225
Range (max payload)	R	km	4440
Cruise Mach number	M_{CR}		0,8
Cruise speed	V_{CR}	m/s	241
Cruise altitude	h_{CR}	m	11795
Wing area	S_W	m²	185,25
Wing span	b_W	m	38,05
Aspect ratio	A		7,8
Maximum take-off mass	m_{MTO}	kg	115650
Payload mass	m_{PL}	kg	22650
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,196
Maximum landing mass	m_{ML}	kg	89800
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,776
Operating empty mass	m_{OE}	kg	60800
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,526
Maximum zero fuel mass	m_{MZF}	kg	83460
Wing loading	m_{MTO}/S_W	kg/m²	538,7
Number of engines	n_E		2
Engine type			RB211-535E4
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	178,5
Total take-off thrust	T_{TO}	kN	357
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,37
Bypass ratio	μ		4,4
Overall pressure ratio	OAPR		25,8
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	1,72E-05
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	1,69E-05
Available fuel volume	$V_{fuel,available}$	m³	42,68
Sweep angle	ϕ_{25}	°	25
Mean aerodynamic chord	c_{MAC}	m	5,64
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		0,243

Table 5. 48 Reverse engineering results of the Boeing 757-200

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,92**	0
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,09**	
Maximum aerodynamic efficiency	E_{max}	-	**15,54**	15
Specific fuel consumption	SFC	kg/N/s	**1,74E-05**	-3

5.25 Airbus A380-800

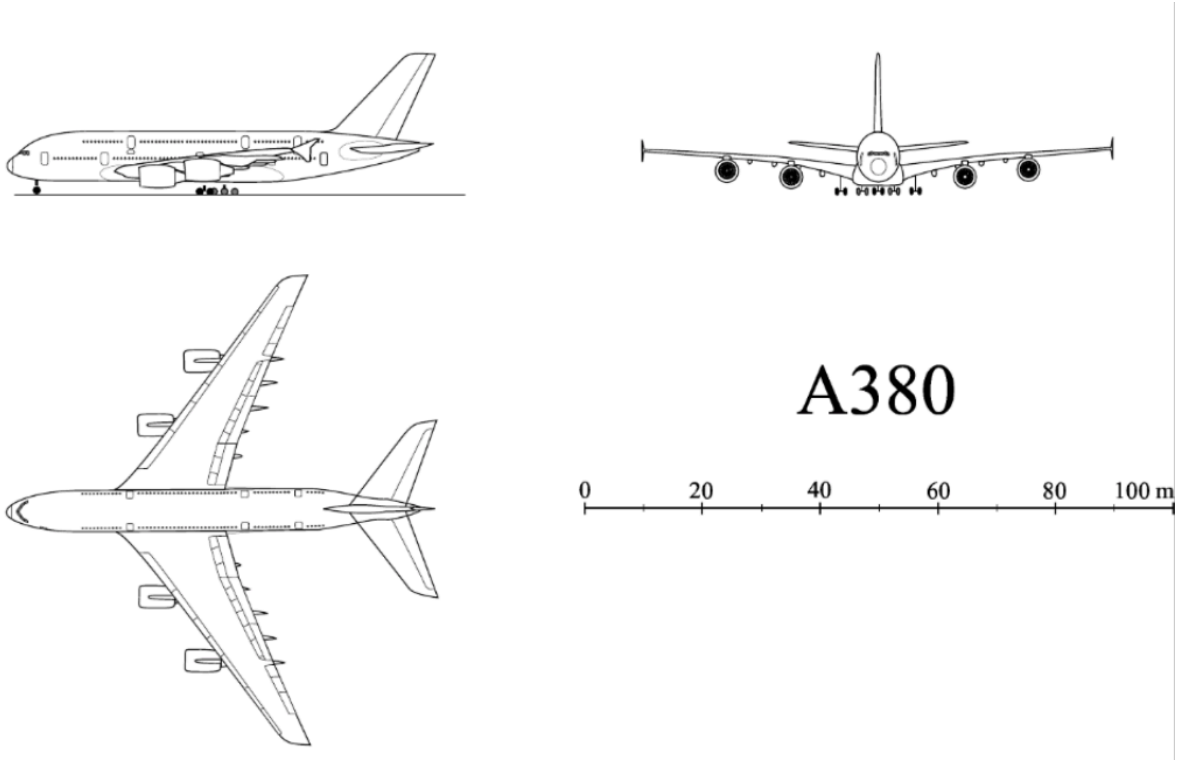


Figure 5. 25 3 view drawing of the Airbus A380-800 (**Roux 2007a**)

The A380-800 is a very large wide-bodied jet with capacity for a maximum seating of 853 passengers whose first flight took place on April 27, 2005. The double deck A380-800 has been the largest passenger aircraft in production, since it made its first flight in April 2005. According to Airbus, the A380 offers 49% more cabin floor space which results in 26% more seat space than the Boeing 747-400. Also, the A380 is quieter and is claimed to have 1500km more range and 17% better operating economics. The Airbus A380 is offered with a two engine choice. The GP7200 of Engine Alliance and the RR Trent 900. With a market share of 42% for the GP2700 and 49% for the RR Trent, it seems that there is some equilibrium between the two engine manufacturers.

The A380's main competitor is the 747-8I which still will accommodate 58 less seats than A380 but certainly closes in on range and operating economics. It however failed to impress the market so far. Airbus has the opportunity to stretch the current design into an A380-900 to obtain an even larger aircraft with better seat-mile economics, though such stretch seems unlikely in the foreseeable future.

Only 19 different operators have ordered the A380, and its fleet is mainly concentrated with one airline. 45 % of all A380 (in service and on order) are operated or will be operated by Emirates. A380 sales got a highly needed boost in 2013 but since 2013 the order intake of the A380 has again been slow. With this shrinking backlog, Airbus has decided to cut the production from the A380 from twenty-seven aircraft per year to twelve from 2018. Since the very slow order intake for the A380 and some awkward announcements from an Airbus official in 2014 about a possible end of production for the A380 due to the difficulty of turning a profit from the programme, the future of the A380 has been intensely discussed.

Table 5. 49 Input values of the A380-800

Parameter	Symbol	Units	Chosen value
PAX			853
Landing field length (ISA)	s_{LFL}	m	2100
Approach speed	V_{APP}	m/s	71
Take-off field length (ISA)	s_{TOFL}	m	2950
Range (max payload)	R	km	12149
Cruise Mach number	M_{CR}		0,85
Cruise speed	V_{CR}	m/s	267,5
Cruise altitude	h_{CR}	m	10668
Wing area	S_W	m²	845,82
Wing span	b_W	m	79,75
Aspect ratio	A		7,52
Maximum take-off mass	m_{MTO}	kg	575000
Payload mass	m_{PL}	kg	83600
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,145
Maximum landing mass	m_{ML}	kg	386000
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,671
Operating empty mass	m_{OE}	kg	270015
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,470
Maximum zero fuel mass	m_{MZF}	kg	361000
Wing loading	m_{MTO}/S_W	kg/m²	662
Number of engines	n_E		4
Engine type			Trent 970-84
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	334,282
Total take-off thrust	T_{TO}	kN	1337,128
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,24
Bypass ratio	μ		7,1
Overall pressure ratio	OAPR		45,6
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	324,562
Sweep angle	ϕ_{25}	°	35
Mean aerodynamic chord	c_{MAC}	m	12,3
Position of maximum camber	$x_{(y\_c),max}$	%c	81
Camber	$(y_c)_{max}/c$	%c	2,5
Position of maximum thickness	$x_{t,max}$	%c	37
Relative thickness	t/c	%	13,4-9,1-9,2
Taper	λ		0,225

Table 5. 50 Reverse engineering results of the Airbus 380-800

Secret parameter	Symbol	Units	RE Value	Verification deviation[%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,25**	-10
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,01**	
Maximum aerodynamic efficiency	E_{max}	-	**18,94**	4
Specific fuel consumption	SFC	kg/N/s	**1,48E-05**	1

5.26 Bombardier CRJ700

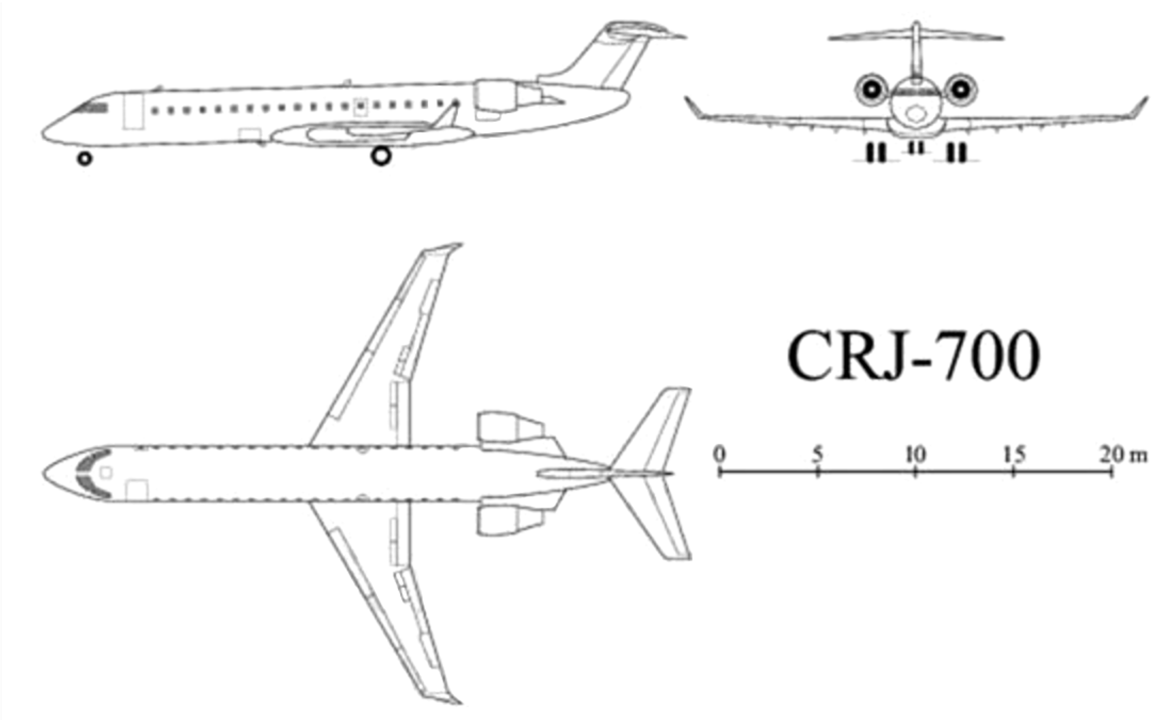


Figure 5. 26 3 view drawing of the Bombardier CRJ700 (**Roux 2007a**)

The CRJ700 is a medium regional jet with capacity for a maximum seating of 78 passengers whose first flight took place on May 27, 1999. The CRJ700 is a stretched CRJ200 which can accommodate 20 additional passengers. In addition, the CRJ700 includes more powerful engines, a larger wing and tail and a lowered floor and higher cabin windows for increased passenger comfort. The CRJ700 comes in three series: Series 700 for 68 passengers, Series 701 for 70 passengers and Series 702 for 78 passengers. The CRJ 705 is essentially a CRJ900. All series are offered as basic or as a higher gross weight -ER and LR - variant for more range.

Because of the regional jets' dependence on the US market, the success of the CRJ700 was mostly reliant on the relaxation of scope clauses which allowed airlines to replace (a limited number of) 50-seaters on markets that better fit the more efficient 70-seaters. However, further scope clause relaxation could turn the regional operators to the CRJ705/900/1000 and/or

E190/195. Compared to its main Embraer 170 competitor, the CRJ700 benefits from its commonality with the large CRJ-fleet and from lower operating costs. However, the E170 has a larger and more comfortable passenger cabin and has a broader operator base that is much less concentrated to the North American market.

In 2008 the CRJ700 was replaced by the CRJ700 NextGen with an upgraded cabin with larger bins and windows and slightly reduced weights for improved fuel burn. The current order backlog is very limited with just eight aircraft on order. The CRJ700 /CRJ700 NextGen fleet remains very concentrated in the North American market and faces some competition from more efficient larger turboprops as the Dash8-Q400 and ATR72-600. Twelve CRJ700 / CRJ700NextGen are in use as Corporate/VIP aircraft (one stored).

Table 5. 51 Input values of the Bombardier CRJ700

Parameter	Symbol	Units	Chosen value
PAX			78
Landing field length (ISA)	s_{LFL}	m	1550
Approach speed	V_{APP}	m/s	69,45
Take-off field length (ISA)	s_{TOFL}	m	1564
Range (max payload)	R	km	1556
Cruise Mach number	M_{CR}		0,77
Cruise speed	V_{CR}	m/s	228
Cruise altitude	h_{CR}	m	
Wing area	S_W	m²	68,63
Wing span	b_W	m	23,24
Aspect ratio	A		7,87
Maximum take-off mass	m_{MTO}	kg	34019
Payload mass	m_{PL}	kg	8528
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,251
Maximum landing mass	m_{ML}	kg	30390
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,893
Operating empty mass	m_{OE}	kg	19269
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,566
Maximum zero fuel mass	m_{MZF}	kg	28259
Wing loading	m_{MTO}/S_W	kg/m²	480,8
Number of engines	n_E		2
Engine type			CF34-8C1
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	61,341
Total take-off thrust	T_{TO}	kN	122,682
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,38
Bypass ratio	μ		4,9
Overall pressure ratio	OAPR		28,5
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	1,05E-05
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	10,989
Sweep angle	ϕ_{25}	°	26,6
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		

Table 5. 52 Reverse engineering results of the Bombardier CRJ700

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,67**	1
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,02**	
Maximum aerodynamic efficiency	E_{max}	-	**13,54**	30
Specific fuel consumption	SFC	kg/N/s	**1,48E-05**	21

5.27 Comac C919

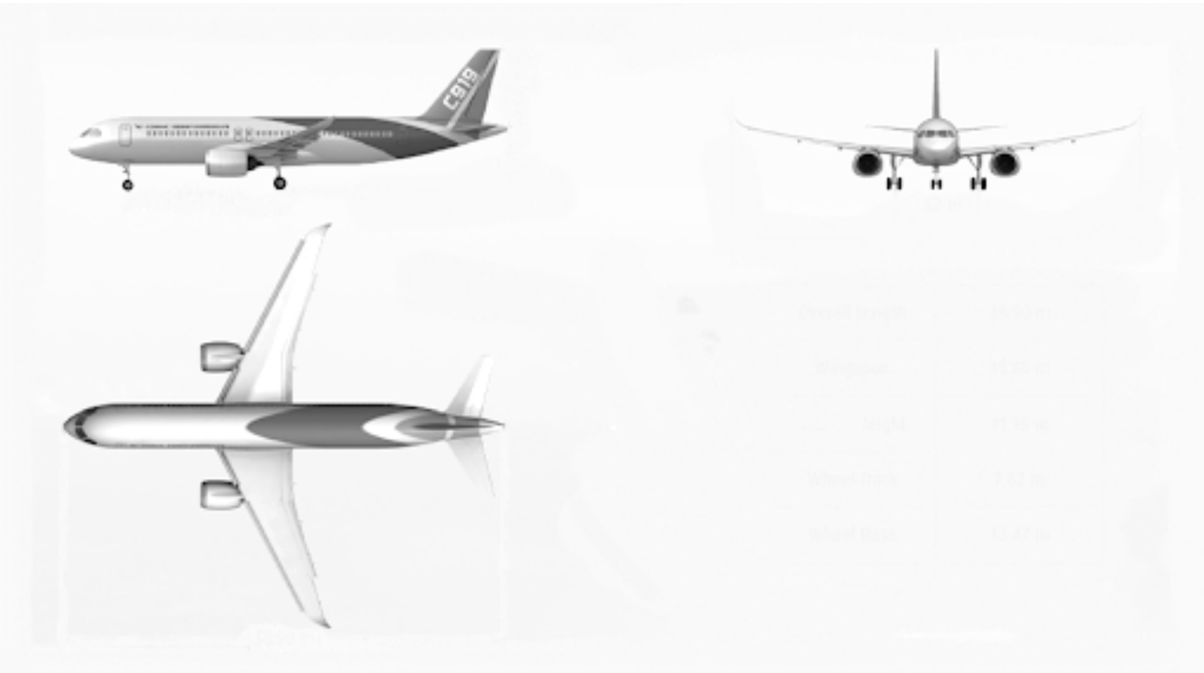


Figure 5. 27 3 view drawing of the Comac C919 (**Comac 2018**)

The C919 is a medium narrow-bodied jet with capacity for a maximum seating of 168 passengers whose first flight took place on May 5, 2017. In terms of range and PAX capacity, the C919 is very similar to the A320Neo. However, when compared to the A320 family and 737 family, the C919's fuselage is approximately 25cm wider and is able to accommodate an LD3 container in its belly. Initially, the C919 is only offered in one size and features CFM's new Leap-1C engines but this could be complemented with a Chinese domestically developed engine at a later stage as well. The Leap-1C engines are claimed to be up to 15% better than today's standard but A320neo features the same engines and also Pratt & Whitney's PW1000G GTF engines which will probably be equally efficient.

With the C919, Commercial Aircraft Corporation of China (COMAC) makes a serious attempt to break into the Airbus and Boeing hold on the mainline single aisle market. The C919 is designed and built in China with support from reputably western aviation industry suppliers such as CFMI, Hamilton Sundstrand, Honeywell and GE. Besides the A320Neo the C919 will also compete against the new Boeing 737 Max and Russia's Irkut MS-21. So far 287 C919s have been ordered, mainly by Chinese airlines or leasing companies. It is already clear that the C919s will fulfil a not insignificant part of the aircraft demand in the Chinese market.

It is not yet clear whether this first Chinese commercial mainline aircraft will also be successful abroad. In 2011, Bombardier and COMAC signed an agreement to cooperate in the fields of marketing and support but also collaboration on the complementary C919 and CSeries programmes and future aircraft development was not excluded. It is not totally clear what the partial take-over of the CSeries program by Airbus may mean for the cooperation between Bombardier and COMAC. In 2015 COMAC closed a deal with Boeing to jointly operate a 737 completion centre in China. This agreement already seemed to put stress on the cooperation between Bombardier and COMAC, as engineering experience, certification and after service knowledge can now be obtained by COMAC from the American manufacturer.

Table 5. 53 Input values of the Comac C919

Parameter	Symbol	Units	Chosen value
PAX			168
Landing field length (ISA)	s_{LFL}	m	1600
Approach speed	V_{APP}	m/s	69,45
Take-off field length (ISA)	s_{TOFL}	m	2000
Range (max payload)	R	km	4075
Cruise Mach number	M_{CR}		0,785
Cruise speed	V_{CR}	m/s	231,5
Cruise altitude	h_{CR}	m	7965
Wing area	S_W	m²	129,15
Wing span	b_W	m	35,8
Aspect ratio	A		
Maximum take-off mass	m_{MTO}	kg	77300
Payload mass	m_{PL}	kg	20400
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,264
Maximum landing mass	m_{ML}	kg	66682
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,863
Operating empty mass	m_{OE}	kg	42100
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,545
Maximum zero fuel mass	m_{MZF}	kg	62679
Wing loading	m_{MTO}/S_W	kg/m²	600
Number of engines	n_E		2
Engine type			CFM LEAP-1C
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	104,384
Total take-off thrust	T_{TO}	kN	208,768
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	
Bypass ratio	μ		11
Overall pressure ratio	OAPR		
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	24,45
Sweep angle	ϕ_{25}	°	
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		

Table 5. 54 Reverse engineering results of the Comac C919

Secret parameter	Symbol	Units	RE Value	Verification deviation[%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,02**	-8
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**1,75**	
Maximum aerodynamic efficiency	E_{max}	-	**17,97**	9
Specific fuel consumption	SFC	kg/N/s	**1,09E-05**	24

5.28 Boeing 777-9

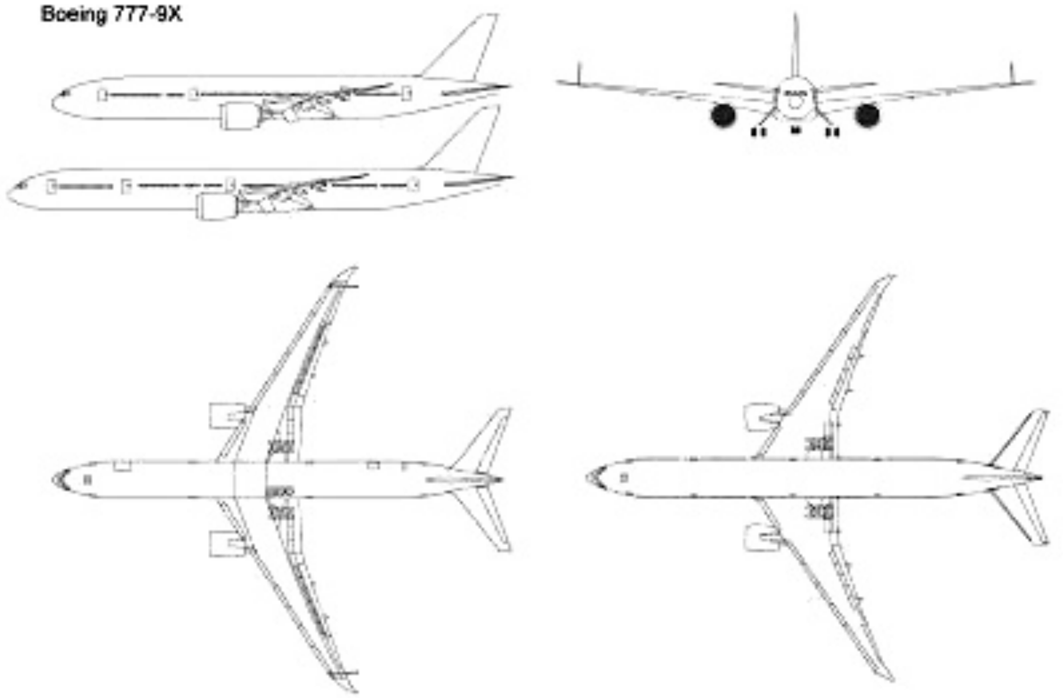


Figure 5. 28 3 view drawing of the Boeing 777-9 (**Blueprints 2020**)

The 777-9 is a large wide-bodied jet with capacity for a maximum seating of 414 passengers. It is the largest variant of the 777X family and has the program lead with service entry in 2020. It has a stretched fuselage in comparison with the 777-300ER. As of summer 2017, a total of 263 777-9s were ordered by ANA, Cathay, Emirates, Etihad, Lufthansa, Qatar and Singapore Airlines.The new 777X aircraft will feature a new scaled up version of the composite wings used for the smaller 787. Its new wing is the largest wingspan of any twin-engine Boeing aircraft type to date and is going to have a considerably better lift-to-drag ratio being significantly lighter than the wings on the current models. It will be built using carbon-fibre reinforced plastic and will feature folding wingtips to allow the new wing 777 models to operate at airfields without the facilities to handle aircraft with longer wing-spans. Another novelty on the 777X is the advanced aluminium-lithium fuselage which is lighter. In the cabin, Boeing looks to accommodate a more comfortable 10 abreast economy arrangement and nine-abreast premium economy offering while maintaining the same cross section. Core to the new variants will be a new General Electric GE9X engine, offering the latest generation engine technology. All these improvements will make the 777X 15-20% more efficient than the current 777 variants.

After years of studying, Boeing formally launched the new 777X family at the Dubai Air Show in November 2013. These new 777X family is growth derivative of the current 777 line up and is intended to compete with the new Airbus A350-900/1000. Initially two series of the new 777X were offered, the 777-8X and 777-9X. In November 2015 Boeing formally dropped the “X” suffix for the individual 777X variants, although the combined family however will still be known as 777X. In the summer of 2016, Boeing acknowledged, that a stretch of the 777-9 is technically possible. If pursued, this new 777-10 derivative of the 777X family would give Boeing a very capable two engine competitor to the Airbus A380. Boeing has said it will launch the 777-10 as there is enough customer interest.

Table 5. 55 Input values of the Boeing 777-9

Parameter	Symbol	Units	Chosen value
PAX			414
Landing field length (ISA)	s_{LFL}	m	
Approach speed	V_{APP}	m/s	
Take-off field length (ISA)	s_{TOFL}	m	
Range (max payload)	R	km	
Cruise Mach number	M_{CR}		
Cruise speed	V_{CR}	m/s	
Cruise altitude	h_{CR}	m	
Wing area	S_W	m²	
Wing span	b_W	m	64,82
Aspect ratio	A		
Maximum take-off mass	m_{MTO}	kg	351534
Payload mass	m_{PL}	kg	
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		
Maximum landing mass	m_{ML}	kg	266258
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,757
Operating empty mass	m_{OE}	kg	188241
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,535
Maximum zero fuel mass	m_{MZF}	kg	254918
Wing loading	m_{MTO}/S_W	kg/m²	
Number of engines	n_E		2
Engine type			GE9X-105B1A
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	466,7465487
Total take-off thrust	T_{TO}	kN	933,4930975
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	
Bypass ratio	μ		
Overall pressure ratio	OAPR		
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	197,977
Sweep angle	ϕ_{25}	°	
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		

5.29 Boeing 737-10

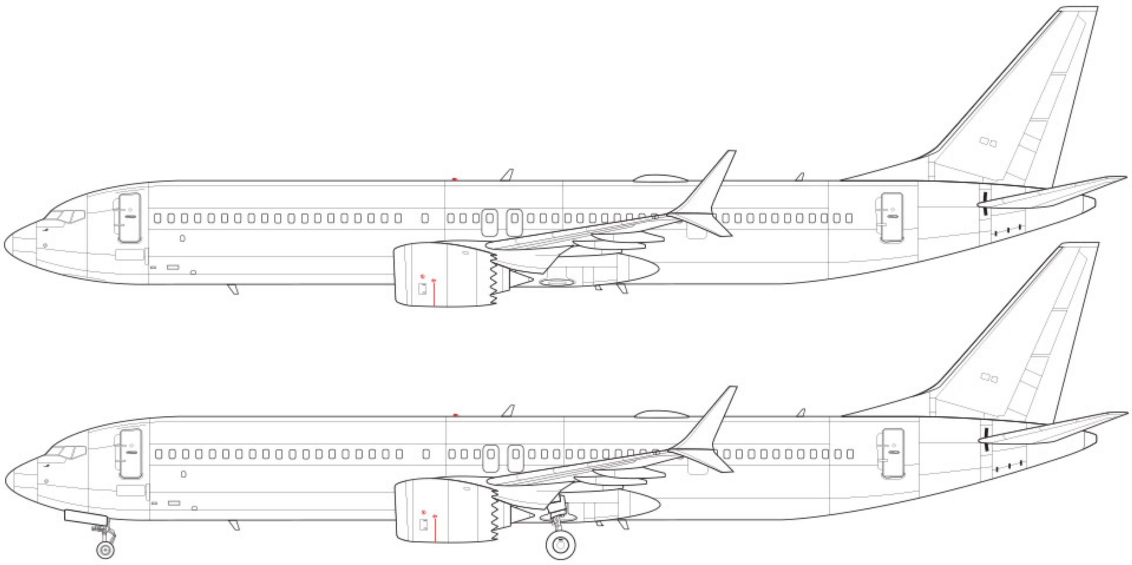


Figure 5. 29 3 view drawing of the Boeing 737-10 (**Norebbo 2020**)

The 737-10 is a large narrow-bodied jet with capacity for a maximum seating of 230 passengers which was Boeing's respond to two rather disappointing events: the poor sales of the 737-9 and the huge success of the A321neo. The new aircraft, a further two seat rows stretch of the 737-9, is called the 737-10 and was officially launched at the Paris Air Show in June 2017. It features the same "mid-exit" door (for a variable exit-limit rating) but, besides its length there are few other visible differences. Despite the greater clearance, Boeing chose to stick with the Leap-1B engine to minimise development cost and offers a thrust-bump version of the engine for the 737-10, rather than choosing a larger fan engine like the Leap-1A which might provide lower fuel consumption but less commonality. To support the greater passenger capacity, the aircraft will also have an increased MTOW. With 256 orders, the 737-10 had a very successful start and several airlines converted their 737-9 orders into 737-10 orders. For example, United swapped its 100 strong 737-9 order for the 737-10. In total, 214 of the 256 orders were swapped from other MAX variants. Boeing has said the 737-10 is scheduled to enter commercial service in 2020

One of the solutions would be the introduction of an all new design aircraft, dubbed in the media as the New Midsize Aircraft ("NMA"). The NMA is expected to fit between the larger narrow-bodied aircraft like the 737-900ER and smaller wide-bodied aircraft like the 767-200 or 787-8, and might be capable of transporting 220-280 passenger over transatlantic and/or transcontinental distances. The introduction of a possible NMA is a hot topic in the aviation media and at various business conferences. The question is whether this market segment will be big enough to make enough sales for Boeing's business case.

Table 5. 56 Input values of the Boeing 737-800

Parameter	Symbol	Units	Chosen value
PAX			230
Landing field length (ISA)	s_{LFL}	m	
Approach speed	V_{APP}	m/s	
Take-off field length (ISA)	s_{TOFL}	m	
Range (max payload)	R	km	5960
Cruise Mach number	M_{CR}		0,79
Cruise speed	V_{CR}	m/s	233,89
Cruise altitude	h_{CR}	m	
Wing area	S_W	m²	
Wing span	b_W	m	35,92
Aspect ratio	A		
Maximum take-off mass	m_{MTO}	kg	89765
Payload mass	m_{PL}	kg	
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		
Maximum landing mass	m_{ML}	kg	75931
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,846
Operating empty mass	m_{OE}	kg	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		
Maximum zero fuel mass	m_{MZF}	kg	72574
Wing loading	m_{MTO}/S_W	kg/m²	
Number of engines	n_E		2
Engine type			
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	
Total take-off thrust	T_{TO}	kN	0
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	
Bypass ratio	μ		
Overall pressure ratio	OAPR		
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	25,817
Sweep angle	ϕ_{25}	°	
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		

5.30 Mitsubishi MRJ90

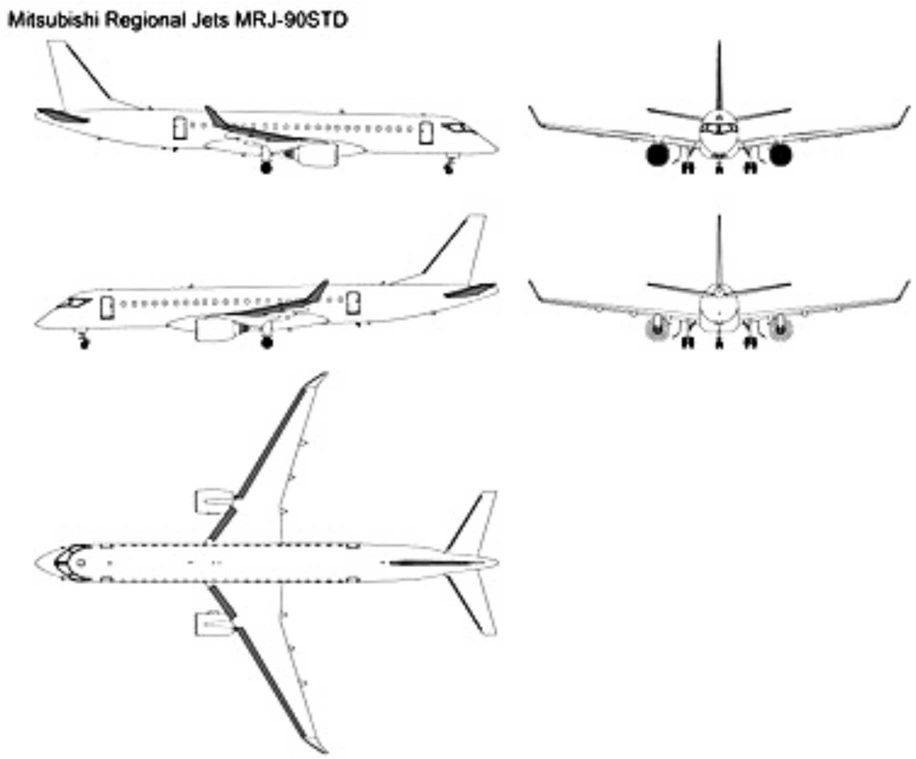


Figure 5. 30 3 view drawing of the Mitsubishi MRJ90 (**Blueprints 2020**)

The MRJ90 is a large regional jet with capacity for a maximum seating of 96 passengers whose first flight took place on November 11, 2015. The MRJ90 will be the first and base line MRJ model to enter service in mid-2020. It will feature a fuselage which will be longer than the MRJ70 to accommodate approximately 12 more passengers. An important element of the MRJ product will be the PW1217G geared turbo fan engine (GTF) which is claimed to be 15% more fuel efficient, 50% less noisy and up to 40% cheaper to maintain than current technology engines. The MRJ fuselage is of a simple circular cross section with cargo compartment in the back. The MRJ90 will have three variants (STD, -ER and -LR) with the same size but higher MTOWs for increasing range capability

With its Mitsubishi Regional Jet (MRJ) programme, the Mitsubishi Aircraft Corporation aims to set a new standard of regional jets. Its main competitors – the E-Jets -mostly features a double-bubble design with underfloor cargo space. The MRJ90 faces strong competition from the latest versions of the E175, E175-E2, E190, E190-E2 and the CRJ900 which have been dominating the 90-seater market segment for quite some years. Additionally, slightly larger aircraft such as the E195, E195-E2, CRJ1000 and CS100 (using the same engine technology) could turn out to be competitors, especially in a growth market.

The success of the MRJ90 is largely depending on the scope clause dominated US domestic regional market. Generally, more easing of scope clauses could create demand if more 90 seaters would be permitted but if further loosened, larger aircraft become competitors. To date, Mitsubishi Aircraft Corporation is actually quite successful in this market and managed to get two landmark orders for the MRJ90 in the US. Trans States Holdings ordered 50 MRJs (+ 50 options) in 2009 and in 2012 SkyWest Airlines ordered 100 MRJ90s (+ 100 Options).

Table 5. 57 Input values of the Mitsubishi MRJ90

Parameter	Symbol	Units	Chosen value
PAX			88
Landing field length (ISA)	s_{LFL}	m	1480
Approach speed	V_{APP}	m/s	70
Take-off field length (ISA)	s_{TOFL}	m	1500
Range (max payload)	R	km	1610
Cruise Mach number	M_{CR}		0,78
Cruise speed	V_{CR}	m/s	230
Cruise altitude	h_{CR}	m	11900
Wing area	S_W	m²	86
Wing span	b_W	m	30,9
Aspect ratio	A		
Maximum take-off mass	m_{MTO}	kg	40995
Payload mass	m_{PL}	kg	8976
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,219
Maximum landing mass	m_{ML}	kg	38400
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,937
Operating empty mass	m_{OE}	kg	24900
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,607
Maximum zero fuel mass	m_{MZF}	kg	36150
Wing loading	m_{MTO}/S_W	kg/m²	
Number of engines	n_E		2
Engine type			PW1217G
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	78,2
Total take-off thrust	T_{TO}	kN	156,4
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,4
Bypass ratio	μ		8,4
Overall pressure ratio	OAPR		
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	
Sweep angle	ϕ_{25}	°	
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		

Table 5. 58 Reverse engineering results of the Mitsubishi MRJ90

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,82**	1
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**1,91**	
Maximum aerodynamic efficiency	E_{max}	-	**17,41**	19
Specific fuel consumption	SFC	kg/N/s	**1,68E-05**	-1

5.31 Bombardier DHC-8-401 (Dash-8 Q400)

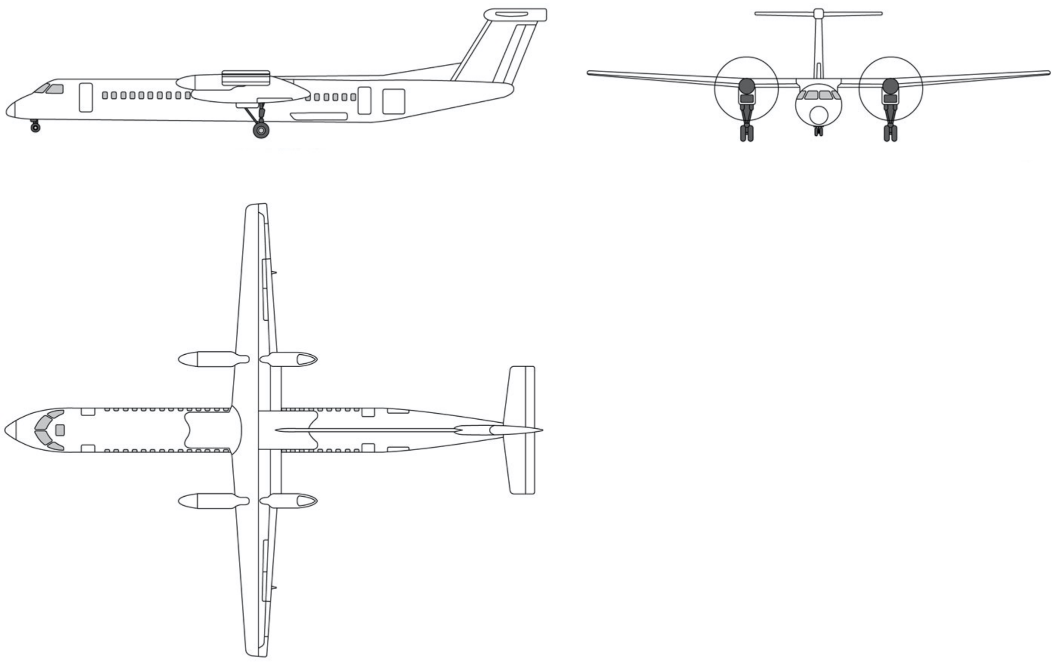


Figure 5. 31 3 view drawing of Bombardier Dash-8 Q400 (**Blueprints 2020**)

The Dash-8 Q400 is a twin-engined, medium range regional turboprop airliner with capacity for a maximum seating of 82 passengers whose first flight took place on January 31, 1998. The Q400 has a new stretched fuselage compared to the Q300. It has the same nose section and vertical tail as the other Dash-8 family aircraft, but has a new developed horizontal tail. The fuselage's cross section and structure are based on the earlier Dash-8s but with two entry doors at forward and aft ends of the fuselage on the left side. The inner wing section and wing fuselage wing joint are also developed new for the Q400. The outer wing of the Q400 has been strengthened. The Dash-8 Q400 is powered by two FADEC equipped PW150 turboprop engines with six bladed propellers. To improve the passenger's comfort, the Q400 is fitted with Bombardier's newest systems to reduce noise and vibration to levels comparable with a CRJ. The flightdeck consist of five LCD screens, showing the same information to the pilot as in the earlier versions, so all the Dash-8s have a common type rating.

The –Q400 is the latest and longest member of the Dash-8 family, which besides the –Q400 consists of the original Series 100 (39 seats), the Series 200 (same capacity, more powerful engines) and the Series 300 (a stretched fuselage 50 seater). All models delivered after mid 1996 have cabin noise and vibration suppression systems and are redesignated with the Q(uiet)-prefix. Bombardier stopped production of the Q100 in 2006 and of the Q200 and Q300 in 2009, leaving only the Q400 in production. The Q400 was developed in the late nineties and entered commercial service in 2000. It was developed to meet the requirements of regional airlines for larger aircraft on high density, short-haul routes competing against the faster regional jets.

Table 5. 59 Input values of the Bombardier Dash-8 Q400

Parameter	Symbol	Units	Chosen value
PAX			82
Landing field length (ISA)	s_{LFL}	m	1290
Approach speed	V_{APP}	m/s	
Take-off field length (ISA)	s_{TOFL}	m	1300
Range (max payload)	R	km	1390
Cruise Mach number	M_{CR}		0,62
Cruise speed	V_{CR}	m/s	185,2
Cruise altitude	h_{CR}	m	5334
Wing area	S_W	m²	63,08
Wing span	b_W	m	28,42
Aspect ratio	A		12,8
Maximum take-off mass	m_{MTO}	kg	28998
Payload mass	m_{PL}	kg	8480
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,292
Maximum landing mass	m_{ML}	kg	28009
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,966
Operating empty mass	m_{OE}	kg	17150
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,591
Maximum zero fuel mass	m_{MZF}	kg	25855
Wing loading	m_{MTO}/S_W	kg/m²	459,7
Number of engines	n_E		2
Engine type			PW150A
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	3781 kW
Total take-off thrust	T_{TO}	kN	7562 kW
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	3,84 kg/kW
Bypass ratio	μ		
Overall pressure ratio	OAPR		
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	6,526
Sweep angle	ϕ_{25}	°	
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		

5.32 Boeing 737-300

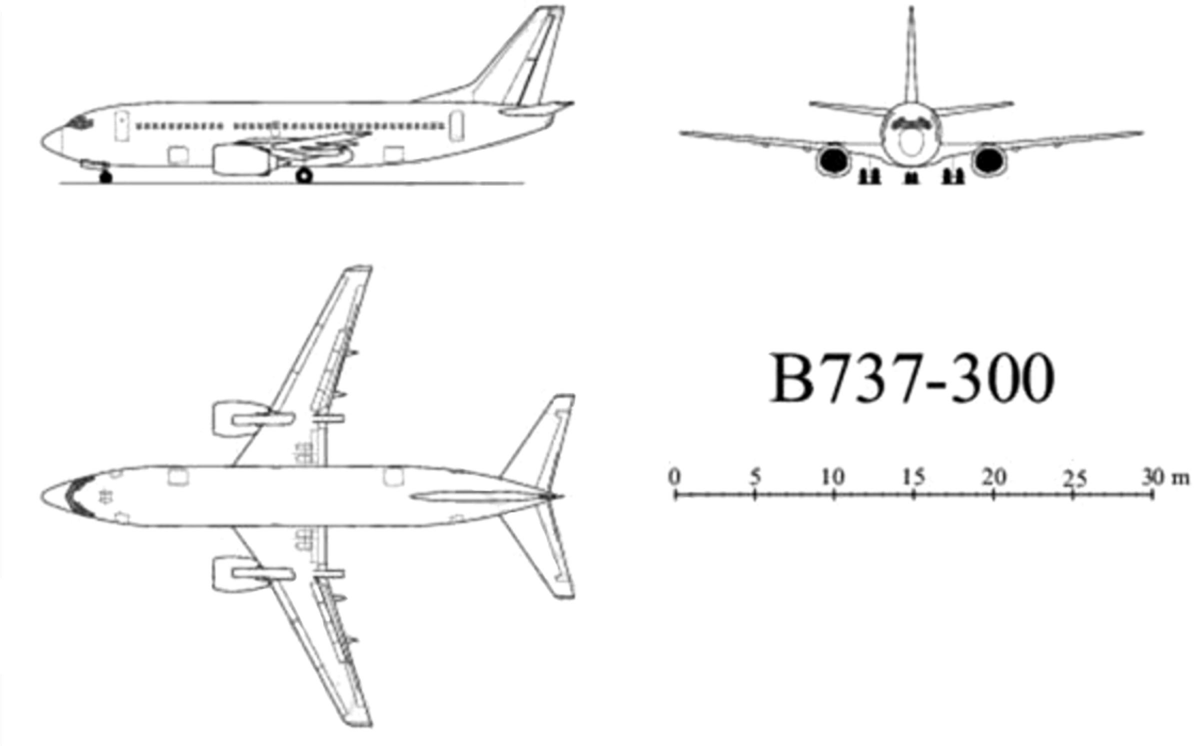


Figure 5. 32 3 view drawing of the Boeing 737-300 (**Roux 2007a**)

The 737-300 is a moderate size narrow-bodied jet with capacity for a maximum seating of 149 passengers whose first flight took place on February 24, 1984. The 737-300 was the first version of the 737 'Classic' Family and was derived from the 737-200 as a growth replacement. It would become the most successful of the three-version family with over 1,000 delivered from 1984 to 1999. Early built 737 Classics were still equipped with analogue cockpit displays. Digital CRT displays became standard in 1988. The 737 'Classic' is preferred above its MD-80 competitors, mostly due to its cleaner, more economical CFM56 engine versus the older PW JT8D-200.

Compared with its modern competitors (737-700 and A319), the 737-300 is more expensive to maintain, less fuel efficient and offers much less range. With low fuel prices, the 737-300 could still be attractive as its capital costs are minimal and modifications like winglets (145 modified) could improve performance. Nevertheless, many 737-300s were parked during the last economic crisis with only a few coming back when markets recovered, almost all with second tier airlines. More and more phase-outs and part-outs illustrate the type nearing the end of its service life.

As of summer 2017, more than 100 operators still fly with the 737-300, most of them having very small fleets. Southwest Airlines was the exception and was for long time by far the biggest operator with a fleet of 93 737-300 aircraft. However, with the introduction of the 737 Max in its fleet, Southwest accelerated the retirement of its 737-300s and all aircraft were phased out by 1 October 2017. Cargo conversion programmes are offered for the 737-300 which may extend the operating lives of some suitable 737-300s. Currently around five 737-300s are converted to freighter per year.

Table 5. 60 Input values of the Boeing 737-300

Parameter	Symbol	Units	Chosen value
PAX			149
Landing field length (ISA)	s_{LFL}	m	1433
Approach speed	V_{APP}	m/s	69,45
Take-off field length (ISA)	s_{TOFL}	m	1940
Range (max payload)	R	km	1464
Cruise Mach number	M_{CR}		0,745
Cruise speed	V_{CR}	m/s	220,7
Cruise altitude	h_{CR}	m	10668
Wing area	S_W	m²	105,4
Wing span	b_W	m	28,88
Aspect ratio	A		7,9
Maximum take-off mass	m_{MTO}	kg	58967
Payload mass	m_{PL}	kg	16148
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,274
Maximum landing mass	m_{ML}	kg	51710
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,877
Operating empty mass	m_{OE}	kg	31869
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,540
Maximum zero fuel mass	m_{MZF}	kg	47627
Wing loading	m_{MTO}/S_W	kg/m²	535,6
Number of engines	n_E		2
Engine type			CFM56-3B1
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	88,964
Total take-off thrust	T_{TO}	kN	177,928
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,32
Bypass ratio	μ		6
Overall pressure ratio	OAPR		22,6
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	1,08E-05
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	1,89E-05
Available fuel volume	$V_{fuel,available}$	m³	20,102
Sweep angle	ϕ_{25}	°	25
Mean aerodynamic chord	c_{MAC}	m	3,73
Position of maximum camber	$x_{(y\_c),max}$	%c	10
Camber	$(y_c)_{max}/c$	%c	0,8
Position of maximum thickness	$x_{t,max}$	%c	29,7
Relative thickness	t/c	%	12,9
Taper	λ		0,24

Table 5. 61 Reverse engineering results of the Boeing 737-300

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,20**	-17
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,19**	
Maximum aerodynamic efficiency	E_{max}	-	**14,84**	18
Specific fuel consumption	SFC	kg/N/s	**1,78E-05**	-6

5.33 Airbus A350-1000

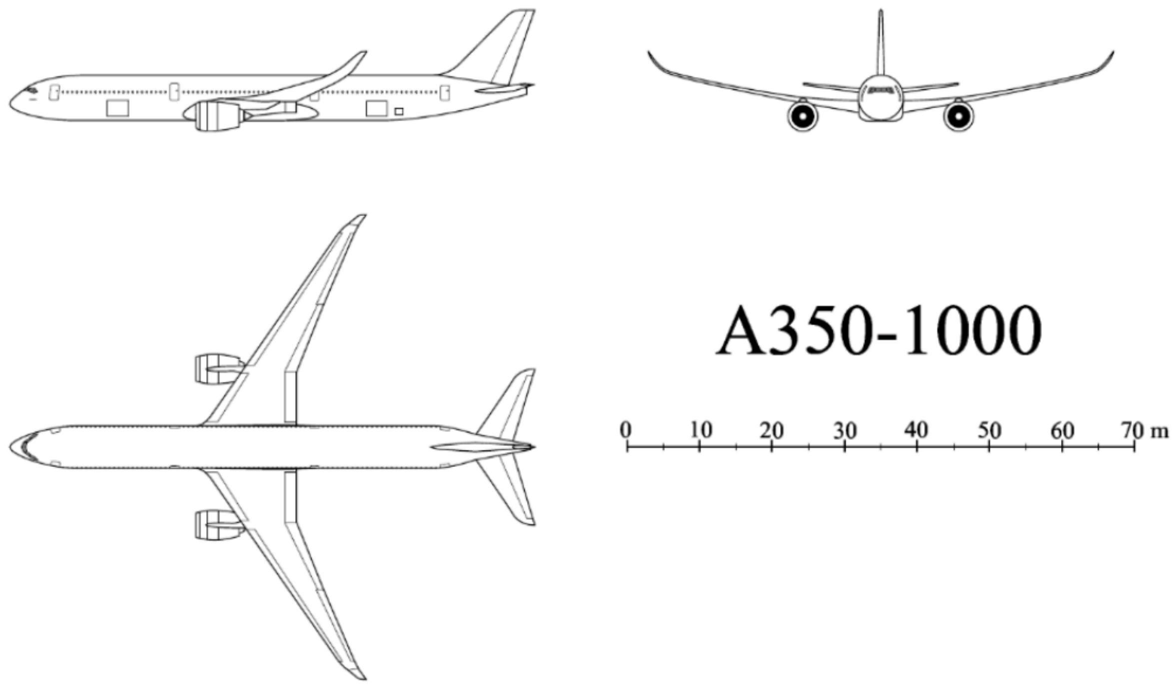


Figure 5. 33 3 view drawing of the Airbus A350-1000 (**Roux 2007a**)

The A350-1000 is a very large wide-bodied jet with capacity for a maximum seating of 369 passengers whose first flight took place on November 24, 2016. The A350-1000 will be a stretch of the base line -900 to accommodate 40 more seats. In terms of payload/range, the A350-1000 is expected to be a competitor to the 777-300ER which has the same range and 30 more seats. If the Rolls-Royce Trent XWB engines are indeed as efficient and as powerful as planned and the airframe will not be too heavy, the A350-1000 might turn out to be considerably more efficient and a strong contender of the very successful 777-300ER. GE refused to offer GEnx engines for the A350 family as the type poses a threat to exclusively GE powered 777-300ERs. The first aircraft was delivered to launch customer Qatar Airways early 2018.

As stated before, the A350 family could be seen as Airbus' answer to the slightly smaller Boeing 787 family and effectively also competes with the slightly larger Boeing 777 family. In order to be able to compete with the 787, Airbus redesigned the family to the A350'XWB' (eXtra Wide Body) which featured a wider fuselage, a new (composite) wing, upgraded A380 based systems and an advanced technology cockpit with 6 large LCD screens.

So far 212 A350-1000s have been ordered of which 58 were former A350-800 and A350-900 orders. In September 2017 three high profile A350-1000 customers, United, Cathay and LATAM, converted their A350 orders to the smaller A350-900 variant. This meant that the A350-1000 lost 20% of its order backlog. As Airbus didn’t lose these customers, as they swapped their orders to the smaller A350-900 variant, it looks like this lesser interest in the A350-1000 is more the result of the trend that Airlines prefer relatively smaller widebodies and the market for twin-engined aircraft in the highest capacity sector has substantially weakened, as also Boeing has difficulties finding new orders for their 777X and 787-10 aircraft.

Table 5. 62 Input values of the Airbus 350-1000

Parameter	**Symbol**	**Units**	**Chosen value**
PAX			369
Landing field length (ISA)	s_{LFL}	m	2110
Approach speed	V_{APP}	m/s	75
Take-off field length (ISA)	s_{TOFL}	m	2950
Range (max payload)	R	km	14815
Cruise Mach number	M_{CR}		0,85
Cruise speed	V_{CR}	m/s	250,5
Cruise altitude	h_{CR}	m	12190
Wing area	S_W	m²	443
Wing span	b_W	m	64,75
Aspect ratio	A		9,25
Maximum take-off mass	m_{MTO}	kg	290000
Payload mass	m_{PL}	kg	67250
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,232
Maximum landing mass	m_{ML}	kg	225500
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,778
Operating empty mass	m_{OE}	kg	115700
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,398965517
Maximum zero fuel mass	m_{MZF}	kg	210000
Wing loading	m_{MTO}/S_W	kg/m²	666
Number of engines	n_E		2
Engine type			Trent XWB-74
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	329
Total take-off thrust	T_{TO}	kN	658
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,22
Bypass ratio	μ		8,9
Overall pressure ratio	OAPR		50
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	156
Sweep angle	ϕ_{25}	°	35
Mean aerodynamic chord	c_{MAC}	m	8,35
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		0,113

Table 5. 63 Reverse engineering results of the Airbus 350-1000

Secret parameter	Symbol	Units	RE Value	Verification deviation[%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,36**	-4
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,03**	
Maximum aerodynamic efficiency	E_{max}	-	**20,76**	9
Specific fuel consumption	SFC	kg/N/s	**1,53E-05**	-4

5.34 Boeing 737-8-200

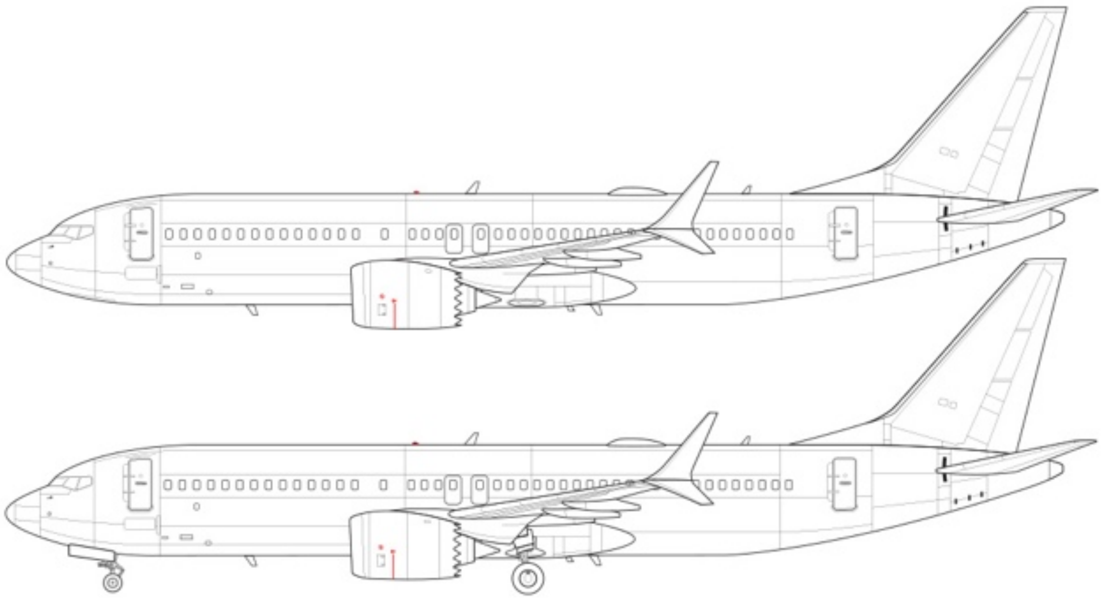


Figure 5. 34 3 view drawing of the Boeing 737-8-200 (**Norebbo 2020**)

The 737-8-200 is a medium narrow-bodied jet with capacity for a maximum seating of 200 passengers. In September 2014 Boeing introduced a new high density variant of the 737 MAX Family, marketed as the 737 MAX 200 but designated the 737-8-200. The 737-8-200 is based on the 737-8 airframe. Modifications to the cabin such as smaller front and rear galleys and the addition of two "mid-exit" doors, installed in the rear fuselage section to meet the FAA evacuation regulations, have made it possible to accommodate up to 200 passengers. The 737-8-200 will have the same MTOW as the 737-8 and will therefore have a shorter range of 5000km. The 737-8-200 is specifically intended for low cost carriers, as Boeing expects that the low cost sector will account for 35% of the single-aisle airline capacity by 2033. With 200 seats, a 737-8-200 will have 5% lower operating costs than the 737-8. Launch customer of the 737-8-200 is Ryanair which ordered 100 aircraft and took options for a 100 more in November 2014. In May 2016, Vietnamese low-cost carrier VietJet Air ordered 100 737-8-200s. A remarkable order as VietJet Air is currently an all Airbus operator with a fleet of 37 Airbus A320Ceo aircraft in service and 91 A320Neo family aircraft on order. During the Paris Air Show in June 2017, Ryanair ordered an additional 10 737-8-200s.

Table 5. 64 Input values of the Boeing 737-8-200

Parameter	Symbol	Units	Chosen value
PAX			200
Landing field length (ISA)	s_{LFL}	m	1650
Approach speed	V_{APP}	m/s	
Take-off field length (ISA)	s_{TOFL}	m	2540
Range (max payload)	R	km	4630
Cruise Mach number	M_{CR}		
Cruise speed	V_{CR}	m/s	
Cruise altitude	h_{CR}	m	
Wing area	S_W	m²	
Wing span	b_W	m	35,92
Aspect ratio	A		
Maximum take-off mass	m_{MTO}	kg	82190
Payload mass	m_{PL}	kg	
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		
Maximum landing mass	m_{ML}	kg	69308
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,843
Operating empty mass	m_{OE}	kg	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		
Maximum zero fuel mass	m_{MZF}	kg	65952
Wing loading	m_{MTO}/S_W	kg/m²	
Number of engines	n_E		2
Engine type			LEAP-1B25
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	
Total take-off thrust	T_{TO}	kN	0
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	
Bypass ratio	μ		
Overall pressure ratio	OAPR		
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	25,817
Sweep angle	ϕ_{25}	°	
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		

5.35 Airbus A330-900Neo

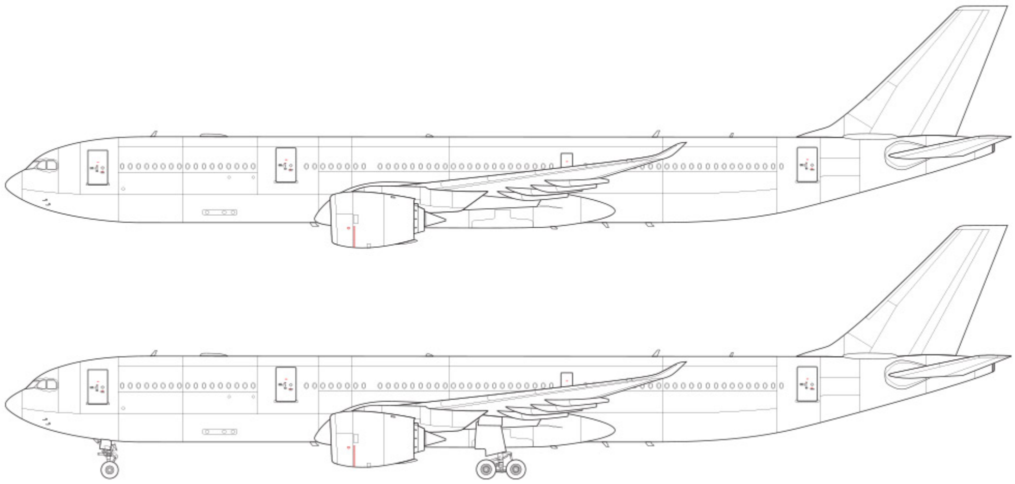


Figure 5. 35 3 view drawing of the Airbus 330-900Neo (**Norebbo 2020**)

The A330-900Neo is a very large wide-bodied jet with capacity for a maximum seating of 440 passengers whose first flight took place on October 19, 2017. Central to the new A330 concept are the new RR Trent 7000 engines. Contrary to the A330Ceo (current engine option), the A330neo will only have one engine manufacturer. Besides these new engines the A330Neo also features new larger winglets, an increased wingspan and some aerodynamic improvements to the wings and fuselage. The cabin design is also optimised and includes new-design lavatories and crew rests. These increased cabin efficiencies will result in up to ten seats more than in the current A330. All new techniques and improvements contribute to 11% lower trip costs and (thanks to 10 extra seats) 14% lower fuel burn per seat. The A330Neo has more than 95% spare parts commonality with the current generation A330s and both generations have the same type rating. This minimises the entry in service costs for airlines that already operated the A330, as they would not need to spend money on new spares or additional flight crew training. The A330NEO comes in two sizes, the A330-800N and A330-900N. The A330-900N is the larger of the two and will be the successor of the A330-300. With a backlog of 204, the A330-900N is far more popular than the A330-800N, so the main focus of the A330NEO programme will be on the -900N variant.

After months of speculation, Airbus launched the A330NEO (new engine option) at the Farnborough Air show in July 2014. Airbus studied hard to introduce a new version of the A330. The current A330 was still its best-selling wide bodied airliner as it was a relatively inexpensive wide-bodied positioned in the lower half of the Wide-bodied market; it was very well positioned to serve high density routes in the market segment below 7400km. A final reason to be hesitant about a new A330 design was that a more efficient A330Neo might easily steal orders from the

A350 XWB. Current A330 customers such as Delta and AirAsiaX kept pushing Airbus to develop a more efficient version of the A330. The fact was that developing a new version of the A330 would be relatively cheap as Airbus could use the same principles employed to develop the A320neo and benefit from engine technology developed for the A350 XWB, therefore Airbus decided to introduce the A330NEO.

Table 5. 65 Input values of the Airbus A330-900Neo

Parameter	Symbol	Units	Chosen value
PAX			440
Landing field length (ISA)	s_{LFL}	m	
Approach speed	V_{APP}	m/s	73
Take-off field length (ISA)	s_{TOFL}	m	
Range (max payload)	R	km	
Cruise Mach number	M_{CR}		
Cruise speed	V_{CR}	m/s	154,44
Cruise altitude	h_{CR}	m	
Wing area	S_W	m²	465
Wing span	b_W	m	64
Aspect ratio	A		8,8
Maximum take-off mass	m_{MTO}	kg	247000
Payload mass	m_{PL}	kg	44000
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,178
Maximum landing mass	m_{ML}	kg	191000
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,773
Operating empty mass	m_{OE}	kg	132000
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,534
Maximum zero fuel mass	m_{MZF}	kg	181000
Wing loading	m_{MTO}/S_W	kg/m²	
Number of engines	n_E		2
Engine type			RR Trent 7000
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	150
Total take-off thrust	T_{TO}	kN	300
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	
Bypass ratio	μ		
Overall pressure ratio	OAPR		
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	139,09
Sweep angle	ϕ_{25}	°	
Mean aerodynamic chord	c_{MAC}	m	7,27
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		

5.36 Bombardier CS300 / Airbus A220

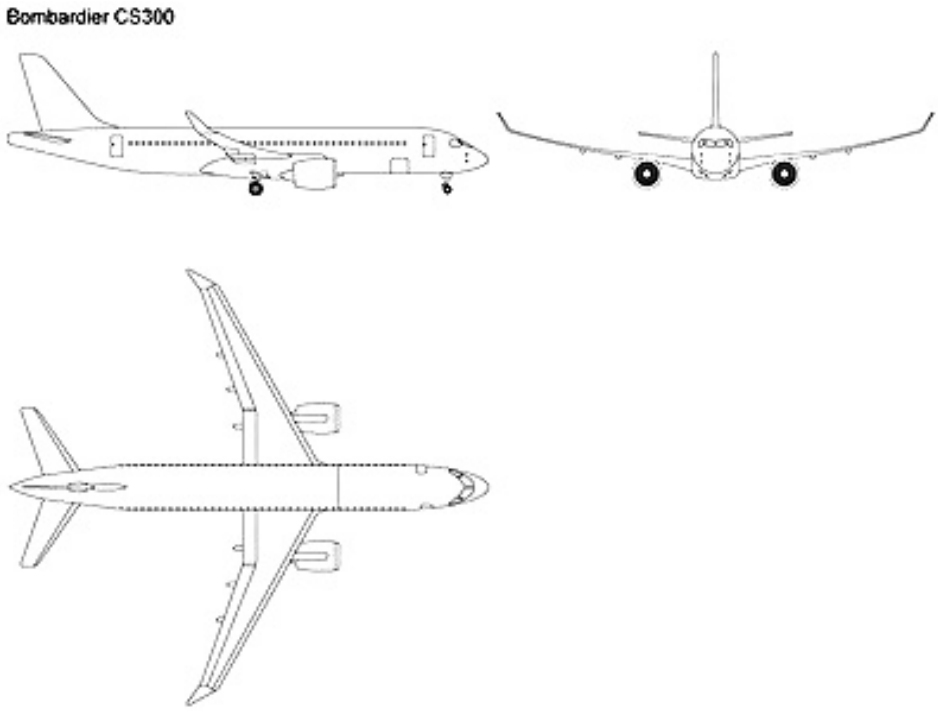


Figure 5. 36 3 view drawing of the Bombardier CS300 / Airbus A220 (**Blueprints 2020**)

The CS300 is a moderate size narrow-bodied jet with capacity for a maximum seating of 160 passengers whose first flight took place on February 27, 2015. Bombardier's CS300 is a stretch of the CS100 design. The two version together are specifically designed to cover the 100-149 seats market segment between the larger regional jets and the smaller narrowbodies. The CS300 competes with the smaller mainliners like the A318/A319 and 737-600/700. Initially the main technology improvement compared to these types was the Geared Turbofan engine technology, although this advantage was lost, when the Neo and MAX were introduced equally featuring advanced engine technology. The CSeries will be powered by two PW Geared Turbo Fan (GTF) engines which are claimed to be up to 15% more fuel efficient, 50% less noisy and up to 40% cheaper to maintain than today's technology engines. Next to that, the CSeries will feature a fuselage and wing structure of new lightweight (composite) materials, fly-by-wire and a very modern LCD cockpit. A higher MTOW version for extended range (CS300ER) and an eXtra Thrust version for short field length operations (CS300XT) will also be developed. The cabin will accommodate 3+2 abreast seating in economy class and roll-aboard sized overhead bins.

This all should make the CS300 at least 15% more efficient than its competitors today. But Airbus and Boeing have not been idle and the A319Neo and the 737 MAX 7 will come a lot closer to the CS300 performance than today's (NG and ceo) products in terms of efficiency. In March 2013 Bombardier disclosed a high density variant of the CS300, which could accommodate up to 160 seats. By launching the high-density design Bombardier added two extra over-wing exit doors and increasing the length of the fuselage as well as of the MTOW. With a seat capacity of up to 160, the CS300 competes with established names as the Airbus A320neo and Boeing 737-8. So far 200 CS300s have been ordered by eight airlines and three lease companies.

Table 5. 66 Input values of the Bombardier CS300 / Airbus A220

Parameter	Symbol	Units	Chosen value
PAX			160
Landing field length (ISA)	s_{LFL}	m	1509
Approach speed	V_{APP}	m/s	66,1
Take-off field length (ISA)	s_{TOFL}	m	1890
Range (max payload)	R	km	3610
Cruise Mach number	M_{CR}		0,78
Cruise speed	V_{CR}	m/s	230
Cruise altitude	h_{CR}	m	11126
Wing area	S_W	m²	112,3
Wing span	b_W	m	35,1
Aspect ratio	A		10,97
Maximum take-off mass	m_{MTO}	kg	67585
Payload mass	m_{PL}	kg	18711
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,277
Maximum landing mass	m_{ML}	kg	51029
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,755
Operating empty mass	m_{OE}	kg	35221
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,521
Maximum zero fuel mass	m_{MZF}	kg	55792
Wing loading	m_{MTO}/S_W	kg/m²	615
Number of engines	n_E		2
Engine type			PW1524G
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	103,6
Total take-off thrust	T_{TO}	kN	207,2
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,299
Bypass ratio	μ		12
Overall pressure ratio	OAPR		
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	0,0000112
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	21,805
Sweep angle	ϕ_{25}	°	
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		

Table 5. 67 Reverse engineering results of the Bombardier CS300 / Airbus A220

Secret parameter	Symbol	Units	RE Value	Verification deviation[%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,81**	-9
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,28**	
Maximum aerodynamic efficiency	E_{max}	-	**20,98**	-2
Specific fuel consumption	SFC	kg/N/s	**1,26E-05**	20

5.37 Boeing 767-300F

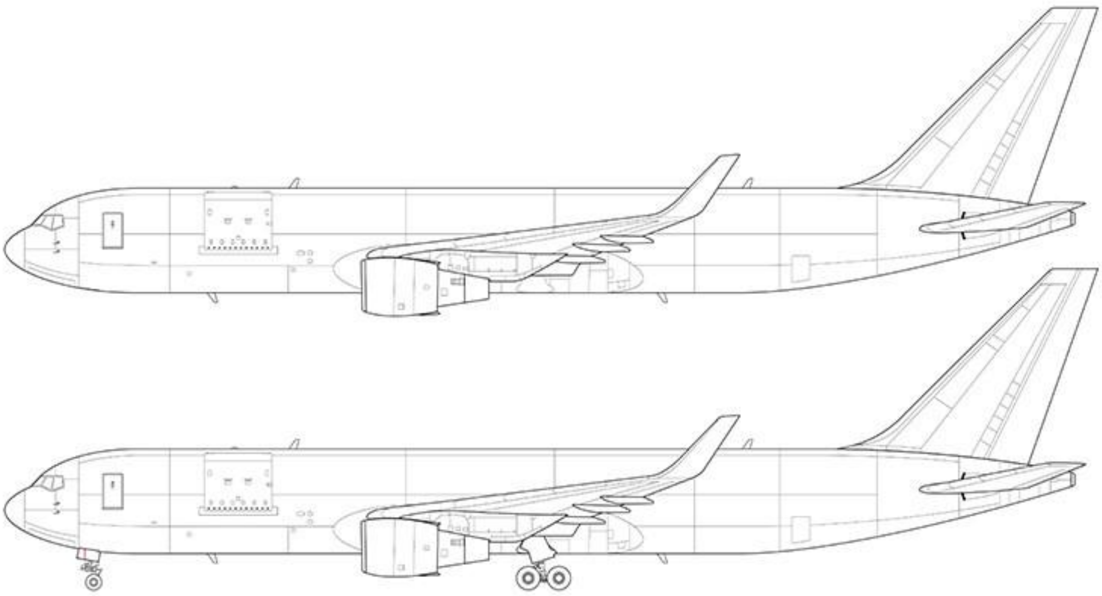


Figure 5. 37 3 view drawing of the Boeing 767-300F (**Norebbo 2020**)

The 767-300 is a medium size medium range wide-bodied freighter, based on the passenger 767-300ER platform, with capacity for 52480kg payload, whose first flight took place on June 20, 1995. It competes with Airbus' A300-600F and the larger A330-200F which arrived in 2010 but hasn't gained much traction yet. Compared to the 767-300F, the Airbus products have a slightly larger fuselage cross section which enables them to accommodate standard containers in a transverse position. This maximizes volume and avoids costly re-packaging of containerized freight in interline operations. The 767-300F can hold up to 24 standard pallets. However, with customized unit load devices, the 767-300F enjoys a significantly better payload/range capability than the A300-600F.

The biggest user of the 767-300F is currently UPS who operates 59 767-300F aircraft. Besides UPS, there had for a long time not been many orders for the 767-300F and other operators of the type only have a marginal fleet of 4 maximum, with the only exception LAN Cargo which together with its subsidiaries operated 11 aircraft. The 767-300F got a big boost in December 2011 when FedEx chose the 767-300F as replacement for their MD-10Fs. So far Fedex has ordered 109 767-300Fs. Today the only outstanding orders for the 767 freighter are from Fedex.

Table 5. 68 Input values of the Boeing 767-300F

Parameter	Symbol	Units	Chosen value
PAX			
Landing field length (ISA)	s_{LFL}	m	1740
Approach speed	V_{APP}	m/s	
Take-off field length (ISA)	s_{TOFL}	m	2926
Range (max payload)	R	km	5556
Cruise Mach number	M_{CR}		0,8
Cruise speed	V_{CR}	m/s	238,33
Cruise altitude	h_{CR}	m	11887
Wing area	S_W	m²	283,3
Wing span	b_W	m	47,57
Aspect ratio	A		7,99
Maximum take-off mass	m_{MTO}	kg	186880
Payload mass	m_{PL}	kg	50800
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,272
Maximum landing mass	m_{ML}	kg	147871
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,791
Operating empty mass	m_{OE}	kg	85275
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,456
Maximum zero fuel mass	m_{MZF}	kg	140160
Wing loading	m_{MTO}/S_W	kg/m²	653
Number of engines	n_E		2
Engine type			CF6-80C2B7F
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	276,233
Total take-off thrust	T_{TO}	kN	552,466
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,3
Bypass ratio	μ		5,3
Overall pressure ratio	OAPR		31,8
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	9,15E-06
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	91,38
Sweep angle	ϕ_{25}	°	31,5
Mean aerodynamic chord	c_{MAC}	m	6,98
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	11,5
Taper	λ		0,207

Table 5. 69 Reverse engineering results of the Boeing 767-300F

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,80**	-1
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**1,75**	
Maximum aerodynamic efficiency	E_{max}	-	**15,95**	15
Specific fuel consumption	SFC	kg/N/s	**1,43E-05**	9

5.38 Comac ARJ21-700

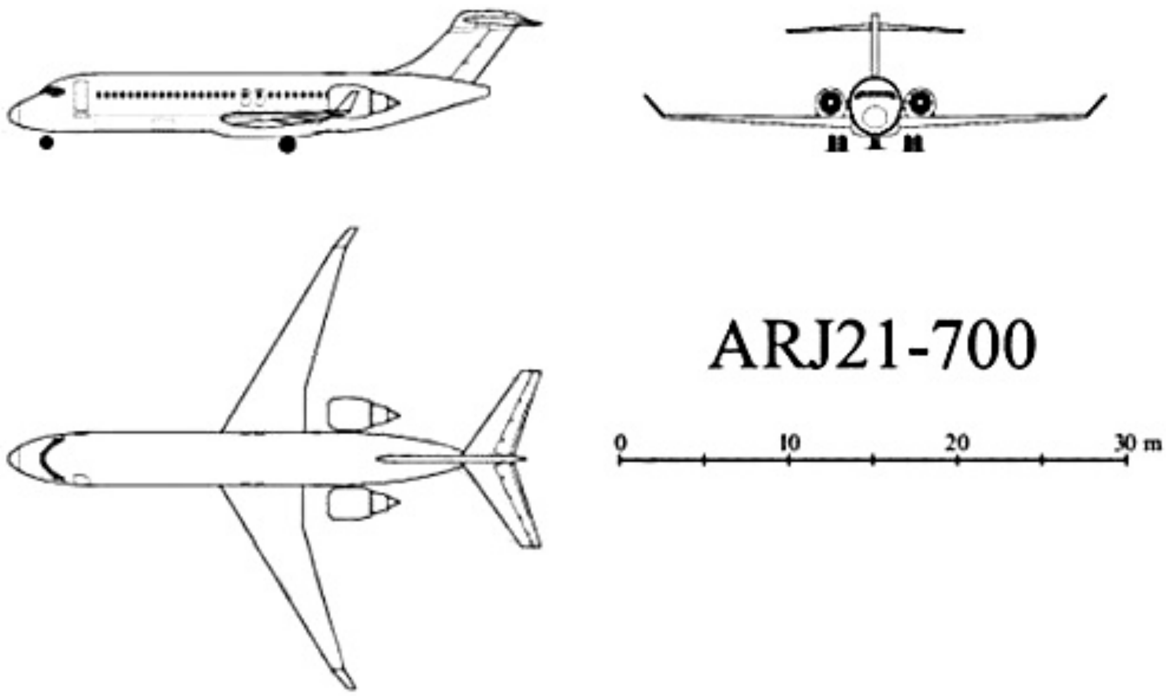


Figure 5. 38 3 view drawing of the Comac ARJ21-700 (**Roux 2007a**)

The ARJ21-700 is a large regional jet with capacity for a maximum seating of 90 passengers whose first flight took place on November 28, 2008. The ARJ21 regional jet is China's first domestically developed aircraft by government-controlled COMAC. The initial family is planned to consist of two passenger types - the ARJ21-700 and the stretched ARJ21-900. The ARJ21s are primarily aimed at the Chinese domestic regional market. Both versions will have a standard and an extended range (-ER) variant. The design has some exterior resemblance with the DC-9, though features a newly (Antonov) designed wing with winglets and GE's CF34-10 engines which also power the E190/195. Other involvement from western countries is Rockwell Collins avionics and Honeywell's fly bywire systems.

So far, only the smaller ARJ21-700 has been ordered, making a total of 180 ordered aircraft. The great part of the orders come from: Henan Airlines, the largest customer with 50 aircraft on order; launch customer Chengdu Airlines has ordered 30 ARJ21-700s and Hebei Airlines and Shandong Airlines each 10.

The first commercial delivery of the ARJ21-700 slipped several times the manufacturers encountered problems in the development as well in the certification process. Late December 2014, COMAC finished the last functional and reliability tests on one of the prototypes, marking the completion of all test modules required for the ARJ21-700. On 30 December 2014, the Chinese aviation authorities finally issued the type certification for the ARJ21 (initially scheduled for 2007). A major milestone for the commercial aviation sector in China. COMAC worked hard to make all the necessary improvements and on 9 July 2017, more than 2,5 year after the type certification, COMAC received the production certificate for the ARJ21 from the Civil Aviation Administration of China

Table 5. 70 Input values of the Comac ARJ21-700

Parameter	Symbol	Units	Chosen value
PAX			90
Landing field length (ISA)	s_{LFL}	m	1550
Approach speed	V_{APP}	m/s	
Take-off field length (ISA)	s_{TOFL}	m	1700
Range (max payload)	R	km	2225
Cruise Mach number	M_{CR}		0,78
Cruise speed	V_{CR}	m/s	230
Cruise altitude	h_{CR}	m	10668
Wing area	S_W	m²	79,86
Wing span	b_W	m	27,29
Aspect ratio	A		9,32
Maximum take-off mass	m_{MTO}	kg	43500
Payload mass	m_{PL}	kg	8935
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,205
Maximum landing mass	m_{ML}	kg	37665
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,866
Operating empty mass	m_{OE}	kg	24955
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,574
Maximum zero fuel mass	m_{MZF}	kg	33890
Wing loading	m_{MTO}/S_W	kg/m²	507,1
Number of engines	n_E		2
Engine type			CF34-10A
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	80,068
Total take-off thrust	T_{TO}	kN	160,136
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,4
Bypass ratio	μ		5
Overall pressure ratio	OAPR		29
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	12,719
Sweep angle	ϕ_{25}	°	25
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		

Table 5. 71 Reverse engineering results of the Comac ARJ21-700

Secret parameter	Symbol	Units	RE Value	Verification deviation[%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,84**	0
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,35**	
Maximum aerodynamic efficiency	E_{max}	-	**14,89**	27
Specific fuel consumption	SFC	kg/N/s	**1,72E-05**	3

5.39 Boeing 787-10

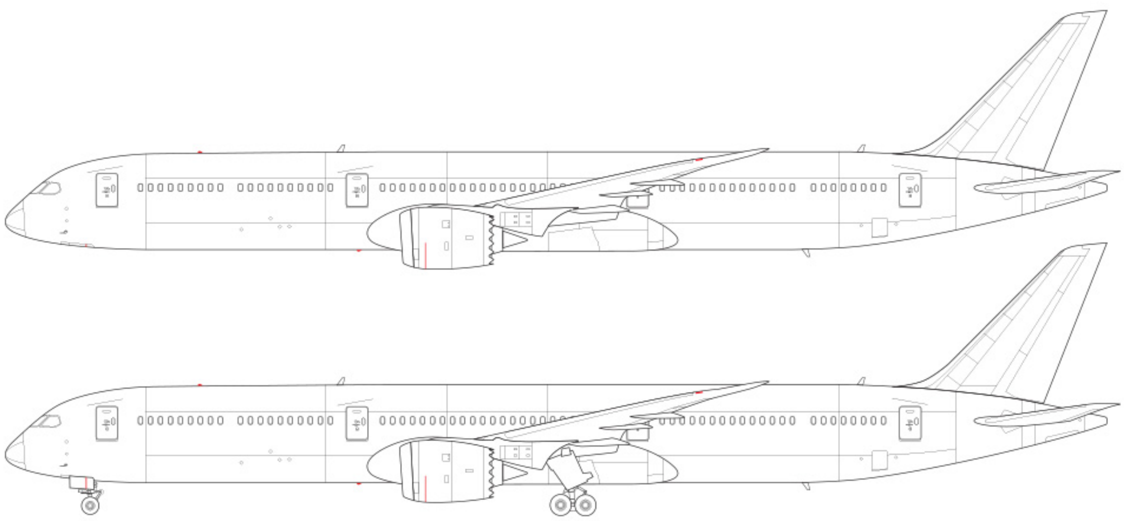


Figure 5. 39 3 view drawing of the Boeing 787-10 (**Norebbo 2020**)

The 787-10 is a large wide-bodied jet with capacity for a maximum seating of 440 passengers whose first flight took place on March 31, 2017. It has the same wingspan and engines as the 787-9, which indicates that the 787-10 would probably be targeted for thick, medium-long routes such as transpacific or transatlantic. As such, it would be a strong competitor to today's very successful Airbus A330-300 (having slightly more pax and more range) as well as to the Airbus A330-800/900Neo and Airbus A350-800 and -900 which probably will be heavier but probably beat the -10 on range. In general, the 787 family features many new technologies like a full composite structure including wing and barrel shaped fuselage sections (accommodates 9 abreast seating), new up to 15-20% more efficient and relatively quiet engines, improved aerodynamics and many new electric systems instead of pneumatics/hydraulics. A clear advantage for the 787-10 would be that it could benefit from the design, production and operational experience gained with the 787-8 and -9.

Initially the 787-10 was very well received in the market and in the first half year after its introduction at the Paris Air Show 2013, more than 120 aircraft had been ordered. Since then, the new order intake has been slow with only 48 new 787-10 orders, which in combination with a few order swaps from the 787-9 to 787-10 makes for a total backlog of 168 aircraft.

Table 5. 72 Input values of the Boeing 787-10

Parameter	Symbol	Units	Chosen value
PAX			440
Landing field length (ISA)	s_{LFL}	m	1855
Approach speed	V_{APP}	m/s	
Take-off field length (ISA)	s_{TOFL}	m	2995
Range (max payload)	R	km	7710
Cruise Mach number	M_{CR}		0,85
Cruise speed	V_{CR}	m/s	253,61
Cruise altitude	h_{CR}	m	10700
Wing area	S_W	m²	325
Wing span	b_W	m	60,12
Aspect ratio	A		11,1
Maximum take-off mass	m_{MTO}	kg	254011
Payload mass	m_{PL}	kg	
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		
Maximum landing mass	m_{ML}	kg	201848
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,795
Operating empty mass	m_{OE}	kg	135500
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,533
Maximum zero fuel mass	m_{MZF}	kg	192776
Wing loading	m_{MTO}/S_W	kg/m²	
Number of engines	n_E		2
Engine type			Genx 72A1
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	340
Total take-off thrust	T_{TO}	kN	680
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	
Bypass ratio	μ		9
Overall pressure ratio	OAPR		53,3
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	138,7
Sweep angle	ϕ_{25}	°	32,2
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	
Taper	λ		

Table 5. 73 Reverse engineering results of the Boeing 787-310

Secret parameter	Symbol	Units	RE Value	Verification

				deviation[%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,13**	-6
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,24**	
Maximum aerodynamic efficiency	E_{max}	-	**19,62**	9
Specific fuel consumption	SFC	kg/N/s	**1,14E-05**	31

5.40 Boeing 747-400

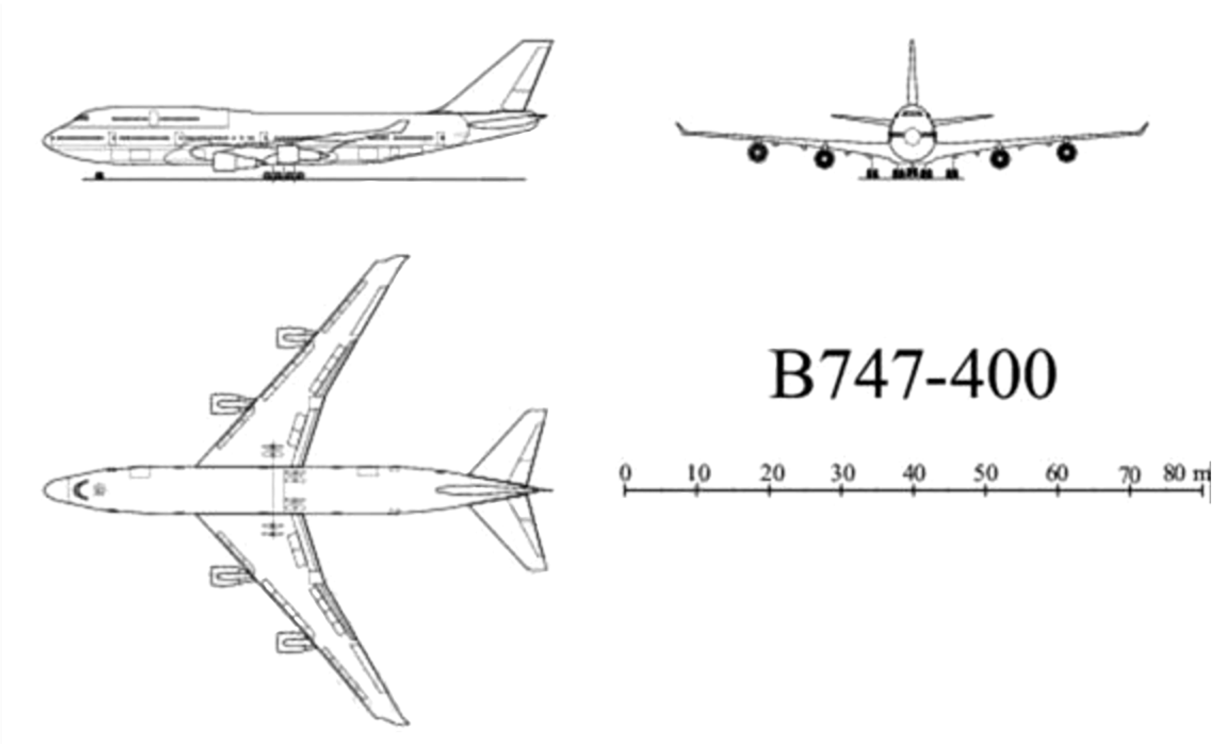


Figure 5. 40 3 view drawing of the Boeing 747-400 (**Roux 2007a**)

The 747-400 is a large wide-bodied jet with capacity for a maximum seating of 620 passengers whose first flight took place on April 29, 1988. The 747 was the first Wide-bodied in service and remained the largest passenger airliner until the A380 entered into service in 2007. The 747-400 was introduced into service in 1989 and enjoyed a monopoly in the 3-class over 400 seat capacity class for almost 20 years. The introduction of the A340-600 and 777-300ER as well as the A380 served to fragment market demand for the 747-400. Although none of these aircraft exactly matches the capacity of the 747-400, they do offer an alternative option and reduced the market for the new passenger 747-400s. Boeing unsuccessfully tried to re-start demand by offering the extended range 747-400ER which was only sold to Qantas (6). Boeing's 747-400's replacement product is the 747-8I which is the latest 747 derivative. Production of the 747-400 passenger aircraft ended in March 2005 followed by the last -400ERF freighter produced in October 2009. The 2008 economic crisis accelerated the phase out of the passenger 747-400s. By lack of a large secondary market, part out has already become a viable end-of-life solution for some vintages. 64 747-400s have been permanently withdrawn from used since January 2015. Many of these aircraft have been scrapped.

Once the Queen-of-the-Skies and the flagship of many top-notch airlines, the 747-400 has now the old-age-aircraft stigma and many airlines who once operated large fleets of 747-400s has phased them out or will phase them out in the very near future. Most 747-400 are / will be replaced by Airbus A380s or Boeing 777-300ERs. As the costs of operating a used 747-400 are very high, there is little appetite for used 747-400s. There are 13 747-400s in service as corporate/VIP/government aircraft (one VIP 747-400 stored) and one 747 been converted to water bomber.

Table 5. 74 Input values of the Boeing 747-400

Parameter	Symbol	Units	Chosen value
PAX			620
Landing field length (ISA)	s_{LFL}	m	2100
Approach speed	V_{APP}	m/s	75,1
Take-off field length (ISA)	s_{TOFL}	m	3200
Range (max payload)	R	km	10695
Cruise Mach number	M_{CR}		0,85
Cruise speed	V_{CR}	m/s	253
Cruise altitude	h_{CR}	m	10668
Wing area	S_W	m²	541,16
Wing span	b_W	m	64,44
Aspect ratio	A		7,67
Maximum take-off mass	m_{MTO}	kg	396830
Payload mass	m_{PL}	kg	63657
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,160
Maximum landing mass	m_{ML}	kg	260362
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,656
Operating empty mass	m_{OE}	kg	179015
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,451
Maximum zero fuel mass	m_{MZF}	kg	242672
Wing loading	m_{MTO}/S_W	kg/m²	670,5
Number of engines	n_E		4
Engine type			PW4056
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	252
Total take-off thrust	T_{TO}	kN	1008
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,28
Bypass ratio	μ		4,9
Overall pressure ratio	OAPR		30,2
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	9,06E-06
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	204,333
Sweep angle	ϕ_{25}	°	37,5
Mean aerodynamic chord	c_{MAC}	m	9,68
Position of maximum camber	$x_{(y\_c),max}$	%c	15
Camber	$(y_c)_{max}/c$	%c	1,4
Position of maximum thickness	$x_{t,max}$	%c	35
Relative thickness	t/c	%	9,4
Taper	λ		0,278

Table 5. 75 Reverse engineering results of the Boeing 747-400

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**2,14**	0
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,07**	
Maximum aerodynamic efficiency	E_{max}	-	**16,42**	18
Specific fuel consumption	SFC	kg/N/s	**1,46E-05**	15

5.41 Boeing 737-500

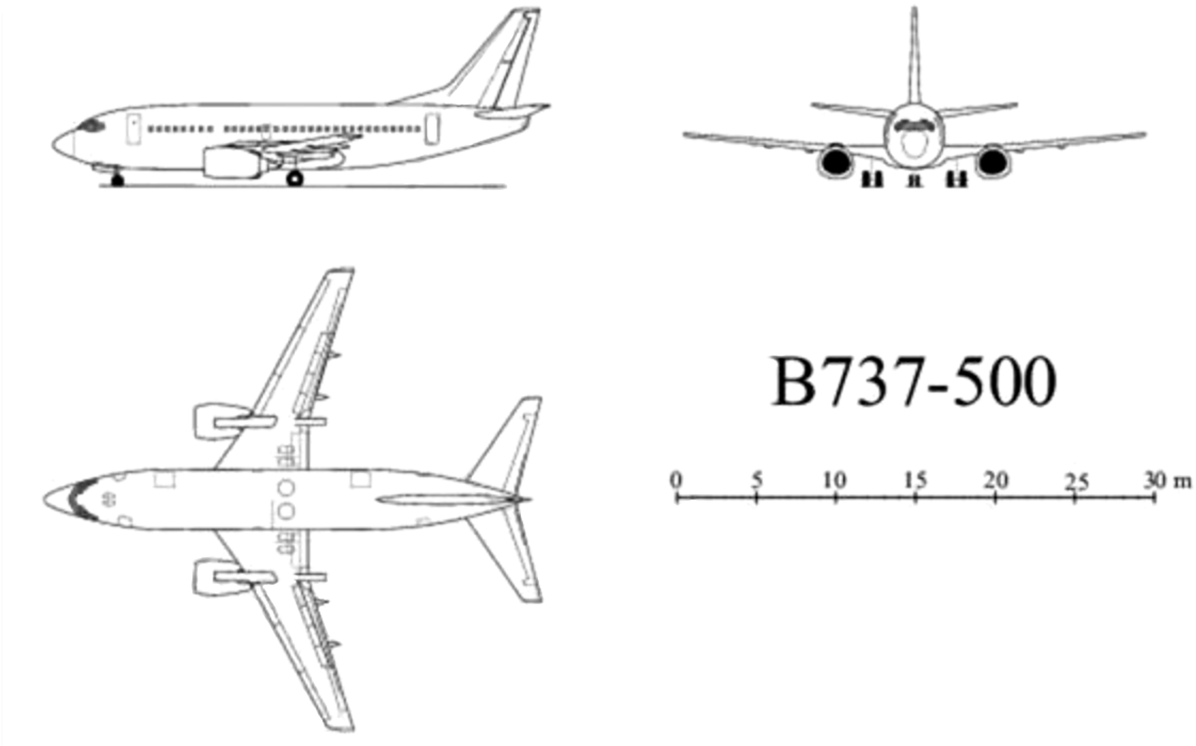


Figure 5. 41 3 view drawing of the Boeing 737-500 (**Roux 2007a**)

The 737-500 is a small narrow-bodied jet with capacity for a maximum seating of 149 passengers whose first flight took place on June 30, 1989. The -500 is the smallest member of the 737 Classic family with the longest range. It replaced the similar sized 737-200. Commonality with the -300 and -400 and the large US domestic market gave the -500 the upper hand. Additional winglets can improve the aircraft performance. So far about 60 737-500s have been retrofitted with winglets. For high cycled aircraft structural issues will lead to increased maintenance/inspection costs with repairs, possibly further shortening the economic life. Given its small size, there is very little interest in conversion to freighter, so there are no conversion programmes for the 737-500.

Competition came from the less successful A318 and 737-600. In the secondary market, the 737-500 isn't widely accepted as it is relatively heavy and has comparatively high seat-mile costs. Newer competitors like E190/195 and C-Series are much more efficient. In 2015 and 2016, main operators Southwest (25 aircraft) and Lufthansa (33 aircraft) phased out the type. The biggest current operator UTAir (32 aircraft) has already announced that it will phase out the fleet in the near future and the first 10 aircraft will leave the fleet before 2018. Because of its long range the type has been popular in Russia and as of today, Russia is still home to the largest population of 737-500s, with 42 aircraft flying for 4 different commercial operators.

Table 5. 76 Input values of the Boeing 737-500

Parameter	Symbol	Units	Chosen value
PAX			149
Landing field length (ISA)	s_{LFL}	m	1362
Approach speed	V_{APP}	m/s	66
Take-off field length (ISA)	s_{TOFL}	m	1832
Range (max payload)	R	km	2519
Cruise Mach number	M_{CR}		0,745
Cruise speed	V_{CR}	m/s	221
Cruise altitude	h_{CR}	m	10668
Wing area	S_W	m²	91,04
Wing span	b_W	m	28,88
Aspect ratio	A		9,16
Maximum take-off mass	m_{MTO}	kg	52390
Payload mass	m_{PL}	kg	15182
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,290
Maximum landing mass	m_{ML}	kg	49895
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,952
Operating empty mass	m_{OE}	kg	31312
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,598
Maximum zero fuel mass	m_{MZF}	kg	46490
Wing loading	m_{MTO}/S_W	kg/m²	575
Number of engines	n_E		2
Engine type			CFM56-3B1
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	88,964
Total take-off thrust	T_{TO}	kN	177,928
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,35
Bypass ratio	μ		6
Overall pressure ratio	OAPR		22,6
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	1,08E-05
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	1,89E-05
Available fuel volume	$V_{fuel,available}$	m³	20,102
Sweep angle	ϕ_{25}	°	25
Mean aerodynamic chord	c_{MAC}	m	3,73
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	12,9
Taper	λ		0,24

Table 5. 77 Reverse engineering results of the Boeing 737-500

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,76**	-19
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,84**	
Maximum aerodynamic efficiency	E_{max}	-	**15,11**	20
Specific fuel consumption	SFC	kg/N/s	**1,84E-05**	-10

5.42 Boeing 777F

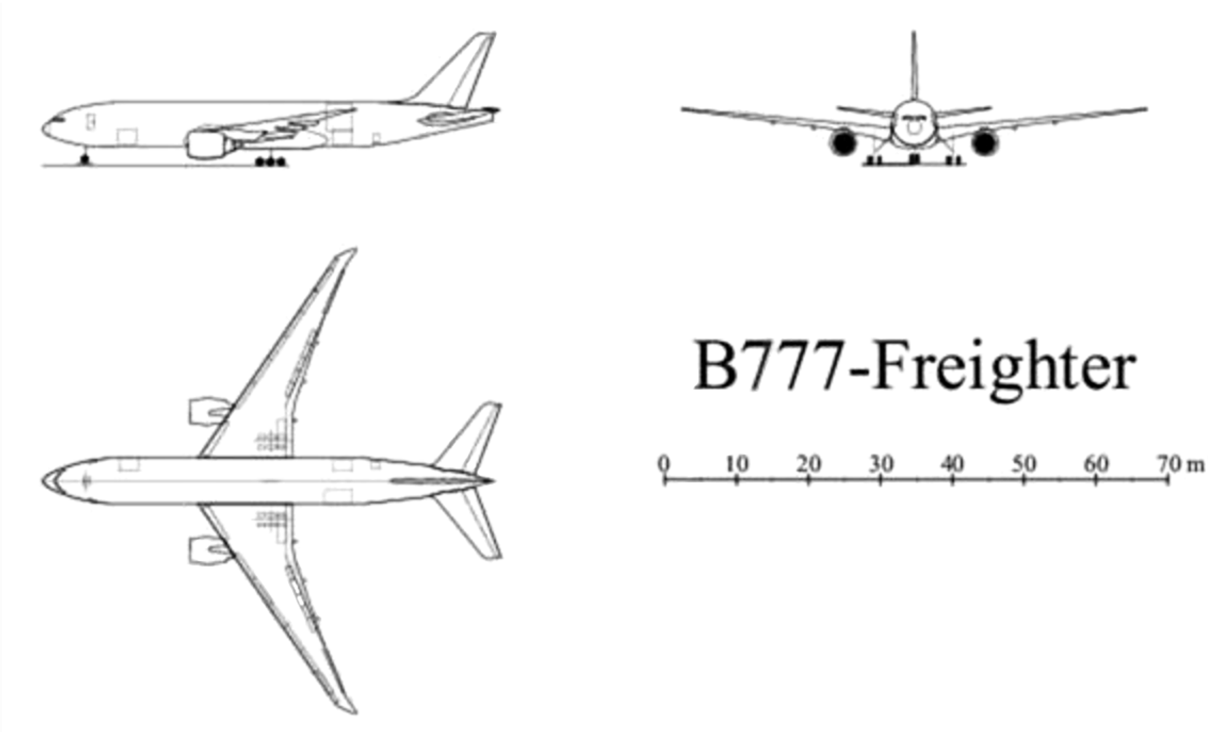


Figure 5. 42 3 view drawing of the Boeing 777F (**Roux 2007a**)

The 777 Freighter is the world's longest range twin-engine freighter. It is a large size long range wide-bodied freighter with capacity for 102000kg payload, whose first flight took place on July 14, 2008. The 777 Freighter is based on the highly efficient 777-200LR passenger airplane, equipped with a large side cargo door and solely powered by GE90-110/115 engines. The 777 Freighter main deck can accommodate 27 standard pallets. The aircraft is complementary to the significantly larger 747-8F while there seems to be no contemporary competitor until e.g. an A350XWB-900F would be introduced. A 777-8F seems still many years away

The Boeing 777 Freighter was generally seen by the airlines as a potential replacement for the 747-200F/SF and the MD-11F. It offers only slightly less payload than the 747-200F and superior payload capacity compared to the MD-11F but significantly more range than either. From

Boeing's perspective, the discontinuation of the 747-400 Freighter production, left customers to choose between moving up a capacity class to the 747-8F or choosing the slightly smaller payload option offered by the efficient 777 Freighter. With the 777 Freighter and the 747-8F, Boeing has a virtual monopoly in the large, long haul cargo aircraft market for the foreseeable future, as Airbus after the failed attempt of the A380 freighter, does not offer any equally capable freighter.

As the capital investment is significant, the 777 Freighter is mainly operated by larger cargo network operators, integrators and dedicated first tier cargo airlines. Biggest operator is Fedex with 30 aircraft in active service and 10 on order. The 777 Freighter is received very well as it is highly efficient and even opened up new markets and considerably extends the cargo cut off times of suppliers as it doesn't need fuel stops on long range routes.

Table 5. 78 Input values of the Boeing 777F

Parameter	**Symbol**	**Units**	**Chosen value**
PAX			
Landing field length (ISA)	s_{LFL}	m	1750
Approach speed	V_{APP}	m/s	72
Take-off field length (ISA)	s_{TOFL}	m	3000
Range (max payload)	R	km	9050
Cruise Mach number	M_{CR}		0,84
Cruise speed	V_{CR}	m/s	252
Cruise altitude	h_{CR}	m	10668
Wing area	S_W	m²	427,8
Wing span	b_W	m	64,8
Aspect ratio	A		
Maximum take-off mass	m_{MTO}	kg	347815
Payload mass	m_{PL}	kg	103737
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,298
Maximum landing mass	m_{ML}	kg	260816
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,750
Operating empty mass	m_{OE}	kg	144379
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,415
Maximum zero fuel mass	m_{MZF}	kg	248115
Wing loading	m_{MTO}/S_W	kg/m²	
Number of engines	n_E		2
Engine type			GE90-110B1L
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	489
Total take-off thrust	T_{TO}	kN	978
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,29
Bypass ratio	μ		9
Overall pressure ratio	OAPR		42
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	181,283
Sweep angle	ϕ_{25}	°	31,64
Mean aerodynamic chord	c_{MAC}	m	
Position of maximum camber	$x_{(y\_c),max}$	%c	30
Camber	$(y_c)_{max}/c$	%c	5,9
Position of maximum thickness	$x_{t,max}$	%c	30
Relative thickness	t/c	%	22
Taper	λ		

Table 5. 79 Reverse engineering results of the Boeing 777F

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,26**	-21
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,21**	
Maximum aerodynamic efficiency	E_{max}	-	**18,30**	10
Specific fuel consumption	SFC	kg/N/s	**1,19E-05**	24

5.43 Embraer 195

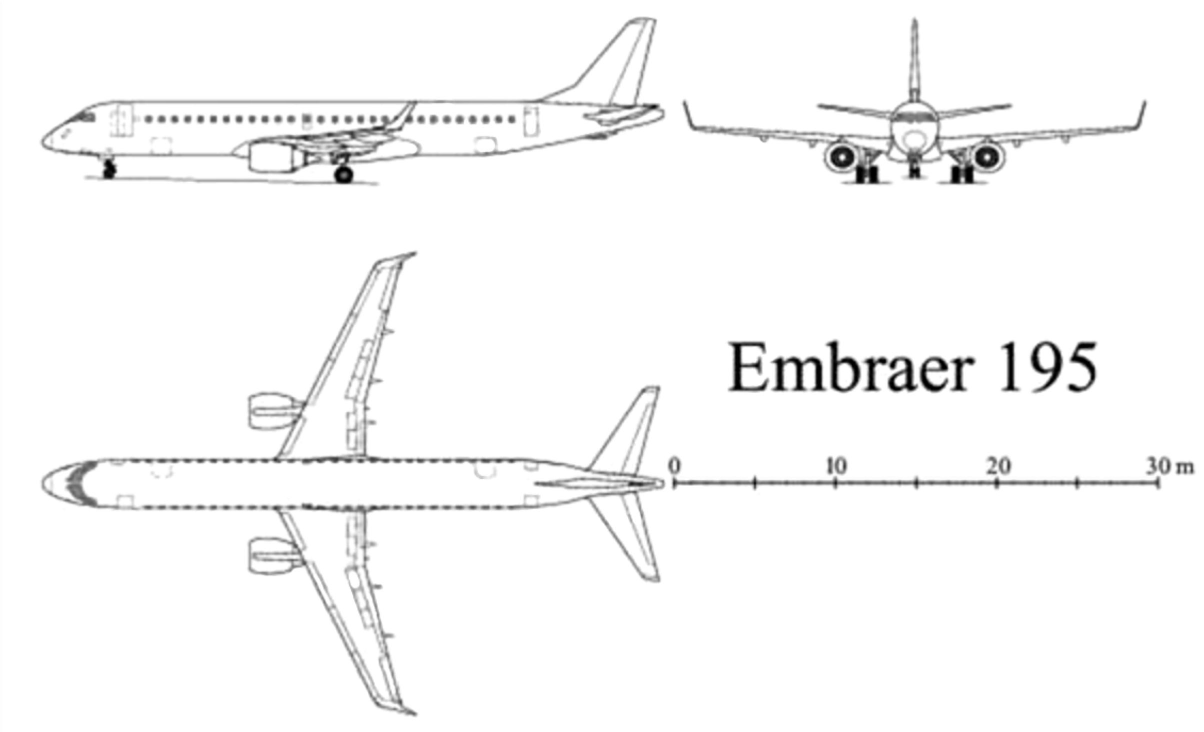


Figure 5. 43 3 view drawing of the Embraer 195 (**Roux 2007a**)

The Embraer 195 is a large regional jet with capacity for a maximum seating of 118 passengers whose first flight took place on December 7, 2004. The E195 is a further stretch of the E190, giving it an additional 10 seats in single class. This makes it the largest member of the E-jets family with over 85% commonality. Like its smaller family members, the E195 is offered in a standard (-STD), long range (–LR) and advanced range (-AR) version. The -AR has become the production standard and can be downgraded to the -LR or -STD specifications. Early built aircraft which didn't have the -AR structure suffer from a weaker (wing) structure resulting in a lower structural MTOW which limits range. If equipped with more than 100 seats, an additional 3rd cabin crew member is required, which increases costs.

The E195's main competitors are the more efficient but narrower CRJ900/1000 but also its slightly smaller sister the E190. For network operators, the E195 could be a slightly smaller and cheaper (trip cost) alternative for the smallest members of the 737 and A320 narrowbody families but it falls a bit short on range. Going forward, competition will further increase with the arrival of the longer range CS100 which will be equipped with considerably more efficient engines. As a consequence of the increased competition, Embraer was forced to revamp its E-jet family enhancing it to a version of the "1st" generation E-Jet, featuring a redesigned wingtip and two packages of aerodynamic, structural and systems improvements to the wing and the fuselage. The new E195 will not feature the new wingtip, designed exclusively for the E175. All these adjustments will lead to a reduction of fuel consumption by 1 – 2% on the E190.

Sales success has been fairly limited and is concentrated at Azul (60 aircraft in service) and airlines belonging to the Lufthansa Group (33 aircraft in service and 1 stored). The current backlog for the E195 consist of eight aircraft, seven of them are destined for China's Tianjin Airlines.

Table 5. 80 Input values of the Embraer 195

Parameter	Symbol	Units	Chosen value
PAX			118
Landing field length (ISA)	s_{LFL}	m	1435
Approach speed	V_{APP}	m/s	
Take-off field length (ISA)	s_{TOFL}	m	2251
Range (max payload)	R	km	1445
Cruise Mach number	M_{CR}		0,78
Cruise speed	V_{CR}	m/s	247
Cruise altitude	h_{CR}	m	10668
Wing area	S_W	m²	92,53
Wing span	b_W	m	28,72
Aspect ratio	A		8,92
Maximum take-off mass	m_{MTO}	kg	52290
Payload mass	m_{PL}	kg	13530
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,259
Maximum landing mass	m_{ML}	kg	45000
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,861
Operating empty mass	m_{OE}	kg	28970
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,554
Maximum zero fuel mass	m_{MZF}	kg	42500
Wing loading	m_{MTO}/S_W	kg/m²	527,3
Number of engines	n_E		2
Engine type			CF34-10E5
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	82,292
Total take-off thrust	T_{TO}	kN	164,584
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,34
Bypass ratio	μ		5
Overall pressure ratio	OAPR		29
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	1,08E-05
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	16,029
Sweep angle	ϕ_{25}	°	
Mean aerodynamic chord	c_{MAC}	m	3,68
Position of maximum camber	$x_{(y\_c),max}$	%c	44,2
Camber	$(y_c)_{max}/c$	%c	2,7
Position of maximum thickness	$x_{t,max}$	%c	35
Relative thickness	t/c	%	11,8
Taper	λ		

Table 5. 81 Reverse engineering results of the Embraer 195

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,17**	-9
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**1,83**	
Maximum aerodynamic efficiency	E_{max}	-	**14,41**	30
Specific fuel consumption	SFC	kg/N/s	**1,70E-05**	2

5.44 Boeing 717-200

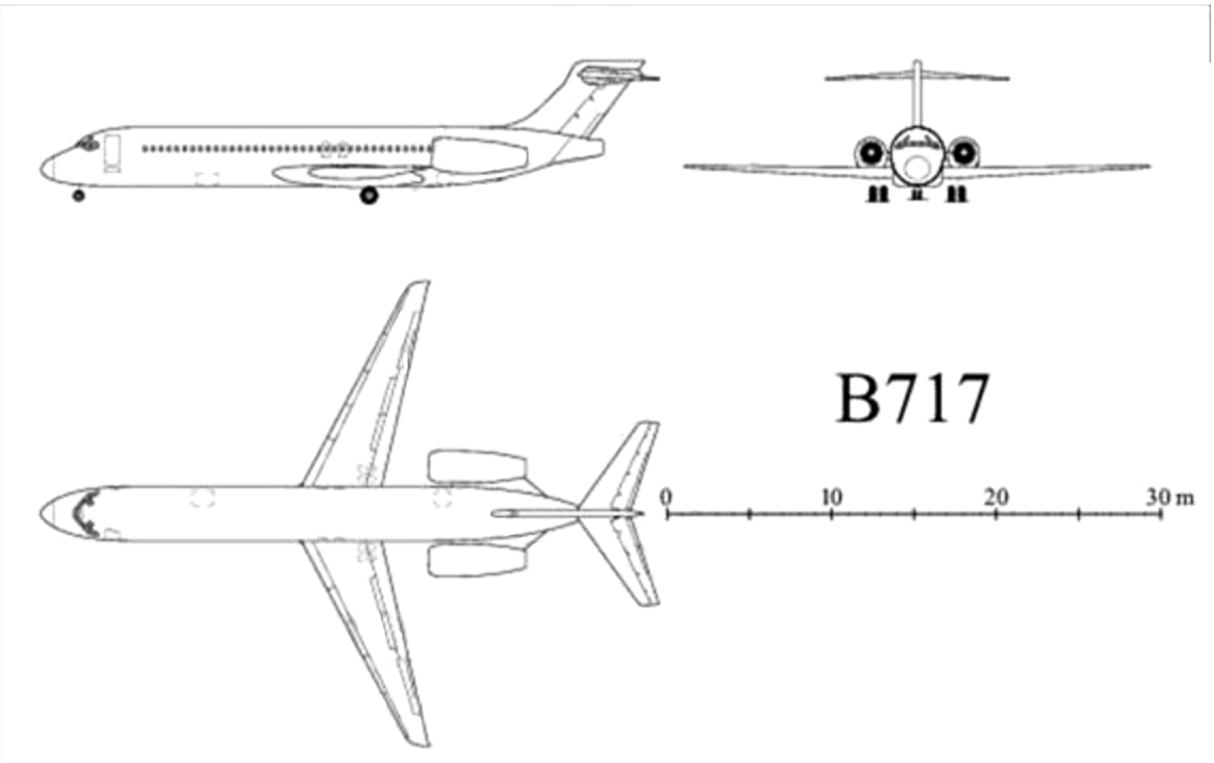


Figure 5. 44 3 view drawing of the Boeing 717-200 (**Roux 2007a**)

The 717-200 is a small narrow-bodied jet with capacity for a maximum seating of 106 passengers whose first flight took place on September 2, 1998. The Boeing 717 was originally developed by McDonnell Douglas as the MD-95, a 100-seat off-shoot of the MD-90. Development started in 1991 and was targeted at the Northwest Airlines requirement for a DC- 9-30 replacement. The MD-95 was the only former McDonnell-Douglas Corporation commercial passenger aircraft programme retained by Boeing after its take-over of MDC and was subsequently renamed the Boeing 717-200. As such it shared no commonality with other aircraft in production, although Boeing considered both shrink and stretched versions.

As a stand-alone aircraft it didn't have a lot of commercial success and only attracted AirTran Airways as large customer. Production ceased in 2006. Southwest Airlines which acquired

AirTran, sub-leased its inherited 88 strong 717 fleet to Delta Airlines. The first 717 was delivered to Delta in October 2013. By early 2016 the entire AirTran fleet had been transitioned to Delta Air Lines. Delta has also acquired some 717s from other operators and with a current fleet of 91 Boeing 717s in service (58,7% of the current fleet), Delta is by far the biggest operator of the type. The majority of the 717 fleet (98 aircraft) is controlled by the Boeing Capital Corporation. With only five airlines currently operating the Boeing 717, the operator base is very small.

Table 5. 82 Input values of the Boeing 717-200

Parameter	Symbol	Units	Chosen value
PAX			106
Landing field length (ISA)	s_{LFL}	m	1450
Approach speed	V_{APP}	m/s	69
Take-off field length (ISA)	s_{TOFL}	m	1677
Range (max payload)	R	km	1375
Cruise Mach number	M_{CR}		0,77
Cruise speed	V_{CR}	m/s	225,3
Cruise altitude	h_{CR}	m	10424
Wing area	S_W	m²	92,97
Wing span	b_W	m	28,45
Aspect ratio	A		8,71
Maximum take-off mass	m_{MTO}	kg	54900
Payload mass	m_{PL}	kg	14515
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,264
Maximum landing mass	m_{ML}	kg	49898
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,909
Operating empty mass	m_{OE}	kg	31071
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,566
Maximum zero fuel mass	m_{MZF}	kg	45586
Wing loading	m_{MTO}/S_W	kg/m²	537
Number of engines	n_E		2
Engine type			BR715A1-30
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	82,292
Total take-off thrust	T_{TO}	kN	164,584
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,34
Bypass ratio	μ		4,7
Overall pressure ratio	OAPR		32,1
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	1,05E-05
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	
Available fuel volume	$V_{fuel,available}$	m³	13,905
Sweep angle	ϕ_{25}	°	24,5
Mean aerodynamic chord	c_{MAC}	m	3,88
Position of maximum camber	$x_{(y\_c),max}$	%c	
Camber	$(y_c)_{max}/c$	%c	
Position of maximum thickness	$x_{t,max}$	%c	
Relative thickness	t/c	%	11,6
Taper	λ		0,206

Table 5. 83 Reverse engineering results of the Boeing 717-200

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,46**	-19
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,70**	
Maximum aerodynamic efficiency	E_{max}	-	**14,30**	24
Specific fuel consumption	SFC	kg/N/s	**1,48E-05**	15

5.45 Boeing 737-400

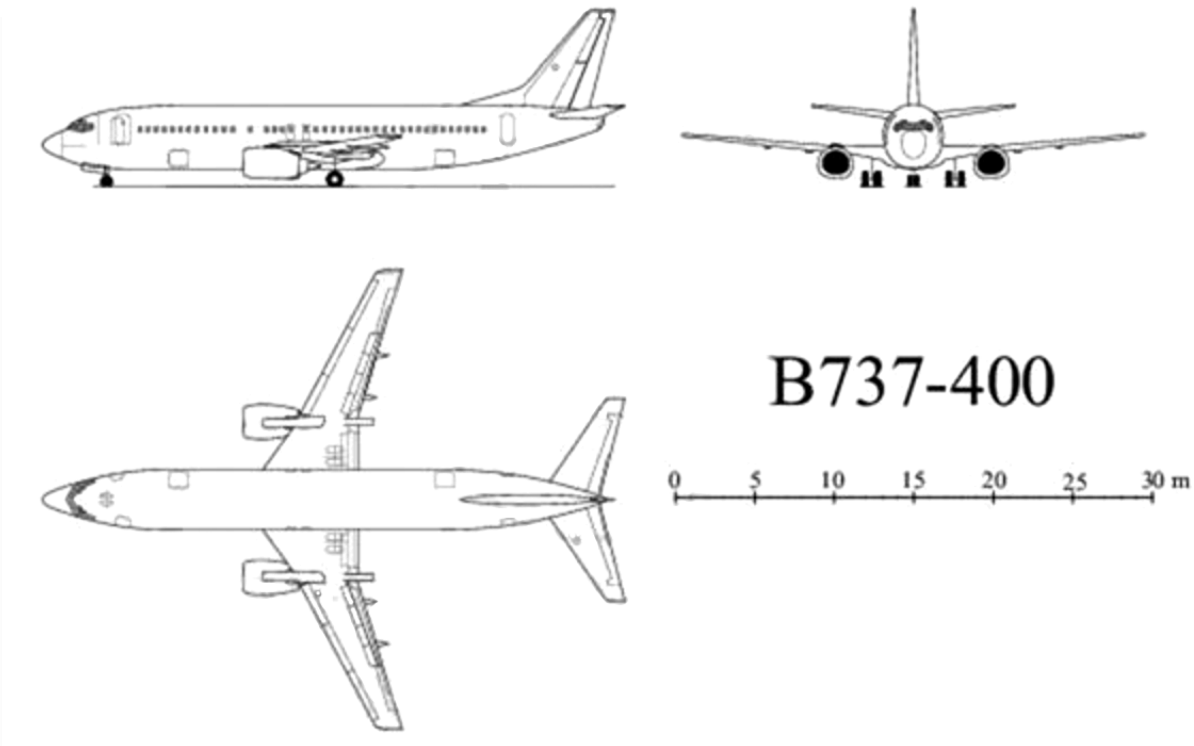


Figure 5. 45 3 view drawing of the Boeing 737-400 (**Roux 2007a**)

The 737-400 is a small narrow-bodied jet with capacity for a maximum seating of 189 passengers whose first flight took place on February 23, 1988. This stretched version of the 737-300 was Boeing's pretty successful attempt to keep Airbus from having the 150-seat market to itself. The 737-400 enjoyed a good sales performance, especially considering the short eleven-year production cycle. However, it was never to become as successful as the smaller 737-300 and suffered from the simultaneous introduction of the more advanced Airbus A320. Boeing also developed a higher gross weight 737-400 for enhanced payload/range with structural reinforcement of the aircraft. When compared with its modern technology competitors (737-800 and A320), the 737-400 lacks range, is more expensive to maintain and is much less fuel efficient. The 737-400 is the only variant of the classic 737 for which there is no winglet modification available. The 737-400 is the heaviest of the 737 classics but, has the same wing. As a result, the wing has not enough residual strength to support the winglets.

At low/moderate fuel prices, a 737-400 can be economically viable if purchased at a low price. For high cycled aircraft structural issues will lead to increased maintenance/inspection costs with repairs, possibly shortening the economic life. The 737-400 is still popular with small, cash-strapped airlines who are specialized in charters and wet-lease operations to provide additional capacity during peak season for mainline and first-tier airlines. The low capital cost for the 737-400 permits operators to generate a profit despite low utilisation. As with the smaller -300, cargo conversion programmes are available. As a converted freighter, the 737-400 freighter has become far more popular than its smaller sibling the 737-300 freighter. As of today, ~130 737-400s have been converted, helped by the availability of affordable feedstock aircraft.

Table 5. 84 Input values of the Boeing 737-400

Parameter	Symbol	Units	Chosen value
PAX			189
Landing field length (ISA)	s_{LFL}	m	1582
Approach speed	V_{APP}	m/s	71
Take-off field length (ISA)	s_{TOFL}	m	2222
Range (max payload)	R	km	3180
Cruise Mach number	M_{CR}		0,745
Cruise speed	V_{CR}	m/s	221,2
Cruise altitude	h_{CR}	m	10668
Wing area	S_W	m²	91,04
Wing span	b_W	m	28,88
Aspect ratio	A		9,16
Maximum take-off mass	m_{MTO}	kg	68040
Payload mass	m_{PL}	kg	18066
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,266
Maximum landing mass	m_{ML}	kg	54885
Mass ratio, landing - take-off	m_{ML}/m_{MTO}		0,807
Operating empty mass	m_{OE}	kg	33190
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}		0,488
Maximum zero fuel mass	m_{MZF}	kg	51256
Wing loading	m_{MTO}/S_W	kg/m²	690
Number of engines	n_E		2
Engine type			CFM56-3B2
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	97,86
Total take-off thrust	T_{TO}	kN	195,72
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$	$T_{TO}/(m_{MTO}*g)$	0,32
Bypass ratio	μ		5,9
Overall pressure ratio	OAPR		24,3
Specific fuel comsumption (dry)	SFC (dry)	kg/N s	1,11E-05
Specific fuel comsumption (cruise)	SFC (cruise)	kg/N s	1,89E-05
Available fuel volume	$V_{fuel,available}$	m³	20,102
Sweep angle	ϕ_{25}	°	25
Mean aerodynamic chord	c_{MAC}	m	3,73
Position of maximum camber	$x_{(y\_c),max}$	%c	20,4
Camber	$(y_c)_{max}/c$	%c	1,5
Position of maximum thickness	$x_{t,max}$	%c	39,9
Relative thickness	t/c	%	12,9
Taper	λ		0,24

Table 5. 85 Reverse engineering results of the Boeing 737-400

Secret parameter	Symbol	Units	RE Value	Verification deviation [%]
Maximum lift coefficient, landing	$C_{L,max,L}$	-	**3,56**	-10
Maximum lift coefficient, take-off	$C_{L,max,TO}$	-	**2,68**	
Maximum aerodynamic efficiency	E_{max}	-	**15,19**	20
Specific fuel consumption	SFC	kg/N/s	**1,73E-05**	-6

6 Discussion

When comparing the two methods of reverse engineering and verification, it can be seen that the results for the maximum lift coefficient (at landing) are very close to one another, since almost all the deviations values are below 15%, as shown in Figure 6.1 and the deviation average absolute value is 7,7%. From this, it can be concluded that the assumptions for the aerodynamics with regard to some profile values are well suited for the majority of aircraft. This is also a confirmation that the calculation for the lift coefficient from reverse engineering leads to reliable results. It is interesting to notice that almost all the values from the verification are smaller than the values from the reverse engineering. This could be explained through the contribution of the high lift devices, as they may have to be higher in the verification process.

It is important for the user to know that the verification of the maximum lift coefficient for take-off and landing is difficult to carry out. The reason for this is that information about the aerodynamics of an aircraft is difficult to obtain because that data is classified information. Specifically, the verification method is based on data that contains fixed values and formulas. These formulas are based on **Bathia 2010** and these values are provided by **DATCOM 1978**, This method is known for underpredicting the verification values and that may be the reason why almost all of them turned out to be smaller than the reverse engineering values. As a result, verification may not be a good reference in every case.

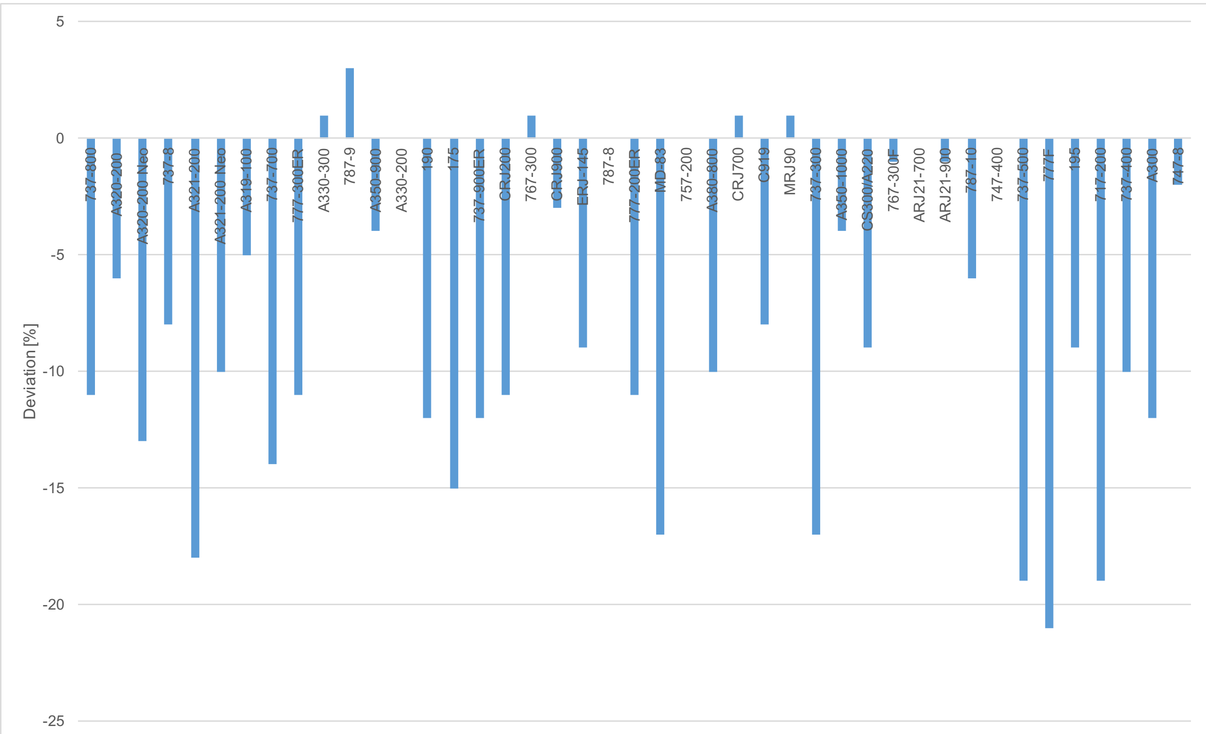


Figure 6. 1 Lift coefficient deviation values

The results from reverse engineering are also close to the verification values for the results for the specific fuel consumption being the deviation average absolute value just 7,7%. Almost all of them have a deviation below 20%, as shown in Figure 6.2. Although it was found that the fuel mass fractions and the operating empty weight mass fraction have a very large influence on the result, the conservative fuel mass fractions according to **Roskam 1989** give good results. This means that the user must choose the highest maximum take-off weight when searching for the parameters. This way, both the fuel and the operating empty mass fractions will remain as conservative as possible. The user will check that when searching throuout the different sources of information, several values for the maximum take-off weight are provided. It is of vital importance that the user selects the highest one if one is to perform the verification process as accurate as possible.

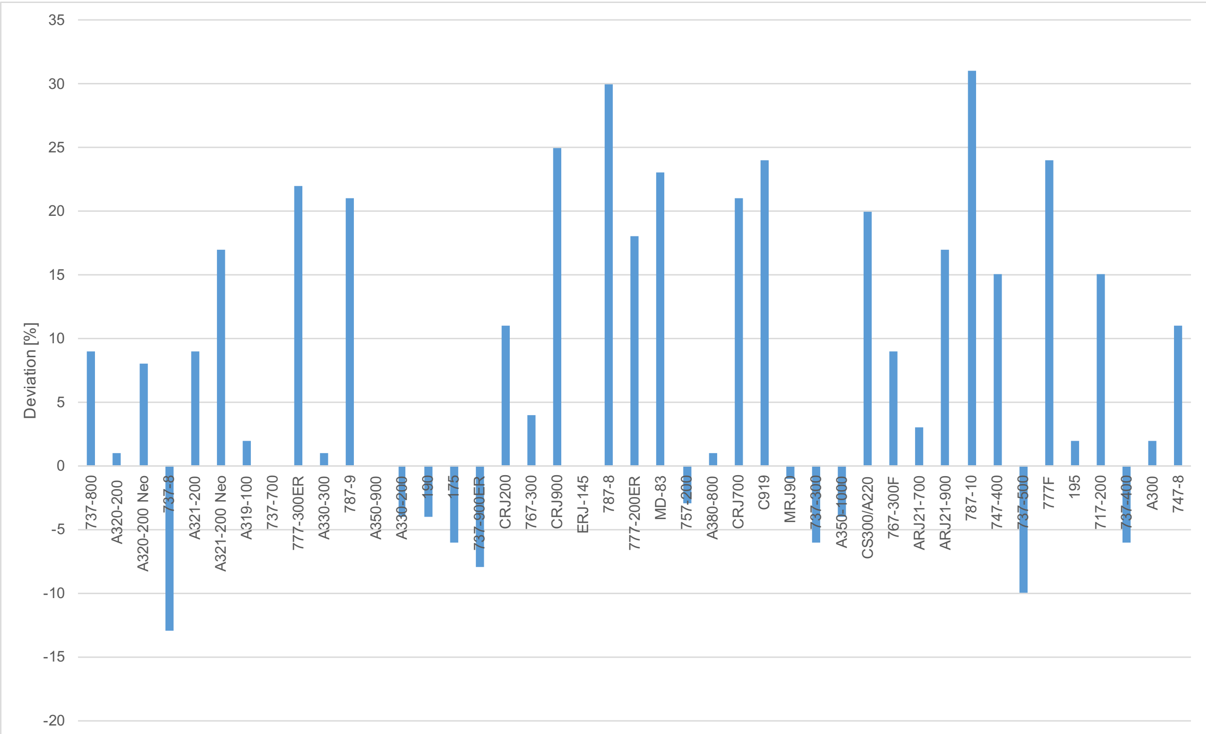


Figure 6. 2 Specific fuel comsumption deviation values

With the maximum aerodynamic efficiency, it can be clearly seen that the results from the verification calculation are greater and that there is a large deviation. The deviation average absolute value of 15,8% is greater than in the other parameters. This pattern can already be seen in the results of the **De Grave 2017** and **Cheema 2019** master's thesis. The results also deviate significantly for aircraft for which a value according to **Raymer 1989** is available for the ratio of wetted surface and wing area S_{WET}/S_W, as this value is often lower than the one used as reference for commertial aircraft, making the deviation even greater. A possible cause is that the k_E value for the various ranges for the verification of the maximum aerodynamic efficiency in cruise is set too high. It cannot be discard that the values from reverse engineering are too low. The tool should therefore be used for an aircraft whose maximum aerodynamic efficiency is known. For this aircraft, the tool should be used to determine the maximum aerodynamic efficiency and then check which result corresponds to the true value of the maximum aerodynamic

efficiency. Only then can it be determined whether the procedure of the tool for determining the maximum aerodynamic efficiency is too imprecise or the k_E value is set too high.
Regarding the values of S_{WET}/S_W and k_E, a further research can be carried out. If the user wishes to select more precise values of these parameters, the Project **Schlüter 2006** can examined, for it provides a wide range of values for different types of commercial aircraft, according to range (short, medium and long) and class (narrow/wide bodied jet).

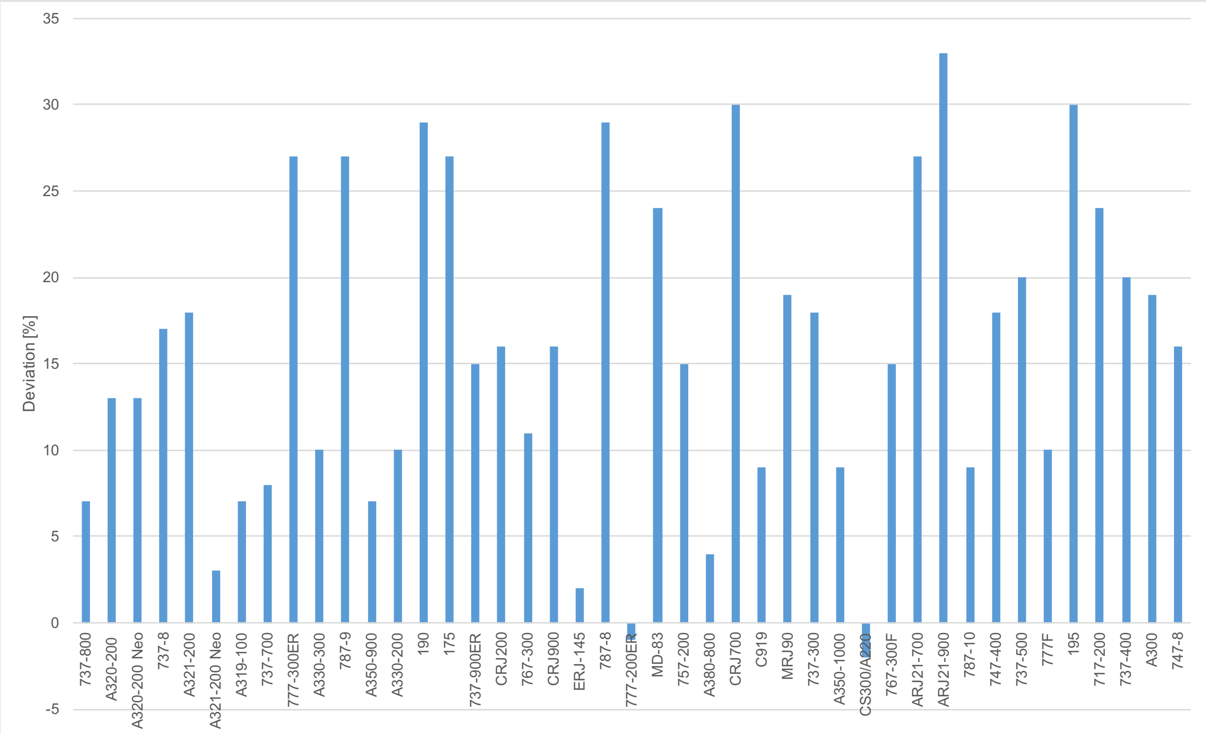


Figure 6. 3 Maximum aerodynamic efficiency deviation values

With regard to the reverse engineering method, the following can still be summarized. By looking at the formulas for the maximum lift coefficient for take-off and landing, it is possible to assess which parameters mainly influence the result. The maximum lift coefficient depends on the requirements of the aircraft. The lift coefficient for landing is determined by the landing field length, the wing loading and the landing mass fraction. The maximum lift coefficient for take-off is determined by the thrust-to-weight ratio and the take-off field length. Short field lengths lead to high lift coefficients.

The formulas for the maximum aerodynamic efficiency and for the specific fuel consumption are more complex than the formulas for the maximum lift coefficient. In addition, more input parameters are required here. The tool uses a numerical iteration for the maximum aerodynamic efficiency. In the case of specific fuel consumption, the tool first calculates other parameters in the formula before calculating the final result. Therefore, it cannot be clearly stated which parameters are decisive for the respective result.

Fort the next conclusions, an attempt on finding useful behaviors and patterns of the obtained parameters has been made. Table 6.1 include all the investigated and reverse engineered aeroplanes in chronological order. This gives an overview of the evolution of certain parameters in aircraft history. The graphs are not always smooth and not every aeroplane seems to fit in the picture. The reason for this is that aircraft are design to fullfil certain requirements. Some aeroplanes are designed for a very specific purpose. This results in deviating parameters. A chronological list of the aeroplanes is shown in Table 6.1.

The chronologically ascending classification according to the year of publication of the aircraft examined in this work gives an overview of the development of a secret parameter. Figure 6.4 analyses the evolution of the maximum aerodynamic efficiency.

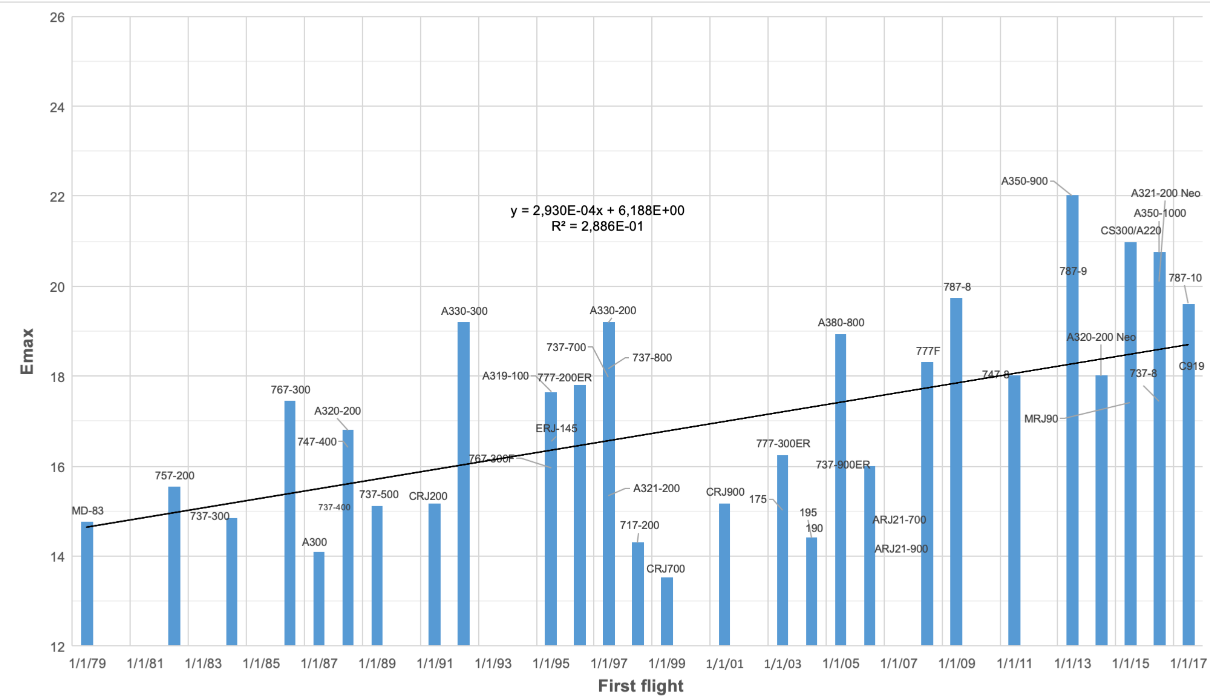


Figure 6. 4 Chronological evolution of E_{max}

Although not in a very smooth way, the graph clearly shows how the maximum aerodynamic efficiency has become higher over time. This shows that the development for more efficient and economical aircraft is proceeding. Especially the most modern aircraft which are equipped with advanced avionics, superior cabin designs and noise reduction capabilities that increase the fuel efficiency and performance of aircrafts. Some of these new aircraft belong to the Airbus Neo (New Engine option) Family, including Airbus A320Neo, A330Neo, the Boeing's NG (New Generation) Family and the MAX Family, including 787, 737 MAX, 777X, and Bombardier's C-series, such as the CS300. All of these aircraft models have a maximum aerodynamic efficiency over 18 and in most of the cases over 20, which is a fairly high value for this parameter, proving the theory that aviation market is focusing on developing more efficient aircraft.

Table 6. 1 Aircraft in chronological order

Date of First Flight	Aircraft
19/10/79	MD-83
19/2/82	757-200
24/2/84	737-300
30/1/86	767-300
9/12/87	A300
23/2/88	737-400
29/4/88	747-400
27/6/88	A320-200
30/6/89	737-500
10/5/91	CRJ200
2/11/92	A330-300
20/6/95	767-300F
11/8/95	ERJ-145
29/8/95	A319-100
7/10/96	777-200ER
9/2/97	737-700
15/3/97	A321-200
31/7/97	737-800
13/8/97	A330-200
2/9/98	717-200
27/5/99	CRJ700
21/2/01	CRJ900
24/2/03	777-300ER
15/6/03	175
12/3/04	190
7/12/04	195
27/4/05	A380-800
5/9/06	737-900ER
14/7/08	777F
28/11/08	ARJ21-700
28/11/08	ARJ21-900
15/12/09	787-8
20/3/11	747-8
14/6/13	A350-900
17/9/13	787-9
25/9/14	A320-200 Neo
27/2/15	CS300/A220
11/11/15	MRJ90
29/1/16	737-8
9/2/16	A321-200 Neo
24/11/16	A350-1000
31/3/17	787-10
15/5/17	C919

In addition, a trend line has been calculated in order to study in a more accurate way how much is the maximum aerodynamic efficiency increasing throughout the years:

$$E_{max} = 2{,}930 \cdot 10^{-4}\ t + 6{,}188 \tag{6.1}$$

with t = time [days]

This means that, on average, the maximum aerodynamic efficiency increases 4,072E-04 for every temporary unit, being one day one temporary unit. Therefore, the annual increase of the maximum aerodynamic efficiency can be calculated as follows:

$$E_{max}\ per\ year = 2{,}930 \cdot 10^{-4}\ \frac{1}{day}\ 365\ \frac{day}{year} = 0{,}106945\ \frac{1}{year} \tag{6.2}$$

Although almost all the obtained result for maximum aerodynamic efficiency seem consistent, it is important to carry out a critical interpretation of the results. In this case, the diagonal stripe bars display excessively high results. It has been easier to notice these suspicious results thank to visual representation of the Figure 6.4 itself. When analyzing the overall results, it has been considered that these results are not plausible. A good explanation for this behavior is the lack of input parameter information that has been found in this specific aircrafts. The reason why there are so few sources providing this information is that these aircraft belong to a modern family of aircrafts and its information is still incipient.

The engine manufacturers are also responsable for the improvement of the fuel consumption. The first positive influence on the fuel consumption is due to the engines. The engine technology improved and the bypass ratio enlarged, as it can be shown in Figure 6.5.

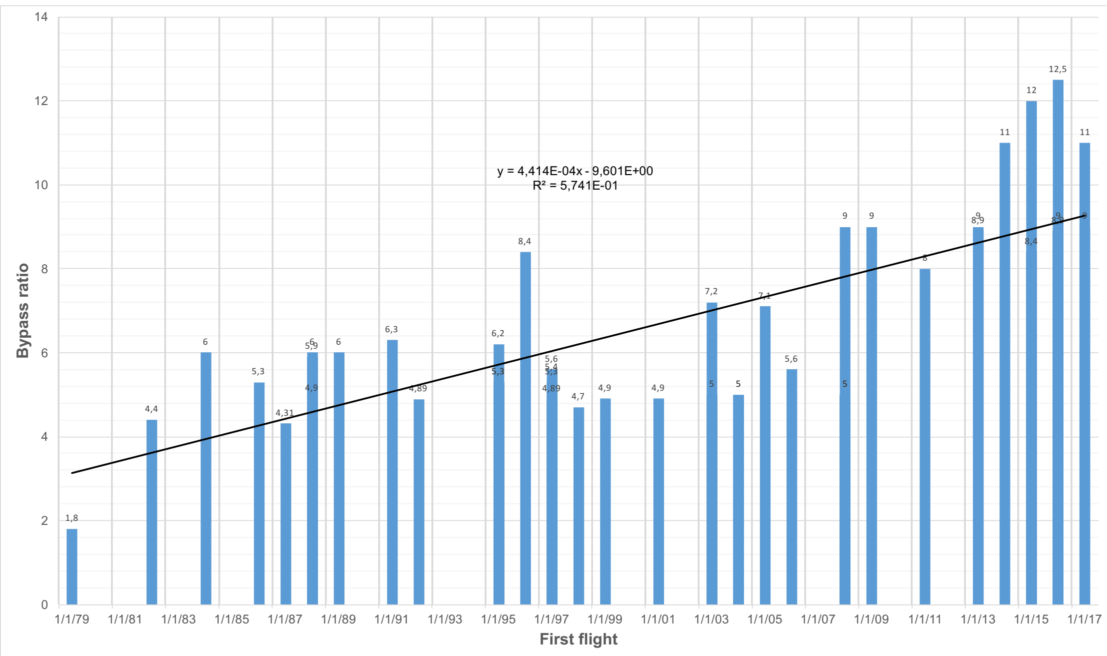


Figure 6. 5 Chronological evolution of bypass ratio

Again, the most modern aircraft offer higher values of bypass ratio. As bypass ratio increases the overall efficiency of the engine increase which is a primary factor that yields lower specific fuel comsumption for the turbofan engine. Additionally, a high bypass ratio engine can produce a greater amount of thrust while consuming the same amount of fuel as a lower bypass ratio engine.
As previously provided in the maximum aerodynamic efficiency section, a trend line for the bypass average evolution has been calculated.

$$\mu = 4{,}414 \cdot 10^{-4}\, t - 9{,}601 \tag{6.3}$$

with $t = \text{time [days]}$

Applying the same logical procedure as in the case of maximum aerodynamic efficiency, we can calculate the annual bypass ratio increase.

$$\mu\, per\ year = 4{,}414 \cdot 10^{-4} \frac{1}{day}\, 365 \frac{day}{year} = 0{,}161111 \frac{1}{year} \tag{6.4}$$

In this case, all the results are consistent since they have not been calculated with the Excel-based tool “PJRE”, they were input parameters instead. The reason why the bypass ratio has been brought into analysis is to prove and calculate accurately its incremental behavior over the years.

The reader will find useful Table 6.2 and Table 6.4 for they are a display of the overall obtained results organized by aircraft manufacturer and type and by engine manufacturer and type. For the engine specifications (Table 6.4) we look for a reliable relation of the results among the same engine family. There are even cases in which the same engine was used and, therefore, the logical outcome would be that the obtained SFC result was the same. However, although the results are similar in the majority of the cases, this cannot be proven in all of them. Even so, the SFC value that has been calculated is not a purely engine parameter. It has been influenced by all the parameters that served as input in the tool and, therefore, although two different aircraft used the same engine, their mission might be completely different and their SFC would come out differently from reverse engineering.

Table 6. 2 Obtained results organized by manufacturer

Manufacturer	Aircraft type	Engine type	$C_{L,max,L}$	$C_{L,max,TO}$	E_{max}	SFC
Embraer	175	CF34-8E2	**3,39**	**2,41**	**15,02**	**1,94E-05**
	190	CF34-10E5	**3,28**	**1,95**	**14,41**	**1,80E-05**
	195	CF34-10E5	**3,17**	**1,83**	**14,41**	**1,70E-05**
	ERJ-145	AE3007A1/1	**2,44**	**1,34**	**16,55**	**1,47E-05**
Boeing	717-200	BR715A1-30	**3,46**	**2,70**	**14,30**	**1,48E-05**
	737-300	CFM56-3B1	**3,20**	**2,19**	**14,84**	**1,78E-05**
	737-400	CFM56-3B2	**3,56**	**2,68**	**15,19**	**1,73E-05**
	737-500	CFM56-3B1	**3,76**	**2,84**	**15,11**	**1,84E-05**
	737-700	CFM56-7B24	**3,11**	**2,44**	**17,99**	**1,72E-05**
	737-8	LEAP-1B25	**3,15**	**1,88**	**17,45**	**1,77E-05**
	737-800	CFM56-7B24	**2,98**	**2,30**	**18,17**	**1,54E-05**
	737-900ER	CFM56-7B26	**2,99**	**1,88**	**16,00**	**1,77E-05**
	747-400	PW4056	**2,14**	**2,07**	**16,42**	**1,46E-05**
	747-8	Genx-2B67	**2,56**	**2,24**	**18,03**	**1,39E-05**
	757-200	RB211-535E4	**2,92**	**2,09**	**15,54**	**1,74E-05**
	767-300	CF6-80C2B2F	**2,73**	**1,73**	**17,44**	**1,52E-05**
	767-300F	CF6-80C2B7F	**2,80**	**1,75**	**15,95**	**1,43E-05**
	777-200ER	GE90-85B	**2,76**	**1,96**	**17,81**	**1,26E-05**
	777-300ER	GE90-115B	**2,98**	**2,13**	**16,25**	**1,22E-05**
	777F	GE90-110B1L	**3,26**	**2,21**	**18,30**	**1,19E-05**
	787-10	Genx 72A1	**3,13**	**2,24**	**19,62**	**1,14E-05**
	787-8	Genx-1B70	**2,96**	**1,91**	**19,73**	**1,16E-05**
	787-9	Genx-1B74	**2,96**	**2,20**	**20,08**	**1,23E-05**
Airbus	A300	CF6-80C2A1	**3,28**	**2,19**	**14,08**	**1,51E-05**
	A319-100	CFM56-5B6	**3,26**	**2,33**	**17,65**	**1,62E-05**
	A320-200	CFM56-5B4	**3,31**	**2,29**	**16,80**	**1,60E-05**
	A320-200 Neo	CFM LEAP-1A	**3,57**	**2,28**	**18,01**	**1,36E-05**
	A321-200	CFM56-5B3/P	**3,76**	**2,62**	**15,35**	**1,44E-05**
	A321-200 Neo	PW1133G-JM	**3,46**	**2,42**	**20,10**	**1,25E-05**
	A330-200	Trent 772B-60	**2,66**	**2,35**	**19,19**	**1,64E-05**
	A330-300	Trent 772-60	**2,73**	**2,53**	**19,19**	**1,55E-05**
	A350-1000	Trent XWB-97	**2,36**	**2,03**	**20,76**	**1,53E-05**
	A350-900	Trent XWB-83	**2,23**	**1,74**	**22,02**	**1,54E-05**
	A380-800	Trent 970-84	**2,25**	**2,01**	**18,94**	**1,48E-05**
Comac	ARJ21-700	CF34-10A	**2,84**	**2,35**	**14,89**	**1,72E-05**
	ARJ21-900	CF34-10A	**2,97**	**2,41**	**14,28**	**1,49E-05**
	C919	CFM LEAP-1C	**3,02**	**1,75**	**17,97**	**1,09E-05**
Bombardier	CRJ200	CF34-3B1	**2,36**	**1,60**	**15,17**	**1,77E-05**
	CRJ700	CF34-8C1	**2,67**	**2,02**	**13,54**	**1,48E-05**
	CRJ900	CF34-8C5	**2,84**	**2,24**	**15,17**	**1,47E-05**
Bombardier /Airbus	CS300/A220	PW1525G	**2,81**	**2,28**	**20,98**	**1,26E-05**
McDonnel D.	MD-83	JT8D-219	**3,32**	**2,26**	**14,76**	**1,67E-05**
Mitsubishi	MRJ90	PW1217G	**2,82**	**1,91**	**17,41**	**1,68E-05**

Despite the thorough research that must be done to ensure that all the results are reliable and accurate, there might be cases in which this is not possible. Therefore, an intensive and individual analysis of all the parameters must be carried out to detect unplausible results, either because their values are too high, too low, or simply not consistent.

Table 6.3 provides a deeper study of the average values of maximum aerodynamic efficiency within the same family of aircraft or between aircraft with the same characteristics.

Table 6. 3 Comparison of maximum aerodynamic efficiency between Airbus family

Manufacturer	Aircraft type	Engine type	E_{max}	Average
Bombardier/Airbus	CS300/A220	PW1525G	**20,98**	**20,98**
Airbus	A319-100	CFM56-5B6	**17,65**	**16,60**
	A320-200	CFM56-5B4	**16,80**	
	A321-200	CFM56-5B3/P	**15,35**	
	A320-200 Neo	CFM LEAP-1A	**18,01**	**19,05**
	A321-200 Neo	PW1133G-JM	**20,10**	
	A350-1000	Trent XWB-97	**20,76**	**21,39**
	A350-900	Trent XWB-83	**22,02**	
	A380-800	Trent 970-84	**18,94**	**18,94**

The first interesting comparison is made between the A320 family and the A320Neo family. The average maximum aerodynamic efficiency of the A320 family is 16,6 and for the A320Neo family it is 19,05. This result is very satisfactory considering that the A320Neo family is more modern than the A320 family besides being the most profitable Airbus family.

The A220 has a maximum aerodynamic efficiency of 20,98 while the A320Neo family has one of 19,05. Overall, they both have the same characteristics, such as a narrow body, payload capacity for approximately 160 passengers and range of approximately 6000 km. Therefore, it is also satisfactory to check that both maximum aerodynamic efficiencies are similar to each other.

Regarding the A350-900/-1000, it is a large wide-bodied jet with an average maximum aerodynamic efficiency of 21,39. The A380-800 is a very large wide-bodied jet with an average maximum aerodynamic efficiency of 18,94. This illustrates that the A350 is a more modern an efficient aircraft compared to the A380, which was built precisely for this purpose, to cover long-haul routes more efficiently than the A380 did.

Table 6. 4 Obtained results organized by engine type

Manufacturer	Engine family	Engine type	SFC	Average	μ
General Electric	CF34	CF34-10A	**1,72E-05**	1,67E-5	5
		CF34-10A	**1,49E-05**		5
		CF34-10E5	**1,80E-05**		5
		CF34-10E5	**1,70E-05**		5
		CF34-3B1	**1,77E-05**		6,3
		CF34-8C1	**1,48E-05**		4,9
		CF34-8C5	**1,47E-05**		4,9
		CF34-8E2	**1,94E-05**		5
	CF6	CF6-80C2A1	**1,51E-05**	1,49E-5	4,31
		CF6-80C2B2F	**1,52E-05**		5,3
		CF6-80C2B7F	**1,43E-05**		5,3
	CFM LEAP	CFM LEAP-1A	**1,36E-05**	1,4E-5	11
		CFM LEAP-1B25	**1,77E-05**		9
		CFM LEAP-1C	**1,09E-05**		11
	CFM56	CFM56-3B1	**1,78E-05**	1,67E-5	6
		CFM56-3B1	**1,84E-05**		6
		CFM56-3B2	**1,73E-05**		5,9
		CFM56-5B3/P	**1,44E-05**		5,4
		CFM56-5B4	**1,60E-05**		6
		CFM56-5B6	**1,62E-05**		6,2
		CFM56-7B24	**1,72E-05**		5,6
		CFM56-7B24	**1,54E-05**		5,3
		CFM56-7B26	**1,77E-05**		5,6
	GE90	GE90-110B1L	**1,19E-05**	1,22E-5	9
		GE90-115B	**1,22E-05**		7,2
		GE90-85B	**1,26E-05**		8,4
	GEnx	Genx-1B74	**1,23E-05**	1,23E-5	9
		Genx-1B70	**1,16E-05**		9
		Genx 72A1	**1,14E-05**		9
		Genx-2B67	**1,39E-05**		8
Pratt & Whitney	JT8D	JT8D-219	**1,67E-05**	1,67E-05	1,8
	PW1000G	PW1133G-JM	**1,25E-05**	1,41E-5	12,5
		PW1217G	**1,68E-05**		8,4
		PW1525G	**1,26E-05**		12
	PW4000	PW4056	**1,46E-05**	1,46E-05	4,9
Rolls-Royce	AE 3007	AE3007A1/1	**1,47E-05**	1,47E-05	5,3
	BR700	BR715A1-30	**1,48E-05**	1,48E-05	4,7
	RB211	RB211-535E4	**1,74E-05**	1,74E-05	4,4
	Trent 700	Trent 772-60	**1,55E-05**	1,59E-5	4,89
		Trent 772B-60	**1,64E-05**		4,89
	Trent 900	Trent 970-84	**1,48E-05**	1,48E-5	7,1
	Trent XWB	Trent XWB-83	**1,54E-05**	1,54E-5	8,9
		Trent XWB-97	**1,53E-05**		8,9

When checking the results from the engine specifications in Table 6.4 it can be noted that the engines with high bypass ratio are the ones that have revealed less SFC. Besides, these engines usually are the most modern ones and the ones that are used in the most modern aircraft. The engine family CFM LEAP is used in the aircraft families A320Neo, A321Neo, 737 MAX and COMAC C919, and the GEnx family is used in the aircraft Boeing families 747-8 and 787 Dreamliner. One of the results is highlighted in yellow because it is a very high value and, therefore, unreliable.

We notice that the GE90, which is mainly used in the Boeing's 777 family, has a very low SFC. This is not so much due to its BPR, but due to its large size, being that he internal engine efficiencies increase with size.

The CF34 engine family is mainly used in the aircraft families Bombardier Challenger and CRJ, COMAC ARJ21 and Embraer E-Jets, giving a satisfactory SFC average of 1,67E-5 kg/Ns.

The CF6 engine family is used in traditional aircraft families like A300, A310, A330, 747 or 767, providing a satisfactory average SFC of 1,49 kg/Ns but it is gradually being replaced by the newer GEnx family.

7 Summary and Conclusions

This thesis has successfully provided the aeronautical community with useful data. This data consists of the commercial aircraft secrets parameters that the manufacturers do not reveal due to competitive reasons. These parameters are the following: maximum lift coefficient (for landing and take-off), maximum aerodynamic efficiency and Specific Fuel Consumption (SFC). However, this is not the first thesis that manages to provide these secret parameters. On the contrary, there are two previous existing thesis that fulfill this task and explain in detail how this process is exactly carried out. This is the reason why this thesis dedicates the whole state of the art to explain in the briefest, most accurate and understandable way the knowledge that these two thesis brought us. The first one achieved to develop an Excel-based tool with which the user can reveal the secret parameters and the second managed to improve it.

Nevertheless, the virtue of this thesis lies in the intensive study that has been carried out. For the first time, the Excel-based tool "Passenger Jet Reverse Engineering" has been used in a large number of aircraft within the same research. The study of the aviation market has shown that in order to cover the 90% of the total in service or on order aircraft, the first 47 most used passenger aircraft must be selected and studied. These aircraft were selected from a total of 117 aircraft (91 passenger aircraft and 26 freighters), which shows that sales are concentrated in a specific segment of aircraft. This segment is the narrow-body segment which has the maximum market share aircraft, as they are fuel-efficient and help in reducing the overall cost. This is one of the crucial factors that have increased the adoption of narrow-body aircraft globally. In the end, of those 47 aircraft, 4 aircraft had to be discarded due to two reasons: 2 aircraft carried turboprop engines and 2 aircraft did not collected enough data to make the tool work.

One of the most important things when using the tool is to provide it with reliable information, otherwise the obtained results could be useless, even if the verification is performed. The best way to collect reliable information is to look for it in several reliable sources and write down all the values to compare them between each other. This thesis has collected the parameters information from 9 different reliable sources and has selected the most suitable value for each parameter in order to obtain the most accurate results.

Regarding the reverse engineering method, it can be assessed which input parameters are going to have some influence in the output parameters just by looking at the formulas. The maximum lift coefficient depends on the requirements of the aircraft. This means that the lift coefficient for landing is determined by the landing field length, the wing loading and the landing mass fraction, and the maximum lift coefficient for take-off is determined by the thrust-to-weight ratio and the take-off field length. Therefore, short field lengths lead to high lift coefficients.
The formulas for the maximum aerodynamic efficiency and for the specific fuel consumption are more complex than the formulas for the maximum lift coefficient and, therefore, it cannot

be clearly stated which parameters are decisive for the respective result, since more input parameters are required here. However, the tool can also be useful to unravel the influence of the input parameters. When the formulas are not clear anymore, the tool can determine whether the input parameters are going to have a direct or indirect proportional influence to the output parameters.

The obtained reverse engineering results have proven to be satisfactory, since every of the three secret parameters from almost every aircraft have not deviated in great quantity from the verification values. For every secret parameter there might be a reason why their values have deviated from the reverse engineering values. In the case of the maximum lift coefficient (at landing), the deviation average absolute value is 7,7% and almost all the values from the verification are smaller than the values from the reverse engineering. In the case of the specific fuel consumption, the deviation average absolute value is 7,7% and it was found that the fuel mass fractions and the operating empty weight mass fraction have a very large influence on the result, which was beneficial to obtain more accurate results. Thirdly, with the maximum aerodynamic efficiency, it can be clearly seen that the deviation average absolute value of 15,8% is greater than in the other parameters, which can be explained by different reasons that must be taken into account for further investigation. These deviations are of vital importance to the research because they allow us to see the flaws of the tool when analyzing such a large number of aircraft and extract statistical data.

Finally, the results have shown that the maximum glide ratio and bypass ratio are continuously increasing as engines and airplanes become more efficient, since the regression line has shown an increase of 0.11 per year in in maximum glide ratio, E_{max} and 0.16 per year in bypass ratio. On average, the next results have been obtained: 2.98 for maximum lift coefficient (for landing), 2.15 for maximum lift coefficient (for take-off), 17 for maximum aerodynamic efficiency and 1,52E-5 kg/Ns for specific fuel consumption.

8 Recommendations

The formulas used for dimensioning an aircraft only apply to jet airliners and business jets. Therefore, the PJRE tool can only be used for this type of aircraft. After implementing the improvements for this tool, a propeller aircraft tool should also be developed in the near future to cover more aircraft.

There are a few aircraft that have been analyzed in this thesis in detail, as well as described the same way the rest of the jet aircraft were. However, they could not be included in the Excel tool because of his turboprop nature. These aircraft were the Bombardier DHC-8-401 (Dash-8 Q400) and the ATR 72-600. An interesting improvement could be the possibility of choosing the type of engine of the aircraft.

When searching for the parameters the user must look for the cruise speed. In various sources, the possibility of choosing different speeds is offered. These speeds are usually the following: maximum cruise speed and long range cruise speed. Therefore, it would be interesting to upgrade the tool by integrating a new feature: a function that does the reverse engineering for both speeds, depending on the value for the optimized speed ratio by the program.

The tool provides a good way of comparing aircraft with one another. The tool is also user-friendly and delivers results quickly. Compared to existing methods, most of the necessary input parameters can be found through intensive research and the right selection of sources. It is very important to invest a lot of time in researching the input parameters in order to get good and realistic results.

In the future, little corrections will have to be done so that these deviations are little by little decreasing and the obtained results are increasingly accurate and reliable.

List of References

AIRBUS, 2020a. *Aircraft Characteristics Airport: Operations & tech data. Airbus, Commercial Aircraft.*
Available from: https://bit.ly/3mNmO5G,
Archived at: https://perma.cc/4RFR-TZPN.

AIRBUS, 2020b. *A300: Airplane Characteristics for Airport Planning.*
Available from: https://bit.ly/36aNAiD,
Archived at: https://perma.cc/89XB-PP8L.

AIRBUS, 2020c. *A319: Aircraft Characteristics Airport and Maintenance Planning.*
Available from: https://bit.ly/2HBPrTn,
Archived at: https://perma.cc/2BL8-VV4Y.

AIRBUS, 2020d. *A320: Aircraft Characteristics Airport and Maintenance Planning.*
Available from: https://bit.ly/3kQ5o6I,
Archived at: https://perma.cc/6L5K-37CX.

AIRBUS, 2020e. *A321: Aircraft Characteristics Airport and Maintenance Planning.*
Available from: https://bit.ly/3j3HiVz,
Archived at: https://perma.cc/PS3F-S7JH.

AIRBUS, 2020f. *A330: Aircraft Characteristics Airport and Maintenance Planning.*
Available from: https://bit.ly/346Rh62,
Archived at: https://perma.cc/555V-LN3B.

AIRBUS, 2020g. *A350: Aircraft Characteristics Airport and Maintenance Planning.*
Available from: https://bit.ly/3jb22L3,
Archived at: https://perma.cc/B8BN-FZYB.

AIRBUS, 2020h. *A380: Aircraft Characteristics Airport and Maintenance Planning.*
Available from: https://bit.ly/3i8JFoO,
Archived at: https://perma.cc/8THY-S6AT.

ALLEN, Robert, 2016. *Penguin Complete English Dictionary*, Penguin Books Ltd, London.

ALLIED MARKET RESEARCH, 2020. *Commercial Aircraft Market.*
Available from: https://www.alliedmarketresearch.com/commercial-aircraft-market,
Archived at: https://perma.cc/77ES-CHVC.

ATR, 2020. *600 Series, the Latest Generation Turboprop*.
Available from: https://bit.ly/2HosdzP,
Archived at: https://perma.cc/PK92-7QRC.

AVIATION PARTNERS BOEING, 2020. *Products.* McComm Group, Inc.
Available from: http://www.aviationpartnersboeing.com/products_757_200.php,
Archived at: https://perma.cc/958P-N5C4.

BÁLINT, ZSUZSA, 2008. *Airline world: Aircraft Winglets.*
Available from: https://airlineworld.wordpress.com/2008/10/01/aircraft-winglets/,
Archived at: https://perma.cc/8SCJ-CGUT.

BHATIA, Ramón, 2020. *Integration der Berechnungsmethode zum Hochauftrieb in die Tabellenkalkulation von PreSTo*. Hamburg, HAW Hamburg, Fahrzeugtechnik und Flugzeugbau, Projektarbeit.
Available from: http://library.profscholz.de/ (Open Access)

BLUEPRINTS, 2020. *Vectors Drawing.*
Available from: https://www.the-blueprints.com/vectordrawings/,
Archived at: https://perma.cc/QZ5P-Q6BP.

BOEING, 2020a. *717-200: Airplane Characteristics for Airport Planning*.
Available from: https://bit.ly/2FTFlwL,
Archived at: https://perma.cc/C2HP-LPT6.

BOEING, 2020b. *737: Airplane Characteristics for Airport Planning*.
Available from: https://bit.ly/3j7DQJA,
Archived at: https://perma.cc/57T8-QJJ8.

BOEING, 2020c. *737MAX: Airplane Characteristics for Airport Planning*.
Available from: https://bit.ly/3kTH5oe,
Archived at: https://perma.cc/BG7Q-GN5R.

BOEING, 2020d. *747-400: Airplane Characteristics for Airport Planning*.
Available from: https://bit.ly/2EEQxg0,
Archived at: https://perma.cc/76YT-HYYR.

BOEING, 2020e. *747-8: Airplane Characteristics for Airport Planning*.
Available from: https://bit.ly/3i79wh1,
Archived at: https://perma.cc/W24D-CR47.

BOEING, 2020f. *757-200/300: Airplane Characteristics for Airport Planning.*
Available from: https://bit.ly/36bVtnJ,
Archived at: https://perma.cc/VLY4-63J3.

BOEING, 2020g. *767: Airplane Characteristics for Airport Planning.*
Available from: https://bit.ly/2Gas4iY,
Archived at: https://perma.cc/2FWW-KT6X.

BOEING, 2020h. *777-200LR / -300ER / -Freighter: Airplane Characteristics for Airport Planning.*
Available from: https://bit.ly/306JnIX,
Archived at: https://perma.cc/6U32-3NMU.

BOEING, 2020i. *777-200/300: Airplane Characteristics for Airport Planning.*
Available from: https://bit.ly/336xp44,
Archived at: https://perma.cc/2M9X-SH96.

BOEING, 2020j. *777-9: Airplane Characteristics for Airport Planning.*
Available from: https://bit.ly/2S2gVU1,
Archived at: https://perma.cc/QQP8-R5YG.

BOEING, 2020k. *787: Airplane Characteristics for Airport Planning.*
Available from: https://bit.ly/2S2hQE2,
Archived at: https://perma.cc/2KRQ-94YT.

BOEING, 2020l. *MD-80 Series: Airplane Characteristics for Airport Planning.*
Available from: https://bit.ly/3j9ltnv,
Archived at: https://perma.cc/7Z92-BDQ7.

BOMBARDIER, 2020a. *CRJ200 Series: Airport Planning Manual.*
Available from: https://bit.ly/3kQ6Vtp,
Archived at: https://perma.cc/2A4Z-YU86.

BOMBARDIER, 2020b. *CRJ700 Series: Airport Planning Manual.*
Available from: https://bit.ly/2EFzcnc,
Archived at: https://perma.cc/X9Z3-B5JC.

BOMBARDIER, 2020c. *CRJ900 Series: Airport Planning Manual.*
Available from: https://bit.ly/3cyQ5fK,
Archived at: https://perma.cc/B74B-6NJG.

BOMBARDIER, 2020d. *Q400 Series: Airport Planning Manual.*
Available from: https://bit.ly/341xC7R,
Archived at: https://perma.cc/4C8U-9K9Q.

BRADY, Chris, 1999. *The Boeing 737 Technical Site: Winglets.*
Available from: http://www.b737.org.uk/winglets.htm#ATWinglets,
Archived at: https://perma.cc/Q69B-6G6B.

CHEEMA, John Singh, 2020. *Fallbeispiele zum Reverse Engineering im Passagierflugzeugentwurf.* Hamburg, HAW Hamburg, Fahrzeugtechnik und Flugzeugbau, Bachelorarbeit.
Available from: https://bit.ly/2Etd0MO (Open Access)

COMAC, 2018. *Comac America Corporation.*
Available from: http://www.comacamerica.com/c919/,
Archived at: https://perma.cc/6X5X-GAZX.

DE GRAVE, Emiel, 2017. *Reverse Engineering of Passenger Jet Classified Design Parameters*. Hamburg, HAW Hamburg, Fahrzeugtechnik und Flugzeugbau, Masterarbeit.
Available from: https://bit.ly/3i8tsA9 (Open Access)

DUBS Fritz, 1987. *Aerodynamik der reinen Unterschallströmung,* Basel: Birkhäuser.

EMBRAER, 2020a. *Airport Planning Manual. Embraer 190.*
Available from: https://bit.ly/3kLA6hf,
Archived at: https://perma.cc/6UCK-9XDY.

EMBRAER, 2020b. *Airport Planning Manual. Embraer 175.*
Available from: https://bit.ly/3mOlAXM,
Archived at: https://perma.cc/DZF7-JAXH.

EMBRAER, 2020c. *Airport Planning Manual. Embraer 195.*
Available from: https://bit.ly/32XC1Ju,
Archived at: https://perma.cc/J27Z-BF9L.

EMBRAER, 2020d. *Airport Planning Manual. Embraer ERJ 145.*
Available from: https://bit.ly/3mOlO14,
Archived at: https://perma.cc/6RK6-AH9F.

HOAK, Axel D. E., 1978. *USAF Stability and Control Datcom*. Wright-Patter-son Air Force Base, Air Force Flight Dynamics Laboratory, Flight Control Division, Ohio.

JACKSON, Paul, 2007. *Jane's All the Worlds Aircraft 2007-08*. UK: MPG Books Group.

JACKSON, Paul, 2008. *Jane's All the Worlds Aircraft 2008-09.* UK: MPG Books Group.

JENKINSON, Lloyd; SIMKIN, Paul; RHODES, Darren, 2019a. *Civil Jet Aircraft Design: Aircraft Data File.*
Available from: https://bit.ly/2G03hOX,
Archived at: https://perma.cc/4H5W-ZT5H.

JENKINSON, Lloyd; SIMKIN, Paul; RHODES, Darren, 2019b. *Civil Jet Aircraft Design: Engine Data File.*
Available from: https://bit.ly/342uB7k,
Archived at: https://perma.cc/RE3M-R8GK.

KROO, Ilan, 2005. *Nonplanar Wing Concepts for Increased Aircraft Efficiency,* Lecture Notes, Von Karman Inst., Brussels.

LOFTIN, Laurence K., 1980. *Subsonic Aircraft: Evolution and the Matching of size to Performance,* NASA Reference Publication 1060.

LONGMAN, 2009. *Longman Dictionary of Contemporary English,* Pearson Education Limited.
Available from: https://www.ldoceonline.com/es-LA/

MEIER, Nathan, 2005. *Engine: Specifications, Civil Turbojet/Turbofan.*
Available from: http://www.jet-engine.net/civtfspec.html.

MORDOR INTELLIGENCE, 2020. *Aviation Market: growth, trends, and forecast (2020 - 2025).*
Available from: https://www.mordorintelligence.com/industry-reports/aviation-market,
Archived at: https://perma.cc/6T2P-X5JJ.

MUNTANE, Albert; VAN LEEUWEN, Bert; CAPELLE, Coen; FINN, Simon; GUO, Steven, 2018. *An Overview of Commercial Aircraft.* DVB Bank SE Aviation Research (AR).
Available from: https://bit.ly/3i0ERBJ,
Archived at: https://perma.cc/DLC4-U4TA.

MÜLLER, Paul, 1999. *Anpassung von Statistik Gleichungen des Flugzeugentwurfts an neue Flugzeugtypen*. Hamburg, HAW Hamburg, Fahrzeugtechnik und Flugzeugbau, Diplomarbeit.
Available from: https://bit.ly/360EDbz (Open Access)

NIEDERKLEINE, Marco; SCHLIEMANN, Karsten, 1999. *Erstellung einer Datenbasis mit Entwurfsdaten für Passagierflugzeuge*. Fachhochschule Hamburg, Fachbereich Fahrzeugtechnik, Theoretische Arbeit.
Available from: https://bit.ly/2Hv2GVR.

NOREBBO, 2020. *Stock Illustration and Design.*
Available from: https://www.norebbo.com,
Archived at: https://perma.cc/99SB-WQ37.

RAYMER, Daniel P., 1989. *Aircraft Design*: *A Conceptual Approach*, AIAA Education Series, Washington D.C.: AIAA.

ROSKAM, Jan, 1989. *Airplane Design. Vol.1: Preliminary Sizing of Airplanes,* Ottawa, Kansas. Sale: Analysis and Research Corporation, 120 East Ninth Street, Suite 2, Lawrence, Kansas, 66044, USA.

ROUX, Élodie, 2007a. *Avions civils à réaction: plan 3 vues et données caractéristiques*, Éditions Élodie Roux, Blagnac, France.

ROUX, Élodie, 2007b. *Turbofan and Turbojet Engines: database handbook*, Éditions Élodie Roux, Blagnac, France, 2007

SCHLÜTER, André John, 2006. *Maximale Gleitzahl, Streckung und benetzte Fläche*. Hamburg, HAW Hamburg, Fahrzeugtechnik und Flugzeugbau, Project.
Available from: https://bit.ly/3cBmBOs (Open Access)

SCHOLZ, Dieter, 2011. *Aircraft Design Klausur und Lösung im Rahmen "Flugzeugentwurf",* Hamburg University of Applied Sciences, Germany.
Available from: https://bit.ly/2GeU3hl (Open Access)

SCHOLZ, Dieter, 2015. *Aircraft Design,* Hamburg University of Applied Sciences, Germany.
Available from: http://www.fzt.haw-ham-burg.de/pers/Scholz/HOOU/ (Open Access)

SCHOLZ, Dieter, 2016. Excel-Datei für: *Tabellenkalkulation zur Berechnung von SFC*. Hamburg, HAW Hamburg, Fahrzeugtechnik und Flugzeugbau.
Available from: https://www.fzt.hawhamburg.de/pers/Scholz/MaterialFM1.html (Open Access)

SCHOLZ, Dieter, 2017. Abschätzung von Nullwiderstand, Wellenwiderstand und Gleitzahl. Hamburg, HAW Hamburg, Fahrzeugtechnik und Flugzeugbau, Vorlesungsunterlage.
Available from: https://www.fzt.hawhamburg.de//pers/Scholz/MaterialFM1.html (Open Access)

SKYBRARY, 2017a. *Category: Aircraft.*
Available from: http://www.skybrary.aero/index.php/Category:Aircraft,
Archived at: https://perma.cc/AUS4-GCE9.

SKYBRARY, 2017b. *Approach Speed Categorisation.*
Available from: https://bit.ly/3kM06sY,
Archived at: https://perma.cc/GKJ9-6XFM.

SKYBRARY, 2017c. *Airplane Design Group.*
Available from: http://www.skybrary.aero/index.php/Airplane_Design_Group_(ADG)
Archived at: https://perma.cc/CDS3-2DDR.

SKYBRARY, 2017d. *ICAO Aerodrome Reference Code.*
Available from: https://bit.ly/2RS7BCe,
Archived at: https://perma.cc/E5FE-DZD4.

STINTON, Darrol, 1983. *The Design of the Aeroplane,* Granada, London.

WIKIPEDIA, 2020a. *Ingeniería inversa.*
Available from: https://es.wikipedia.org/wiki/Ingenier%C3%ADa_inversa,
Archived at: https://perma.cc/9NAM-YUZ3.

WIKIPEDIA, 2020b. *Reverse Engineering.*
Available from: https://en.wikipedia.org/wiki/Reverse_engineering,
Archived at: https://perma.cc/4PQD-T7RE.

WIKIPEDIA, 2020c. *Comac C919.*
Available from: https://en.wikipedia.org/wiki/Comac_C919,
Archived at: https://perma.cc/T9DN-FP7Q.

Appendix A Boeing 737-800

Data Collection			737-800	Source: 1 Aircraft characteristics for airport planning			2 Jane's A	2 Jane's B	3 Jenkinson	4 Engine	5 Scholz	6 Paul Müller	7 Elodie Roux A	7 Elodie Roux B	8 Data collectior	9 Webs
Parameter	Symbol	Units	Chosen value				A	B					A	B		
PAX			189		160-184		162-189		189-160			189	189-162			
Landing field length	s_{LFL}	m	1646		1770		1646		1600			1600	1600		1600	
Approach speed	V_{APP}	m/s	72				72,536667	73,051111				71,39			72,022222	
Temperature above ISA (288,15K)	ΔT_L	K	0		0		0		0			0				
Relative density	s															
Take-off field length	s_{TOFL}	m	2300		2370		2100	2308	2316						2300	2400
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0		15		20							
Relative density	s															
Range (max payload)	R	km	3700		3700		3685	5444				5426	1363			5665
Cruise Mach number	M_{CR}		0,785				0,785			0,8			0,79		0,785	0,785
Wing area	S_W	m²	124,6				125		124,6			125	124,6			
Wing span	b_W	m	34,32		34,32-35,79		34,31	35,79	34,3			34,31	34,32		34,32	35,7
Aspect ratio	A		9,45				9,4		9,44213483			9,4	9,45			9,45
Maximum take-off mass	m_{MTO}	kg	78245	70534	78245	79016	70535	79015	78220			78244	70534		70530	79010
Payload mass	m_{PL}	kg	20276	20276		21319			14690				20276			
Mass ratio, payload - take-off	m_{PL}/m_{MTO}								0,18780363				0,287			
Maximum landing mass	m_{ML}	kg	65315	65317		66361	65315	66360	65310			65317	65317			66361
Mass ratio, landing - take-off	m_{ML}/m_{MTO}								0,8349527							
Operating empty mass	m_{OE}	kg	41145		41413		41145		41480				41413			41413
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}								0,53029916				0,587			
Wing loading	m_{MTO}/S_W	kg/m²	564,3				564,3	632,1	627,76886				566			
Maximum zero fuel mass	m_{MZF}	kg	61690	61689		62732	61690	62730	61680				61689			
Number of engines	n_E		2						2				2		2	2
Engine type	CFM56-7B		CFM56-7B24		CFM56-7B24/-7B26/-7B27		CFM56-7B24	CFM56-7B27	CFM56-7B24	CFM56-7B24			CFM56-7B24	CFM56-7B27	CFM56-7B	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	106,757			115,5714	107,6	121,4	107	106,75733			106,757	121,436	117	60,7
Total take-off thrust	T_{TO}	kN														121,4
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,31				0,3120514	0,3139717	0,27888615				0,31	0,35		0,15663
Bypass ratio	μ		5,3							5,3			5,3	5,1		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	1,05E-05							1,047E-05			1,05E-05	1,08E-05		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s	1,78E-05							1,774E-05			1,78E-05			
Available fuel volume	$V_{fuel,available}$	m³	26,022		26,022		26,025		26,024				26,022			
Cruise speed	V_{CR}	m/s	232,5						232,53						236,64444	269,167
Cruise altitude	h_{CR}	m	11887				11675	10955	11887,2	10668			11887			12500
Sweep angle	ϕ_{25}	°	25						25				25			25,02
Mean aerodynamic chord	c_{MAC}	m	4,17						4,17				4,17			
Position of maximum camber	$x_{(y\_c),max}$	%c	10													10
Camber	$(y_c)_{max}/c$	%c	0,8													0,8
Position of maximum thickness	$x_{t,max}$	%c	29,7													29,7
Relative thickness	t/c	%	12,5													12,5
Taper	λ		0,219				0,218914186		0,278				0,219			
Overall pressure ratio	OAPR		26							26						
Turbine entry temperature	TET	K														

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1646**	m		
Approach speed	**Known**	V_{APP}	**72,00**	m/s	72,0	72,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2300**	m	2300	2300
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**1998**	NM		
Cruise Mach number		M_{CR}	**0,785**			
Wing area		S_W	**125**	m²		
Wing span	**Known**	b_W	**34,32**	m²	34,32	34,32
Aspect ratio		A	9,45			
Maximum take-off mass		m_{MTO}	**78245**	kg		
Maximum payload mass		m_{PL}	**20276**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,259			
Maximum landing mass		m_{ML}	**65315**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,835			
Operating empty mass		m_{OE}	**41145**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,526			
Wing loading		m_{MTO}/S_W	628,0	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**106,757**	kN		
Total take-off thrust		T_{TO}	213,514	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,278			
Bypass ratio		μ	**5,3**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed	V_{CR}	**233**	m/s			
Cruise altitude	h_{CR}	**11887**	m			
Speed ratio	V/V_{md}	**1,000**	-		1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**25**	°		
Mean aerodynamic chord		c_{MAC}	**4,17**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Known**	t/c	**12,5**	%		
Taper		λ	**0,219**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1646	1646	m	0,00%
Approach speed	V_{APP}	72,00	72,0	m/s	0,00%
Take-off field length	s_{TOFL}	2300	2300	m	0,00%
Span	b_W	34,32	34,32	m	0,00%
Aspect ratio	A	9,45	9,45		0,00%
Cruise speed	V_{CR}	232,5	232	m/s	-0,36%
Cruise altitude	h_{CR}	11887	11679	m	-1,75%
Squared Sum					**3,20E-04**
Absolute maximum deviation					1,8%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,98**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,30**	
Maximum aerodynamic efficiency	E_{max}	**18,17**	
Specific fuel consumption	SFC	**1,54E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing			
Landing field length	s_{LFL}	1646	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	72,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,83	
Wing loading at maximum take-off mass	m_{MTO}/S_W	628,0	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,98**	

Take-off			
Take-off field length	s_{TOFL}	2300	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,278	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,30**	

2nd Segment		
Aspect ratio	A	9,453
Lift coefficient, take-off	$C_{L,TO}$	1,60
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,025
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,045
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	9,54
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,258

Missed approach		
Lift coefficient, landing	$C_{L,L}$	1,76
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,033
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,068
Glide ratio in landing configuration	E_L	8,11
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,241

2) Maximum Aerodynamic Efficiency

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications

Mach number, cruise	M_{CR}	0,785	
Aspect ratio	A	9,45	
Bypass ratio	μ	5,30	
Wing loading	m_{MTO}/S_W	628	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,278	

Variables

	V/V_{md}	**1,0**

Calculations

Zero-lift drag coefficient	$C_{D,0}$	0,019
Lift coefficient at E_{max}	$C_{L,md}$	0,69
Ratio, lift coefficient	$C_L/C_{L,md}$	1,000
Lift coefficient, cruise	C_L	0,695
Actual aerodynamic efficiency, cruise	E	18,17
Max. glide ratio, cruise	E_{max}	**18,17**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,23	-0,01	0,00
f'(x)	-0,10	-0,11	-0,11
E_{max}	16	18,26	18,17

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	1998	NM
Mach number, cruise	M_{CR}	0,785	
Bypass ratio	μ	5,30	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,278	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	78245	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,259	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,526	

Calculated values			
Actual aerodynamic efficiency, cruise	E	18,17	
Cruise altitude	h_{CR}	11679	m
Cruise speed	V_{CR}	232	m/s

Mission fuel fraction		
Type of aeroplane (according to Roskam)	**Transport jet**	
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980
Fuel-Fraction, descent	$M_{ff,DES}$	0,990
Fuel-Fraction, landing	$M_{ff,L}$	0,992

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,215	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,785	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,244	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,771	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,54E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 4 digit**	
Wing span	b_W	34,32	m
Structural wing span	$b_{W,struct}$	37,87	m
Wing area	S_W	124,6	m²
Aspect ratio	A	9,45	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	4,17	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	12,5	%
Taper	λ	0,219	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	72,00	m/s
Mach number, landing	M_{APP}	0,22	
Mach number, cruise	M_{CR}	0,785	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	3,3	%c
Leading edge sweep	φ_{LE}	28,9	°
Reynoldsnumber	Re	2,1E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,60	
Correction term, camber	$\Delta_1 c_{L,max}$	0,12	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,118	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,839	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,80	
Correction term, Mach number	$\Delta C_{L,max}$	-0,02	
Lift coefficient, wing	$C_{L,max}$	1,45	

Calculations increase of lift coefficient due to flaps		**2 flap types**	
Correction factor, sweep	K_{φ}	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,42	
Use flapped span	b_W,fA	**6,846**	m
Percentage of flaps allong the wing		18%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,22	
• Flap group B			
Double-slotted flap	$\Delta c_{L,max,fB}$	1,42	
Use flapped span	b_W,fB	**11,84**	m
Percentage of flaps allong the wing		31%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,39	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,61	

Calculations increase of lift coefficient due to slats		**2 slat types**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**26**	°
• Slat group A			
0,1c Kruger flap	$\Delta c_{L,max,sA}$	0,66	
Use slatted span	b_W,sA	**4,46**	m
Percentage of slats allong the wing		12%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,07	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**25,4**	m
Percentage of slats allong the wing		67%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,54	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,61	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,64**
RE value maximum lift coefficient, landing		2,98
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,04**
RE value maximum lift coefficient, take-off		2,30

-11%

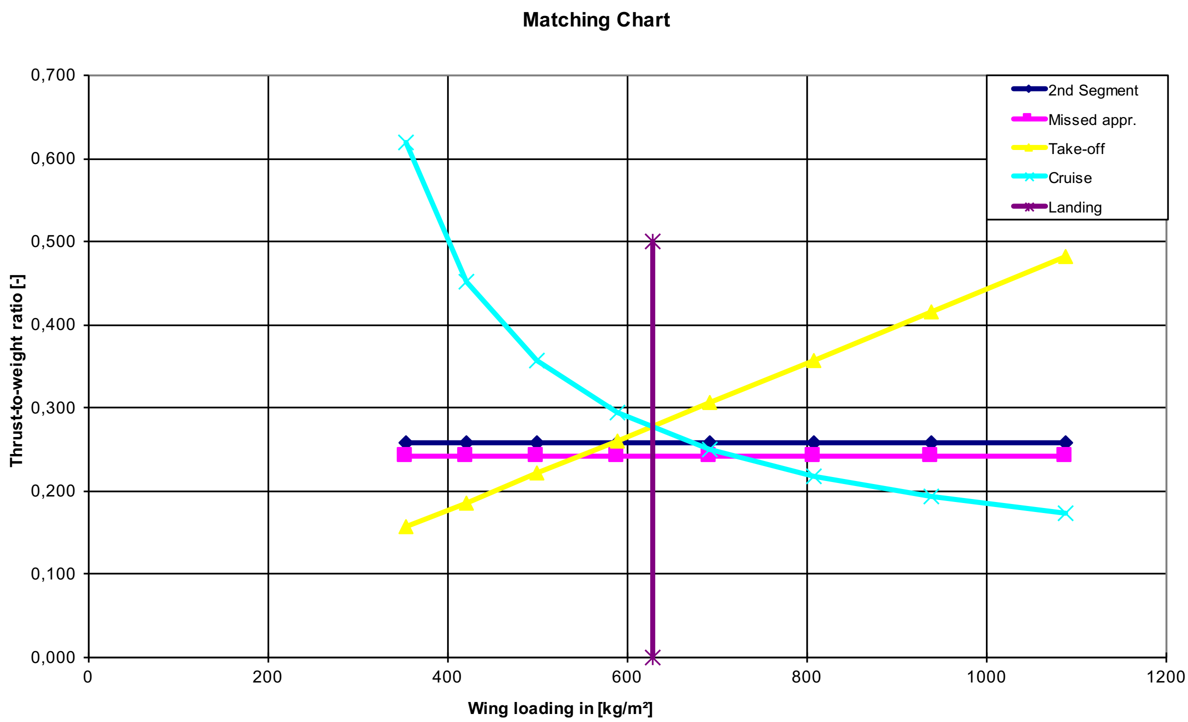
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,11	
Span	b_W	34,32	m
Winglet height	h	**2,49**	m
Aspect ratio	A	9,45	
Effective aspect ratio	A_{eff}	10,45	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**19,4**	
RE value maximum aerodynamic efficiency		18,17	

7%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,785	
Cruise altitude	h_{CR}	11887	m
By Pass Ratio	μ	5,30	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	106,76	kN
Overall Pressure ratio	OAPR	**26,00**	
Turbine entry temperature	TET	**1445,06**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,86	
Compressor efficiency	$\eta_{compresor}$	0,86	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,98	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,67	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,73	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,15	
Verification value specific fuel consumption	SFC	0,60	kg/daN/h
Verification value specific fuel consumption	SFC	**1,68E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,54E-05	kg/N/s
9%			


Matching Chart
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix B Airbus A320-200

Data Collection			A320-200	Source:	1		2			3	4		5	6	7	8	9
					Aircraft characteristics for airport planning		Jane's			Jenkinson	Engine		Scholz	Paul Müller	Elodie Roux	Data collectior	Webs
Parameter	Symbol	Units	Chosen value		WV016	WV017	Basic	Option 1	Option 2								
PAX			180		180		180			179-150				179	164-150		
Landing field length	s_{LFL}	m	1490			1500		1490		1440				1470	1440	1440	
Approach speed	V_{APP}	m/s	70			70				68,9				70,83		70,48	
Temperature above ISA (288,15K)	ΔT_L	K	0			0		0		0				0			
Relative density	s																
Take-off field length	s_{TOFL}	m	2180		1800	2100		1960		2180					2180	2190	2090
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0			15		0							
Relative density	s																
Range (max payload)	R	km	2870		3080	4100	4800	5185	5639	1180				5500	2870		6100
Cruise Mach number	M_{CR}		0,78					0,78			0,8				0,76	0,79	0,78
Wing area	S_W	m²	122,4					122,4		122,4				122,4	122,44		122,6
Wing span	b_W	m	34,1		34,1-35,8			34,09		33,91				33,91	33,91	35,8	34,1
Aspect ratio	A		9,4							9,394511				9,4	9,39		
Maximum take-off mass	m_{MTO}	kg	77000		73500	78000	73500	75500	77000	73500				73500	73500	73500	73700
Payload mass	m_{PL}	kg	19000		18100	19400		18633		19190					20767		
Mass ratio, payload - take-off	m_{PL}/m_{MTO}									0,261088					0,283		
Maximum landing mass	m_{ML}	kg	64500		66000		64500	66000		64500				64500	64500		
Mass ratio, landing - take-off	m_{ML}/m_{MTO}									0,877551							
Operating empty mass	m_{OE}	kg	42100					42100		41310					39733		42600
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}									0,562041					0,541		
Wing loading	m_{MTO}/S_W	kg/m²	600				599,5	615,8	628,1	600,4902					600		
Maximum zero fuel mass	m_{MZF}	kg	61000		62500		61000	62500		60500					60500		
Number of engines	n_E		2							2						2	2
Engine type	CFM56-5A (5%) -5B (55		CFM56-5B4		CFM56			CFM56-5B4/P		CFM56-5A3	CFM56-5A3	CFM56-5B4			CFM56-5A3	CFM56-5A3	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	111,2					120,1		111,2	117,877883	120,102			117,877	118	111,2
Total take-off thrust	T_{TO}	kN	222,4														
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,32				0,32705	0,31888	0,31205	0,308445					0,33		
Bypass ratio	μ		6								6	5,7			6		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	0								9,339E-06	9,62E-06			9,35E-06		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s	0								1,6867E-05	1,54E-05			1,688E-05		
Available fuel volume	$V_{fuel,available}$	m³	23,86		23,859-26,759-29,659			23,86		23,86					23,859		
Cruise speed	V_{CR}	m/s	230					180		230,47-250,53						231,5	230
Cruise altitude	h_{CR}	m	11278					11280		11277,6-853	10668				11278		11000
Sweep angle	ϕ_{25}	°	25							25					25		25
Mean aerodynamic chord	c_{MAC}	m	4,2							4,288					4,19		
Position of maximum camber	$x_{(y\_c),max}$	%c	15														15
Camber	$(y_c)_{max}/c$	%c	1,8														1,8
Position of maximum thickness	$x_{t,max}$	%c	30														30
Relative thickness	t/c	%	15,2												15,2-11,8-10,8		15
Taper	λ		0,24							0,24					0,246		
Overall pressure ratio	OAPR		29,1								27,8	29,1					
Turbine entry temperature	TET	K															

Aeroplane Specifications

Data to apply reverse engineering

					LL	*UL*
Landing field length	**Known**	s_{LFL}	**1490**	m		
Approach speed	**Known**	V_{APP}	**70,00**	m/s	70,0	70,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2180**	m	2180	2180
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**1550**	NM		
Cruise Mach number		M_{CR}	**0,78**			
Wing area		S_W	**122**	m²		
Wing span	**Known**	b_W	**34,1**	m²	34,1	34,1
Aspect ratio		A	9,50			
Maximum take-off mass		m_{MTO}	**77000**	kg		
Maximum payload mass		m_{PL}	**19000**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,247			
Maximum landing mass		m_{ML}	**64500**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,838			
Operating empty mass		m_{OE}	**42100**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,547			
Wing loading		m_{MTO}/S_W	629,1	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**111,2**	kN		
Total take-off thrust		T_{TO}	222,4	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,294			
Bypass ratio		μ	**6**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	*UL*
Cruise speed	V_{CR}	**230**	m/s		
Cruise altitude	h_{CR}	**11278**	m		
Speed ratio	V/V_{md}	**1,069**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**24,967**	°		
Mean aerodynamic chord		c_{MAC}	**4,2**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,6**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1490	1490	m	0,00%
Approach speed	V_{APP}	70,00	70,0	m/s	0,00%
Take-off field length	s_{TOFL}	2180	2180	m	0,00%
Span	b_W	34,1	34,1	m	0,00%
Aspect ratio	A	9,50	9,50		0,00%
Cruise speed	V_{CR}	230,0	230	m/s	0,08%
Cruise altitude	h_{CR}	11278	11278	m	0,00%
Squared Sum					**6,90E-07**
Absolute maximum deviation					0,1%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,31**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,29**	
Maximum aerodynamic efficiency	E_{max}	**16,80**	
Specific fuel consumption	SFC	**1,60E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing			
Landing field length	s_{LFL}	1490	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	70,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,84	
Wing loading at maximum take-off mass	m_{MTO}/S_W	629,1	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,31**	

Take-off			
Take-off field length	s_{TOFL}	2180	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,294	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,29**	

2nd Segment		
Aspect ratio	A	9,500
Lift coefficient, take-off	$C_{L,TO}$	1,59
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,025
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,045
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	9,59
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,257

Missed approach		
Lift coefficient, landing	$C_{L,L}$	1,96
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,043
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,078
Glide ratio in landing configuration	E_L	7,50
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,259

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,78	
Aspect ratio	A	9,50	
Bypass ratio	μ	6,00	
Wing loading	m_{MTO}/S_W	629	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,294	

Variables		
	V/V_{md}	**1,1**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,022
Lift coefficient at E_{max}	$C_{L,md}$	0,75
Ratio, lift coefficient	$C_L/C_{L,md}$	0,876
Lift coefficient, cruise	C_L	0,661
Actual aerodynamic efficiency, cruise	E	16,65
Max. glide ratio, cruise	E_{max}	**16,80**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,09	0,00	0,00
f'(x)	-0,11	-0,12	-0,12
E_{max}	16	16,81	16,80

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	1550	NM
Mach number, cruise	M_{CR}	0,78	
Bypass ratio	μ	6,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,294	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	77000	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,247	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,547	

Calculated values			
Actual aerodynamic efficiency, cruise	E	16,65	
Cruise altitude	h_{CR}	11278	m
Cruise speed	V_{CR}	230	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,206	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,794	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,248	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,767	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,60E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 4 digit**	
Wing span	b_W	34,1	m
Structural wing span	$b_{W,struct}$	37,62	m
Wing area	S_W	122,4	m²
Aspect ratio	A	9,50	
Sweep	φ_{25}	24,967	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,6	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	70,00	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,78	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	3,0	%c
Leading edge sweep	φ_{LE}	28,7	°
Reynoldsnumber	Re	2,1E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,58	
Correction term, camber	$\Delta_1 c_{L,max}$	0,18	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,083	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,835	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,80	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,45	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_{φ}	0,87	
• Flap group A			
0,3c Single-slotted fowler flap	$\Delta c_{L,max,fA}$	1,72	
Use flapped span	b_W,fA	**26,6**	m
Percentage of flaps allong the wing		71%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	1,06	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,74	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	1,06	

Calculations increase of lift coefficient due to slats			**1 slat type**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**27**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,90	
Use slatted span	b_W,sA	**30,82**	m
Percentage of slats allong the wing		82%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,66	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**0**	m
Percentage of slats allong the wing		0%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,00	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,66	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**3,12**
RE value maximum lift coefficient, landing		3,31
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,16**
RE value maximum lift coefficient, take-off		2,29

-6%

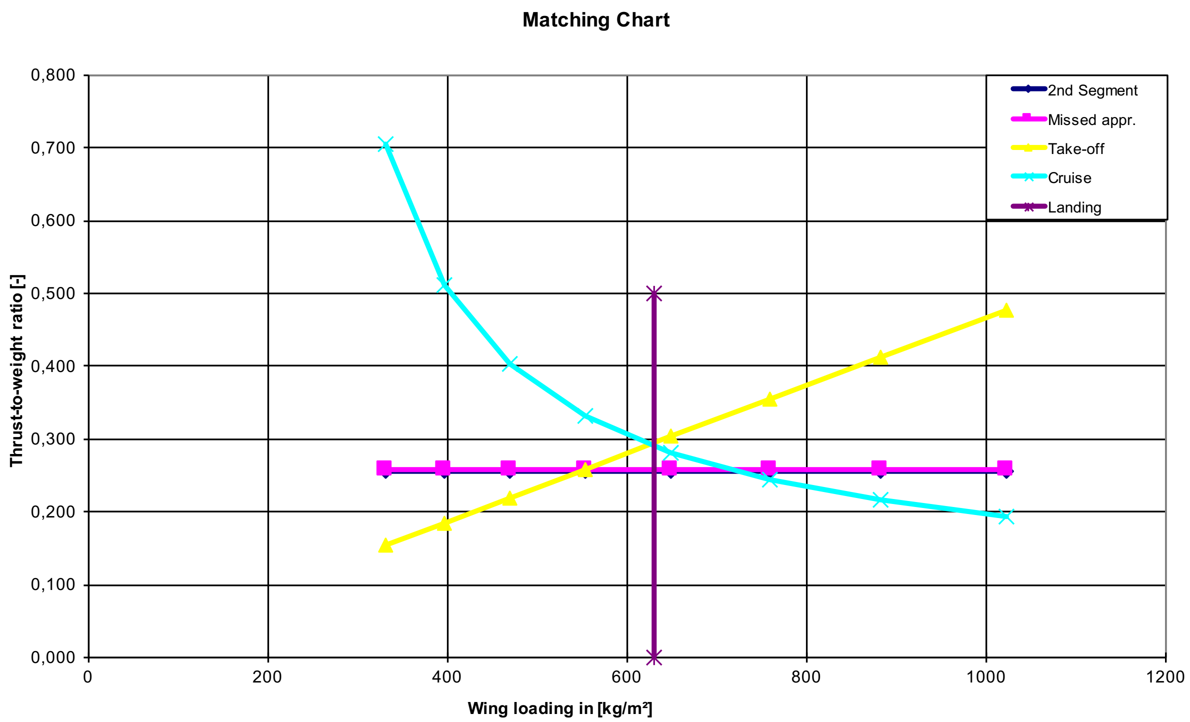
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,05	
Span	b_W	34,1	m
Winglet height	h	**1,1**	m
Aspect ratio	A	9,50	
Effective aspect ratio	A_{eff}	9,94	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**19,0**	
RE value maximum aerodynamic efficiency		16,80	

13%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,780	
Cruise altitude	h_{CR}	11278	m
By Pass Ratio	μ	6,00	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	111,20	kN
Overall Pressure ratio	OAPR	**29,10**	
Turbine entry temperature	TET	**1448,06**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,94	
Ventilator efficiency	$\eta_{ventilator}$	0,87	
Compressor efficiency	$\eta_{compresor}$	0,86	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,98	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,68	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,82	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,14	
Verification value specific fuel consumption	SFC	0,58	kg/daN/h
Verification value specific fuel consumption	SFC	**1,61E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,60E-05	kg/N/s
1%			



Matching Chart
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
200
400
600
800
1000
1200
Thrust-to-weight ratio [-]
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix C Airbus A320-200Neo

Data Collection			A320Neo	Source: 1	1	2	3	4	5	6	7	8	9
				Aircraft characteristics for airport planning									
Parameter	Symbol	Units	Chosen value	WV069	WV055	Jane's	Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collection	Webs
PAX			180	180									
Landing field length	s_{LFL}	m	1440									1440	
Approach speed	V_{APP}	m/s	69		68							70,48	
Temperature above ISA (288,15K)	ΔT_L	K	0										
Relative density	s												
Take-off field length	s_{TOFL}	m	1880	1880								2190	
Temperature above ISA (288,15K)	ΔT_{TO}	K											
Relative density	s												
Range (max payload)	R	km	4500	4500									6300
Cruise Mach number	M_{CR}		0,78									0,79	0,78
Wing area	S_W	m²											
Wing span	b_W	m	35,8	35,8								35,8	35,8
Aspect ratio	A												
Maximum take-off mass	m_{MTO}	kg	79000	75500	79000							73500	79000
Payload mass	m_{PL}	kg	19250		19250								
Mass ratio, payload - take-off	m_{PL}/m_{MTO}		0,243670886										
Maximum landing mass	m_{ML}	kg	67400	67400	67400								67400
Mass ratio, landing - take-off	m_{ML}/m_{MTO}												
Operating empty mass	m_{OE}	kg											
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}												
Wing loading	m_{MTO}/S_W	kg/m²											
Maximum zero fuel mass	m_{MZF}	kg	64300	64300	64300								64300
Number of engines	n_E		2									2	2
Engine type	CFM LEAP-1A (37%), P|		CFM LEAP-1A	LEAP-1A								PW 1100G	LEAP-1A
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	136,5									120	104,5-136,5
Total take-off thrust	T_{TO}	kN	273										
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$												
Bypass ratio	μ		11										11
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s											
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s											
Available fuel volume	$V_{fuel,available}$	m³	26,73	23,859-26,759-29,659									26,73
Cruise speed	V_{CR}	m/s	230									231,5	230
Cruise altitude	h_{CR}	m	11000										11000
Sweep angle	ϕ_{25}	°											
Mean aerodynamic chord	c_{MAC}	m											
Position of maximum camber	$x_{(y\_c),max}$	%c	15										15
Camber	$(y_c)_{max}/c$	%c	1,8										1,8
Position of maximum thickness	$x_{t,max}$	%c	30										30
Relative thickness	t/c	%	15										15
Taper	λ												
Overall pressure ratio	OAPR												
Turbine entry temperature	TET	K											

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1440**	m		
Approach speed	**Known**	V_{APP}	**69,00**	m/s	69,0	69,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**1880**	m	1880	1880
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**2430**	NM		
Cruise Mach number		M_{CR}	**0,78**			
Wing area		S_W	**122**	m²		
Wing span	**Known**	b_W	**35,8**	m²	35,8	35,8
Aspect ratio		A	10,47			
Maximum take-off mass		m_{MTO}	**79000**	kg		
Maximum payload mass		m_{PL}	**19250**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,244			
Maximum landing mass		m_{ML}	**67400**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,853			
Operating empty mass		m_{OE}	**42100**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,533			
Wing loading		m_{MTO}/S_W	645,4	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**136,5**	kN		
Total take-off thrust		T_{TO}	273	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,352			
Bypass ratio		μ	**11**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	*UL*
Cruise speed	V_{CR}	**230**	m/s		
Cruise altitude	h_{CR}	**11000**	m		
Speed ratio	V/V_{md}	**1,096**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**24,967**	°		
Mean aerodynamic chord		c_{MAC}	**4,2**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,6**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1440	1440	m	0,00%
Approach speed	V_{APP}	69,00	69,0	m/s	0,00%
Take-off field length	s_{TOFL}	1880	1880	m	0,00%
Span	b_W	35,8	35,8	m	0,00%
Aspect ratio	A	10,47	10,47		0,00%
Cruise speed	V_{CR}	230,0	230	m/s	0,08%
Cruise altitude	h_{CR}	11000	11000	m	0,00%
Squared Sum					**6,90E-07**
Absolute maximum deviation					0,1%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,57**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,28**	
Maximum aerodynamic efficiency	E_{max}	**18,01**	
Specific fuel consumption	SFC	**1,36E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1440	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	69,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,85	
Wing loading at maximum take-off mass	m_{MTO}/S_W	645,4	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,57**	

Take-off

Take-off field length	s_{TOFL}	1880	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,352	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,28**	

2nd Segment

Aspect ratio	A	10,471
Lift coefficient, take-off	$C_{L,TO}$	1,58
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,024
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,044
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	10,34
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,241

Missed approach

Lift coefficient, landing	$C_{L,L}$	2,11
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,051
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,086
Glide ratio in landing configuration	E_L	7,55
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,262

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,78	
Aspect ratio	A	10,47	
Bypass ratio	μ	11,00	
Wing loading	m_{MTO}/S_W	645	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,352	

Variables		
	V/V_{md}	**1,1**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,022
Lift coefficient at E_{max}	$C_{L,md}$	0,78
Ratio, lift coefficient	$C_L/C_{L,md}$	0,833
Lift coefficient, cruise	C_L	0,647
Actual aerodynamic efficiency, cruise	E	17,71
Max. glide ratio, cruise	E_{max}	**18,01**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,22	-0,01	0,00
f'(x)	-0,10	-0,11	-0,11
E_{max}	16	18,08	18,01

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	2430	NM
Mach number, cruise	M_{CR}	0,78	
Bypass ratio	μ	11,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,352	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	79000	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,244	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,533	

Calculated values			
Actual aerodynamic efficiency, cruise	E	17,71	
Cruise altitude	h_{CR}	11000	m
Cruise speed	V_{CR}	230	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,223	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,777	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,242	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,774	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,36E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	NACA 4 digit	
Wing span	b_W	35,8	m
Structural wing span	$b_{W,struct}$	39,49	m
Wing area	S_W	122,4	m²
Aspect ratio	A	10,47	
Sweep	φ_{25}	24,967	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,6	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	69,00	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,78	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	3,0	%c
Leading edge sweep	φ_{LE}	28,3	°
Reynoldsnumber	Re	2,1E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,58	
Correction term, camber	$\Delta_1 c_{L,max}$	0,18	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,081	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,833	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,80	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,46	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_φ	0,87	
• Flap group A			
0,3c Single-slotted fowler flap	$\Delta c_{L,max,fA}$	1,73	
Use flapped span	b_W,fA	**27,9**	m
Percentage of flaps allong the wing		71%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	1,06	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,75	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	1,06	

Calculations increase of lift coefficient due to slats			**1 slat type**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**27**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,90	
Use slatted span	b_W,sA	**31,5**	m
Percentage of slats allong the wing		80%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,64	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**0**	m
Percentage of slats allong the wing		0%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,00	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,64	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**3,11**
RE value maximum lift coefficient, landing		3,57
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,98**
RE value maximum lift coefficient, take-off		2,28

-13%

Aerodynamic efficiency

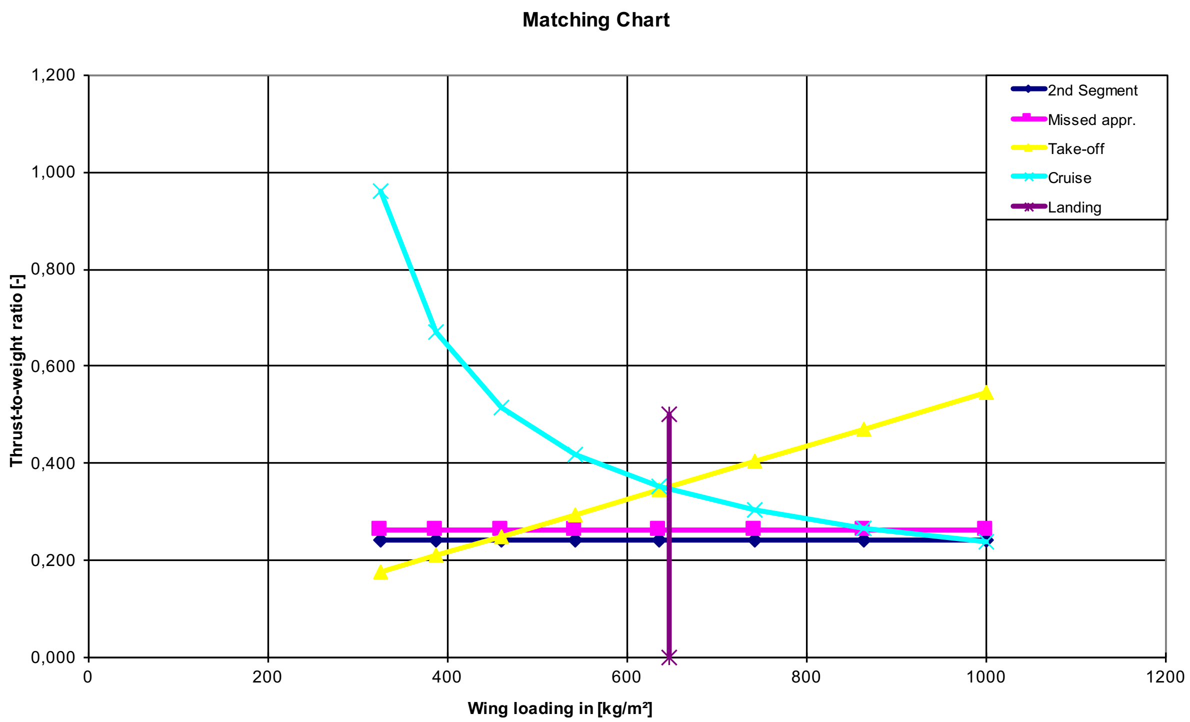
Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,10	
Span	b_W	35,8	m
Winglet height	h	**2,43**	m
Aspect ratio	A	10,47	
Effective aspect ratio	A_{eff}	11,50	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**20,4**	
RE value maximum aerodynamic efficiency		18,01	

13%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,780	
Cruise altitude	h_{CR}	11000	m
By Pass Ratio	μ	11,00	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	136,50	kN
Overall Pressure ratio	OAPR	**40,00**	
Turbine entry temperature	TET	**1461,39**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,92	
Ventilator efficiency	$\eta_{ventilator}$	0,89	
Compressor efficiency	$\eta_{compresor}$	0,87	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,75	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	2,10	
Gas generator efficiency	η_{gasgen}	0,97	
Gas generator function	G	2,07	
Verification value specific fuel consumption	SFC	0,53	kg/daN/h
Verification value specific fuel consumption	SFC	**1,46E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,36E-05	kg/N/s

8%


Matching Chart
Thrust-to-weight ratio [-]
1,200
1,000
0,800
0,600
0,400
0,200
0,000
0
200
400
600
800
1000
1200
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix D Boeing 737-8

Data Collection			737-8	Source:	1	2	3	4	5	6	7	8	9
Parameter	Symbol	Units	Chosen value		Aircraft characteristics for airport planning	Jane's	Jenkinson	Engine	Scholz	Paul Müller	Elodie Rou	Data collectior	Webs
PAX			189		178-189								175-162
Landing field length	s_{LFL}	m	1650		1650								
Approach speed	V_{APP}	m/s											
Temperature above ISA (288,15K)	ΔT_L	K	0		0								
Relative density	s												
Take-off field length	s_{TOFL}	m	2540		2540								
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0								
Relative density	s												
Range (max payload)	R	km	4630		4630								6704
Cruise Mach number	M_{CR}		0,79									0,79	0,79
Wing area	S_W	m²											
Wing span	b_W	m	35,92		35,92							35,9	35,9
Aspect ratio	A												
Maximum take-off mass	m_{MTO}	kg	82190		82190							82191	82191
Payload mass	m_{PL}	kg											
Mass ratio, payload - take-off	m_{PL}/m_{MTO}												
Maximum landing mass	m_{ML}	kg	69308		69308								
Mass ratio, landing - take-off	m_{ML}/m_{MTO}												
Operating empty mass	m_{OE}	kg											
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}												
Wing loading	m_{MTO}/S_W	kg/m²											
Maximum zero fuel mass	m_{MZF}	kg	65952		65952								
Number of engines	n_E		2									2	2
Engine type	CFM LEAP-1B		LEAP-1B25		LEAP-1B25							LEAP-1B	LEAP-1B
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	130									130	
Total take-off thrust	T_{TO}	kN											
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$												
Bypass ratio	μ		9										9
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s											
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s											
Available fuel volume	$V_{fuel,available}$	m³	25,817		25,817								
Cruise speed	V_{CR}	m/s	233,89										233,89
Cruise altitude	h_{CR}	m											
Sweep angle	ϕ_{25}	°											
Mean aerodynamic chord	c_{MAC}	m											
Position of maximum camber	$x_{(y\_c),max}$	%c	20,4										20,4
Camber	$(y_c)_{max}/c$	%c	1,5										1,5
Position of maximum thickness	$x_{t,max}$	%c	39,9										39,9
Relative thickness	t/c	%	10										10
Taper	λ												
Overall pressure ratio	OAPR												
Turbine entry temperature	TET	K											

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1650**	m		
Approach speed	**Unknown**	V_{APP}	69,00	m/s	69,1	69,1
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2540**	m	2540	2540
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**2160**	NM		
Cruise Mach number		M_{CR}	**0,79**			
Wing area		S_W	**125**	m²		
Wing span	**Known**	b_W	**35,92**	m²	35,92	35,92
Aspect ratio		A	10,36			
Maximum take-off mass		m_{MTO}	**82190**	kg		
Maximum payload mass		m_{PL}	**20276**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,247			
Maximum landing mass		m_{ML}	**69308**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,843			
Operating empty mass		m_{OE}	**41145**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,501			
Wing loading		m_{MTO}/S_W	659,6	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**130**	kN		
Total take-off thrust		T_{TO}	260	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,322			
Bypass ratio		μ	**9**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed	V_{CR}	**234**	m/s			
Cruise altitude	h_{CR}	**11000**	m			
Speed ratio	V/V_{md}	**1,108**	-		1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**25**	°		
Mean aerodynamic chord		c_{MAC}	**4,2**	m		
Position of maximum camber		$x_{(y\_c),max}$	**25**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**40**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,5**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1650	1650	m	0,00%
Approach speed	V_{APP}	Unknown	**69,1**	m/s	0,00%
Take-off field length	s_{TOFL}	2540	2540	m	0,00%
Span	b_W	35,92	35,92	m	0,00%
Aspect ratio	A	10,36	10,36		0,00%
Cruise speed	V_{CR}	233,9	233	m/s	-0,31%
Cruise altitude	h_{CR}	11000	10994	m	-0,05%
Squared Sum					**9,95E-06**
Absolute maximum deviation					0,3%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,15**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,88**	
Maximum aerodynamic efficiency	E_{max}	**17,45**	
Specific fuel consumption	SFC	**1,77E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1650	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	69,13	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,84	
Wing loading at maximum take-off mass	m_{MTO}/S_W	659,6	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,15**	

Take-off

Take-off field length	s_{TOFL}	2540	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,322	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,88**	

2nd Segment

Aspect ratio	A	10,355
Lift coefficient, take-off	$C_{L,TO}$	1,31
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,010
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,030
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	12,39
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,209

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,86
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,038
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,073
Glide ratio in landing configuration	E_L	8,25
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,240

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,79	
Aspect ratio	A	10,36	
Bypass ratio	μ	9,00	
Wing loading	m_{MTO}/S_W	660	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,322	

Variables		
	V/V_{md}	**1,1**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,023
Lift coefficient at E_{max}	$C_{L,md}$	0,79
Ratio, lift coefficient	$C_L/C_{L,md}$	0,814
Lift coefficient, cruise	C_L	0,645
Actual aerodynamic efficiency, cruise	E	17,09
Max. glide ratio, cruise	E_{max}	**17,45**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,16	0,00	0,00
f'(x)	-0,11	-0,11	-0,11
E_{max}	16	17,49	17,45

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	2160	NM
Mach number, cruise	M_{CR}	0,79	
Bypass ratio	μ	9,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,322	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	82190	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,247	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,501	

Calculated values			
Actual aerodynamic efficiency, cruise	E	17,09	
Cruise altitude	h_{CR}	10994	m
Cruise speed	V_{CR}	233	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,253	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,747	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,232	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,783	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,77E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	35,92	m
Structural wing span	$b_{W,struct}$	39,63	m
Wing area	S_W	124,6	m²
Aspect ratio	A	10,36	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	25	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	39,9	%c
Relative thickness	t/c	11,5	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	69,13	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,79	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,1	%c
Leading edge sweep	φ_{LE}	28,4	°
Reynoldsnumber	Re	2,1E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,24	
Correction term, camber	$\Delta_1 c_{L,max}$	0,40	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,17	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,040	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,851	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,87	
Correction term, Mach number	$\Delta C_{L,max}$	-0,02	
Lift coefficient, wing	$C_{L,max}$	1,59	

Calculations increase of lift coefficient due to flaps		**2 flap types**	
Correction factor, sweep	K_φ	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,56	
Use flapped span	b_W,fA	**7,18**	m
Percentage of flaps allong the wing		18%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,25	
• Flap group B			
Double-slotted flap	$\Delta c_{L,max,fB}$	1,56	
Use flapped span	b_W,fB	**12,39**	m
Percentage of flaps allong the wing		31%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,42	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,67	

Calculations increase of lift coefficient due to slats		**2 slat types**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**27**	°
• Slat group A			
0,1c Kruger flap	$\Delta c_{L,max,sA}$	0,73	
Use slatted span	b_W,sA	**4,67**	m
Percentage of slats allong the wing		12%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,08	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,99	
Use slatted span	b_W,sB	**26,58**	m
Percentage of slats allong the wing		67%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,59	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,67	

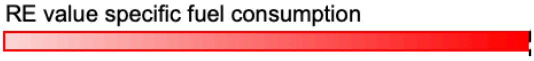
Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,90**
RE value maximum lift coefficient, landing		3,15
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,73**
RE value maximum lift coefficient, take-off		1,88
-8%		

Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,11	
Span	b_W	35,92	m
Winglet height	h	**2,7**	m
Aspect ratio	A	10,36	
Effective aspect ratio	A_{eff}	11,48	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**20,4**	
RE value maximum aerodynamic efficiency		17,45	
17%			

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,790	
Cruise altitude	h_{CR}	11000	m
By Pass Ratio	μ	9,00	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	130,00	kN
Overall Pressure ratio	OAPR	**31,70**	
Turbine entry temperature	TET	**1458,46**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,93	
Ventilator efficiency	$\eta_{ventilator}$	0,88	
Compressor efficiency	$\eta_{compresor}$	0,87	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,98	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,73	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,89	
Gas generator efficiency	η_{gasgen}	0,97	
Gas generator function	G	2,16	
Verification value specific fuel consumption	SFC	0,55	kg/daN/h
Verification value specific fuel consumption	SFC	**1,54E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,77E-05	kg/N/s



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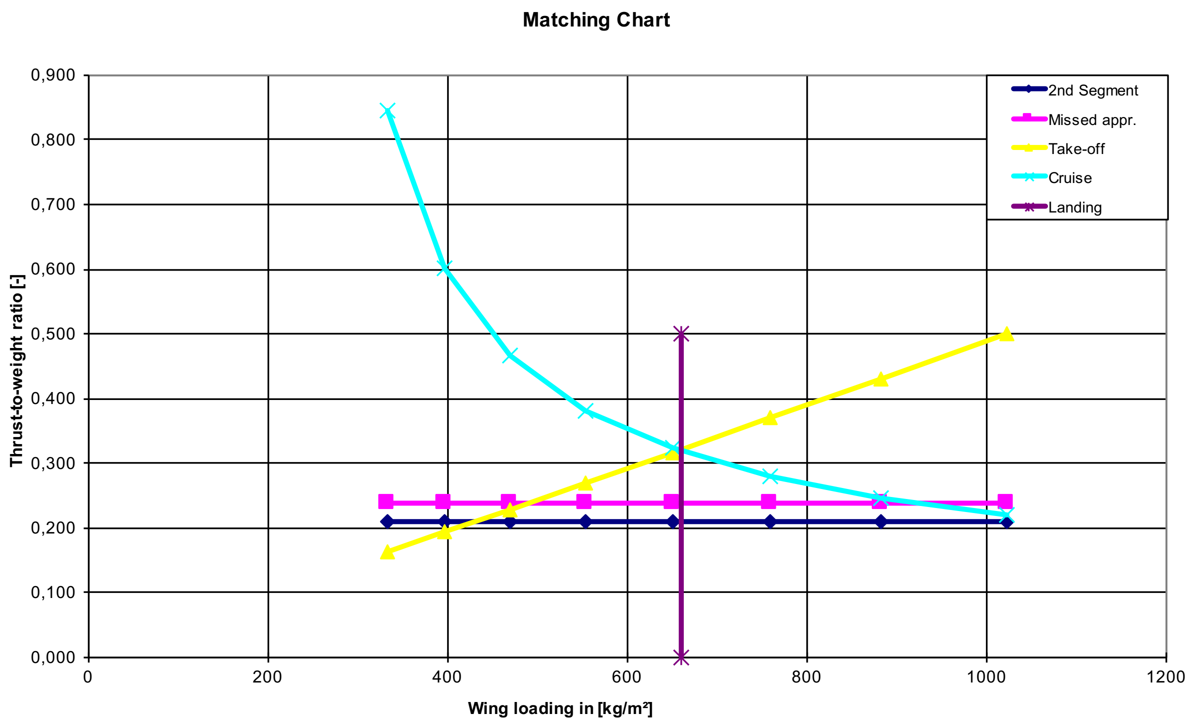


Matching Chart
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix E Airbus A321-200

Data Collection			A321-200	Source:	1 Aircraft characteristics for airport planning		2 Jane's		3	4	5	6	7	8	9
Parameter	Symbol	Units	Chosen value		WV007	WV011	Basic	Option	Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collection	Webs
PAX			185		185		185-220		220-186			212	199-185		
Landing field length	s_{LFL}	m	1580			1700	1577		1580			1587	1580	1600	
Approach speed	V_{APP}	m/s	72			73			71			72,22		68,94	
Temperature above ISA (288,15K)	ΔT_L	K	0			0	0		0						
Relative density	s														
Take-off field length	s_{TOFL}	m	2200		2130	2500	2330		2000				2000	2210	2180
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0		15		0						
Relative density	s														
Range (max payload)	R	km	3700		3700	4160	5000-5556		3620,66			4600	3621		5600
Cruise Mach number	M_{CR}		0,78				0,78			0,8			0,78	0,79	0,78
Wing area	S_W	m²	122,4				122,4		122,4			122,4	126		122,6
Wing span	b_W	m	34,09		34,1		34,09		33,91			34,09	33,91	35,8	34,1
Aspect ratio	A		9,4						9,3945106			9,4	9,13		
Maximum take-off mass	m_{MTO}	kg	93500		83000	93500	83000	93900	89000			83000	89000	89000	93500
Payload mass	m_{PL}	kg	23000		22700	25000			22780				24500		
Mass ratio, payload - take-off	m_{PL}/m_{MTO}								0,2559551				0,275		
Maximum landing mass	m_{ML}	kg	77800		73500	77800	73500	77800	73500			73500	75500		
Mass ratio, landing - take-off	m_{ML}/m_{MTO}								0,8258427						
Operating empty mass	m_{OE}	kg	49200				49200		48000				47000		48500
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}								0,5393258				0,528		
Wing loading	m_{MTO}/S_W	kg/m²	762,6				677	762,6	727,12418				706		
Maximum zero fuel mass	m_{MZF}	kg	73800		69500	73800	69500	73800	71500				71500		73800
Number of engines	n_E		2						2				2	2	2
Engine type	CFM56-5B (41%), IAE V		CFM56-5B3/P		CFM56		CFM56-5B3/P or -5B3/2P		CFM56-5B3	CFM56-5B3			CFM56-5B3/P	CFM56-5B1	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	142,342				142,3		142	142,343104			142,342	133	133-147
Total take-off thrust	T_{TO}	kN													
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,33				0,350656	0,3111	0,3252815				0,33		
Bypass ratio	μ		5,4							5,4			5,4		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	0,0000102							1,0188E-05			0,0000102		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s													
Available fuel volume	$V_{fuel,available}$	m³	26,6		23,7-26,692-29,684		23,7-26,6-29,684		23,7-26,6				29,5		24,05-30,03
Cruise speed	V_{CR}	m/s	231				180		231,5-250,53					231,5	222,22
Cruise altitude	h_{CR}	m	11278						11277,6-8534	10668			11278		
Sweep angle	ϕ_{25}	°	25						25				25		25
Mean aerodynamic chord	c_{MAC}	m	4,3						4,288				4,34		
Position of maximum camber	$x_{(y\_c),max}$	%c													
Camber	$(y_c)_{max}/c$	%c													
Position of maximum thickness	$x_{t,max}$	%c													
Relative thickness	t/c	%													
Taper	λ		0,24						0,24				0,239		
Overall pressure ratio	OAPR		33,7							33,7					
Turbine entry temperature	TET	K													

Aeroplane Specifications

Data to apply reverse engineering

					LL	*UL*
Landing field length	**Known**	s_{LFL}	**1580**	m		
Approach speed	**Known**	V_{APP}	**72,00**	m/s	72,0	72,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2200**	m	2200	2200
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**1955**	NM		
Cruise Mach number		M_{CR}	**0,78**			
Wing area		S_W	**122**	m²		
Wing span	**Known**	b_W	**34,09**	m²	34,09	34,09
Aspect ratio		A	9,49			
Maximum take-off mass		m_{MTO}	**93500**	kg		
Maximum payload mass		m_{PL}	**23000**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,246			
Maximum landing mass		m_{ML}	**77800**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,832			
Operating empty mass		m_{OE}	**49200**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,526			
Wing loading		m_{MTO}/S_W	763,9	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**142,342**	kN		
Total take-off thrust		T_{TO}	284,684	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,310			
Bypass ratio		μ	**5,4**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	**231**	m/s		
Cruise altitude	h_{CR}	**11278**	m		
Speed ratio	V/V_{md}	**1,014**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**24,967**	°		
Mean aerodynamic chord		c_{MAC}	**4,3**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,6**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1580	1580	m	0,00%
Approach speed	V_{APP}	72,00	72,0	m/s	0,00%
Take-off field length	s_{TOFL}	2200	2200	m	0,00%
Span	b_W	34,09	34,09	m	0,00%
Aspect ratio	A	9,49	9,49		0,00%
Cruise speed	V_{CR}	231,0	230	m/s	-0,35%
Cruise altitude	h_{CR}	11278	11278	m	0,00%
Squared Sum					**1,23E-05**
Absolute maximum deviation					0,4%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,76**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,62**	
Maximum aerodynamic efficiency	E_{max}	**15,35**	
Specific fuel consumption	SFC	**1,44E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1580	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	72,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,83	
Wing loading at maximum take-off mass	m_{MTO}/S_W	763,9	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,76**	

Take-off

Take-off field length	s_{TOFL}	2200	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,310	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,62**	

2nd Segment

Aspect ratio	A	9,495
Lift coefficient, take-off	$C_{L,TO}$	1,82
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,036
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,056
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	8,49
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,284

Missed approach

Lift coefficient, landing	$C_{L,L}$	2,22
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,056
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,091
Glide ratio in landing configuration	E_L	6,78
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,281

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,78	
Aspect ratio	A	9,49	
Bypass ratio	μ	5,40	
Wing loading	m_{MTO}/S_W	764	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,310	

Variables		
	V/V_{md}	**1,0**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,027
Lift coefficient at E_{max}	$C_{L,md}$	0,83
Ratio, lift coefficient	$C_L/C_{L,md}$	0,972
Lift coefficient, cruise	C_L	0,803
Actual aerodynamic efficiency, cruise	E	15,34
Max. glide ratio, cruise	E_{max}	**15,35**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,09	0,00	0,00
f'(x)	-0,13	-0,13	-0,13
E_{max}	16	15,36	15,35

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	1955	NM
Mach number, cruise	M_{CR}	0,78	
Bypass ratio	μ	5,40	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,310	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	93500	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,246	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,526	

Calculated values			
Actual aerodynamic efficiency, cruise	E	15,34	
Cruise altitude	h_{CR}	11278	m
Cruise speed	V_{CR}	230	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,228	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,772	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,204	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,812	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,44E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 4 digit**	
Wing span	b_W	34,09	m
Structural wing span	$b_{W,struct}$	37,60	m
Wing area	S_W	122,4	m²
Aspect ratio	A	9,49	
Sweep	φ_{25}	24,967	°
Mean aerodynamic chord	c_{MAC}	4,3	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,6	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	72,00	m/s
Mach number, landing	M_{APP}	0,22	
Mach number, cruise	M_{CR}	0,78	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	3,0	%c
Leading edge sweep	φ_{LE}	28,7	°
Reynoldsnumber	Re	2,2E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,58	
Correction term, camber	$\Delta_1 c_{L,max}$	0,18	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,090	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,842	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,80	
Correction term, Mach number	$\Delta C_{L,max}$	-0,02	
Lift coefficient, wing	$C_{L,max}$	1,45	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_{φ}	0,87	
• Flap group A			
0,3c Single-slotted fowler flap	$\Delta c_{L,max,fA}$	1,72	
Use flapped span	b_W,fA	**26,59**	m
Percentage of flaps allong the wing		71%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	1,06	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,74	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	1,06	
Calculations increase of lift coefficient due to slats			**1 slat type**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**27**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,90	
Use slatted span	b_W,sA	**30**	m
Percentage of slats allong the wing		80%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,64	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**0**	m
Percentage of slats allong the wing		0%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,00	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,64	

Wing			
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**3,10**	
RE value maximum lift coefficient, landing		3,76	
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,16**	
RE value maximum lift coefficient, take-off		2,62	

-18%

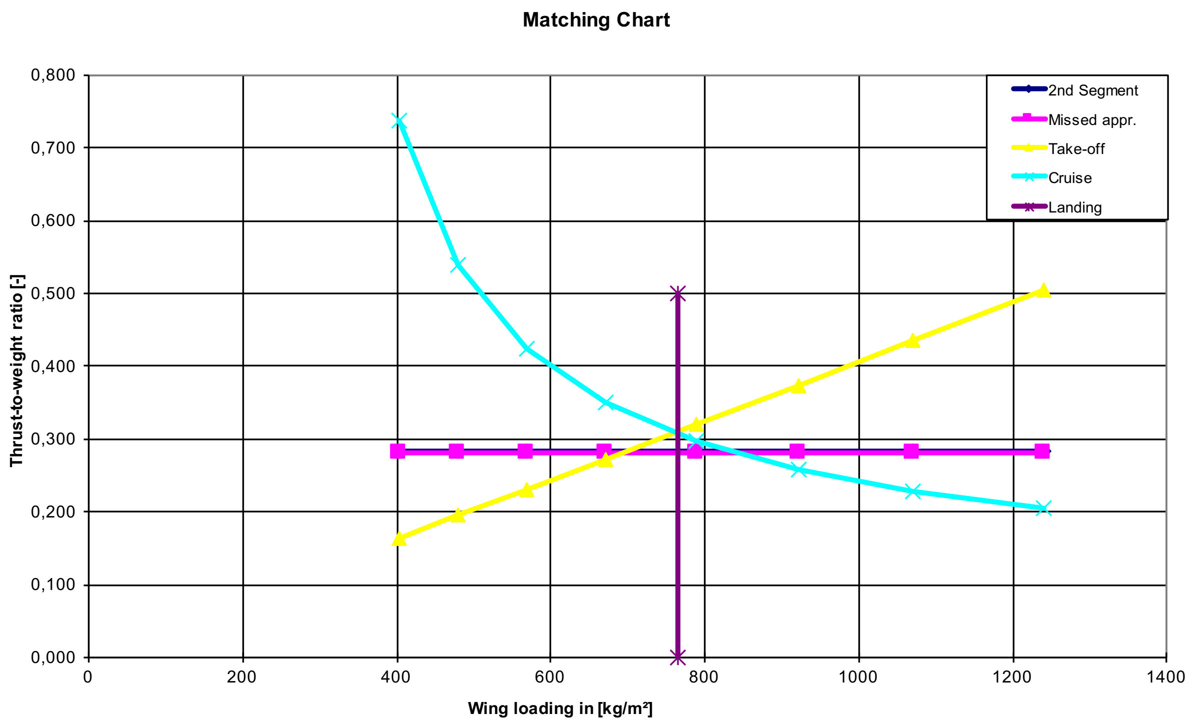
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,05	
Span	b_W	34,09	m
Winglet height	h	**1,1**	m
Aspect ratio	A	9,49	
Effective aspect ratio	A_{eff}	9,93	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**7,01**	
Verification value maximum aerodynamic efficiency	E_{max}	**18,0**	
RE value maximum aerodynamic efficiency		15,35	

18%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,780	
Cruise altitude	h_{CR}	11278	m
By Pass Ratio	μ	5,40	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	142,34	kN
Overall Pressure ratio	OAPR	**33,70**	
Turbine entry temperature	TET	**1463,80**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,88	
Compressor efficiency	$\eta_{compresor}$	0,86	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,76	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,94	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,14	
Verification value specific fuel consumption	SFC	0,56	kg/daN/h
Verification value specific fuel consumption	SFC	**1,57E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,44E-05	kg/N/s
9%			


Matching Chart
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
1400
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix F Airbus A321-200 Neo

Data Collection			A321Neo	Source:	1	2	3	4	5	6	7	8	9
Parameter	Symbol	Units	Chosen value		Aircraft characteristics for airport planning	Jane's	Jenkinson	Engine	Scholz	Paul Müller	Elodie Rou	Data collectior	Webs
PAX			202		202								
Landing field length	s_{LFL}	m	1750		1750							1600	
Approach speed	V_{APP}	m/s	70		70							68,94	
Temperature above ISA (288,15K)	ΔT_L	K	0										
Relative density	s												
Take-off field length	s_{TOFL}	m	2300		2500							2210	
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0								
Relative density	s												
Range (max payload)	R	km	5600		5600								7400
Cruise Mach number	M_{CR}		0,79									0,79	
Wing area	S_W	m²											
Wing span	b_W	m	35,8		35,8							35,8	35,8
Aspect ratio	A												
Maximum take-off mass	m_{MTO}	kg	93500		97000							93500	97000
Payload mass	m_{PL}	kg	24000		24000								
Mass ratio, payload - take-off	m_{PL}/m_{MTO}												
Maximum landing mass	m_{ML}	kg	79200		79200								79200
Mass ratio, landing - take-off	m_{ML}/m_{MTO}												
Operating empty mass	m_{OE}	kg											
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}												
Wing loading	m_{MTO}/S_W	kg/m²											
Maximum zero fuel mass	m_{MZF}	kg	75600		75600								75600
Number of engines	n_E		2									2	2
Engine type	CFM LEAP-1A (41%), PV		PW1133G-JM									PW 1100G	PW1133G-JM
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	147,3									150	147,3309258
Total take-off thrust	T_{TO}	kN											
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$												
Bypass ratio	μ		12,5										12,5
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s											
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s											
Available fuel volume	$V_{fuel,available}$	m³	29,474		29								32,94
Cruise speed	V_{CR}	m/s	231,5									231,5	222,22
Cruise altitude	h_{CR}	m	11278										11278
Sweep angle	ϕ_{25}	°											
Mean aerodynamic chord	c_{MAC}	m											
Position of maximum camber	$x_{(y\_c),max}$	%c											
Camber	$(y_c)_{max}/c$	%c											
Position of maximum thickness	$x_{t,max}$	%c											
Relative thickness	t/c	%											
Taper	λ												
Overall pressure ratio	OAPR												
Turbine entry temperature	TET	K											

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1750**	m		
Approach speed	**Known**	V_{APP}	**70,00**	m/s	70,0	70,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2300**	m	2300	2300
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**3024**	NM		
Cruise Mach number		M_{CR}	**0,79**			
Wing area		S_W	**122**	m²		
Wing span	**Known**	b_W	**35,8**	m²	35,8	35,8
Aspect ratio		A	10,47			
Maximum take-off mass		m_{MTO}	**93500**	kg		
Maximum payload mass		m_{PL}	**24000**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,257			
Maximum landing mass		m_{ML}	**79200**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,847			
Operating empty mass		m_{OE}	**49200**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,526			
Wing loading		m_{MTO}/S_W	763,9	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**147,3**	kN		
Total take-off thrust		T_{TO}	294,6	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,321			
Bypass ratio		μ	**12,5**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	**232**	m/s		
Cruise altitude	h_{CR}	**11278**	m		
Speed ratio	V/V_{md}	**1,000**	-	1	1,316

Data to execute the verification

					Range
Sweep angle		φ_{25}	**24,967**	°	
Mean aerodynamic chord		c_{MAC}	**4,3**	m	
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50 %c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6 %c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45 %c
Relative thickness	**Unknown**	t/c	**11,5**	%	
Taper		λ	**0,24**		

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1750	1750	m	0,00%
Approach speed	V_{APP}	70,00	70,0	m/s	0,00%
Take-off field length	s_{TOFL}	2300	2300	m	0,00%
Span	b_W	35,8	35,8	m	0,00%
Aspect ratio	A	10,47	10,47		0,00%
Cruise speed	V_{CR}	231,5	235	m/s	1,37%
Cruise altitude	h_{CR}	11278	10558	m	-6,38%
Squared Sum					**4,26E-03**
Absolute maximum deviation					6,4%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,46**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,42**	
Maximum aerodynamic efficiency	E_{max}	**20,10**	
Specific fuel consumption	SFC	**1,25E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1750	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	70,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,85	
Wing loading at maximum take-off mass	m_{MTO}/S_W	763,9	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,46**	

Take-off

Take-off field length	s_{TOFL}	2300	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,321	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,42**	

2nd Segment

Aspect ratio	A	10,471
Lift coefficient, take-off	$C_{L,TO}$	1,68
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,029
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,049
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	9,79
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,252

Missed approach

Lift coefficient, landing	$C_{L,L}$	2,04
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,047
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,082
Glide ratio in landing configuration	E_L	7,75
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,254

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,79	
Aspect ratio	A	10,47	
Bypass ratio	μ	12,50	
Wing loading	m_{MTO}/S_W	764	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,321	

Variables		
	V/V_{md}	**1,0**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,017
Lift coefficient at E_{max}	$C_{L,md}$	0,70
Ratio, lift coefficient	$C_L/C_{L,md}$	1,000
Lift coefficient, cruise	C_L	0,696
Actual aerodynamic efficiency, cruise	E	20,10
Max. glide ratio, cruise	E_{max}	**20,10**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,38	-0,03	0,00
f'(x)	-0,09	-0,10	-0,10
E_{max}	16	20,42	20,10

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	3024	NM
Mach number, cruise	M_{CR}	0,79	
Bypass ratio	μ	12,50	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,321	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	93500	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,257	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,526	

Calculated values			
Actual aerodynamic efficiency, cruise	E	20,10	
Cruise altitude	h_{CR}	10558	m
Cruise speed	V_{CR}	235	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,217	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,783	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,204	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,812	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,25E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 4 digit**	
Wing span	b_W	35,8	m
Structural wing span	$b_{W,struct}$	39,49	m
Wing area	S_W	122,4	m²
Aspect ratio	A	10,47	
Sweep	φ_{25}	24,967	°
Mean aerodynamic chord	c_{MAC}	4,3	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,5	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	70,00	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,79	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	3,0	%c
Leading edge sweep	φ_{LE}	28,3	°
Reynoldsnumber	Re	2,1E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,57	
Correction term, camber	$\Delta_1 c_{L,max}$	0,19	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,081	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,836	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,80	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,46	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_φ	0,87	
• Flap group A			
0,3c Single-slotted fowler flap	$\Delta c_{L,max,fA}$	1,73	
Use flapped span	b_W,fA	**27,92**	m
Percentage of flaps allong the wing		71%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	1,06	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,75	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	1,06	

Calculations increase of lift coefficient due to slats			**1 slat type**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**27**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,91	
Use slatted span	b_W,sA	**31,5**	m
Percentage of slats allong the wing		80%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,64	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,91	
Use slatted span	b_W,sB	**0**	m
Percentage of slats allong the wing		0%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,00	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,64	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**3,12**
RE value maximum lift coefficient, landing		3,46
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,18**
RE value maximum lift coefficient, take-off		2,42

-10%

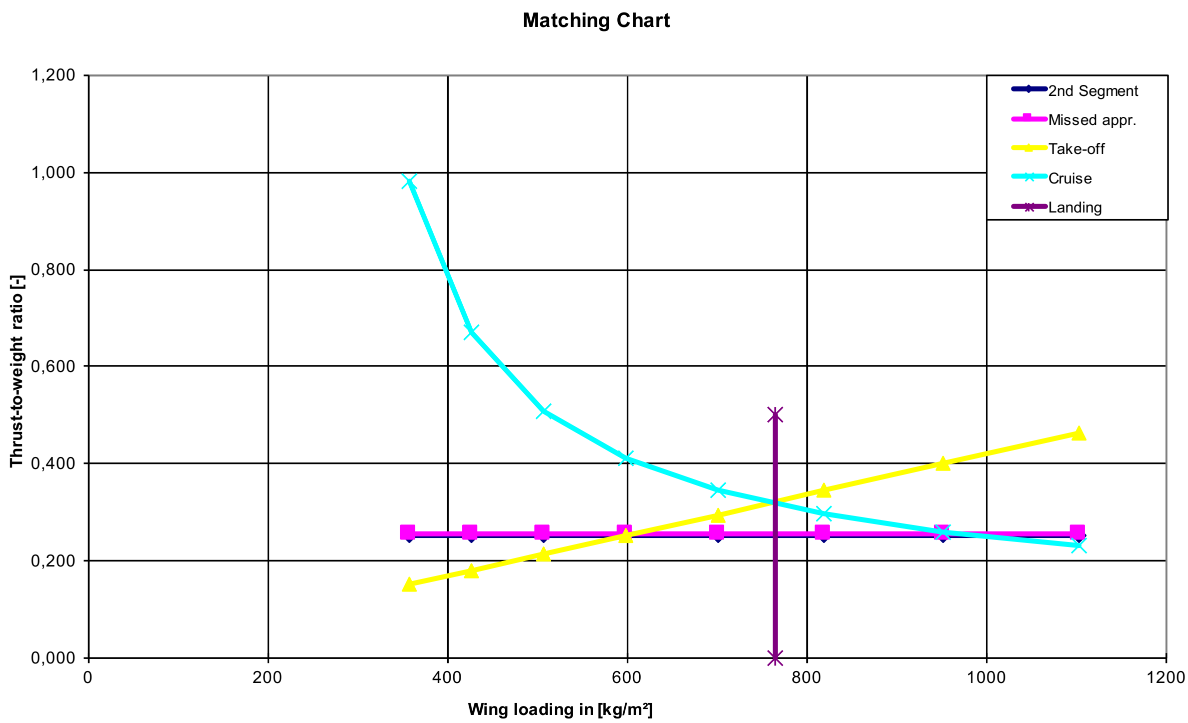
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,10	
Span	b_W	35,8	m
Winglet height	h	**2,43**	m
Aspect ratio	A	10,47	
Effective aspect ratio	A_{eff}	11,50	
Efficiency factor, short range	k_E	16,19	
Relative wetted area	S_{wet}/S_W	**7,01**	
Verification value maximum aerodynamic efficiency	E_{max}	**20,7**	
RE value maximum aerodynamic efficiency		20,10	

3%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,790	
Cruise altitude	h_{CR}	11278	m
By Pass Ratio	μ	12,50	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	147,30	kN
Overall Pressure ratio	OAPR	**44,01**	
Turbine entry temperature	TET	**1465,69**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,91	
Ventilator efficiency	$\eta_{ventilator}$	0,89	
Compressor efficiency	$\eta_{compresor}$	0,88	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,77	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	2,19	
Gas generator efficiency	η_{gasgen}	0,97	
Gas generator function	G	2,04	
Verification value specific fuel consumption	SFC	0,53	kg/daN/h
Verification value specific fuel consumption	SFC	**1,46E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,25E-05	kg/N/s
	17%		



Matching Chart
1,200
1,000
0,800
0,600
0,400
0,200
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix G Airbus A319-100

Data Collection			A319-100		1	2		3	4	5	6	7	8	9
				Source:	Aircraft characteristics for airport planning	Jane's		Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collectior	Webs
Parameter	Symbol	Units	Chosen value			Basic	Option							
PAX			156		156	124-145		153-124			142	134-124		
Landing field length	s_{LFL}	m	1430		1370-1400	1430		1350			1356	1350	1350	
Approach speed	V_{APP}	m/s	67		65			67,39			69,44		66,88	
Temperature above ISA (288,15K)	ΔT_L	K	0					0			0			
Relative density	s													
Take-off field length	s_{TOFL}	m	2200		1400-2200	1720	2640	1750				1750	1750	1950
Temperature above ISA (288,15K)	ΔT_{TO}	K	0			15		0						
Relative density	s													
Range (max payload)	R	km	4630		4630	3357	6846	2509,46			5500	1296		6950
Cruise Mach number	M_{CR}		0,78			0,78			0,8			0,78	0,79	0,78
Wing area	S_W	m²	122,4			122,4		122,4			122,4	122,44		122,6
Wing span	b_W	m	34,09		34,1	34,09		33,91			33,91	33,91	35,8	34,1
Aspect ratio	A		9,4					9,3945106			9,4	9,39		
Maximum take-off mass	m_{MTO}	kg	75500		66000-76500	64000	75500	64000			64000	64000	64000	75500
Payload mass	m_{PL}	kg	17900		17400	17900		17390				17642		58500
Mass ratio, payload - take-off	m_{PL}/m_{MTO}							0,2717188				0,276		
Maximum landing mass	m_{ML}	kg	61000		61000-62500	61000	62500	61000			61000	61000		
Mass ratio, landing - take-off	m_{ML}/m_{MTO}							0,953125						
Operating empty mass	m_{OE}	kg	41200			40160	41203	39200				39358		40800
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}							0,6125				0,615		
Wing loading	m_{MTO}/S_W	kg/m²	616,8			522,9	616,8	522,87582				523		
Maximum zero fuel mass	m_{MZF}	kg	58500		57000-58500	57000	58500	57000				57000		
Number of engines	n_E		2					2				2	2	2
Engine type	CFM56-5A (10%), -5B (5		CFM56-5B6		CFM56-5A	CFM56-5A4/-5B5	CFM56-5A5/-5B6	CFM56-5A4	CFM56-5A4			CFM56-5A4	CFM56-5B	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	104,5			97,9	104,5	99,7	97,860884			97,86	98	98-120
Total take-off thrust	T_{TO}	kN	209											
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,32			0,312051426	0,324970753	0,3175968				0,31		
Bypass ratio	μ		6,2						6,2			6,2		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	9,06E-06						9,056E-06			9,06E-06		
Specific Fuel Comsumption (cruise)	SFC (cruise)	kg/N s												
Available fuel volume	$V_{fuel,available}$	m³	23,859		23,859	23,86		23,86				23,859		
Cruise speed	V_{CR}	m/s	230			180		229,44-250,53					231,5	230
Cruise altitude	h_{CR}	m	11278					11277,6-100	10668			11278		
Sweep angle	ϕ_{25}	°	25					25				25		25
Mean aerodynamic chord	c_{MAC}	m	4,2					4,288				4,19		
Position of maximum camber	$x_{(y\_c),max}$	%c												
Camber	$(y_c)_{max}/c$	%c												
Position of maximum thickness	$x_{t,max}$	%c												
Relative thickness	t/c	%	11,8									15,2-11,8-10,8		
Taper	λ		0,24					0,24				0,246		
Overall pressure ratio	OAPR		24,1						24,1					
Turbine entry temperature	TET	K												

Aeroplane Specifications

Data to apply reverse engineering					LL	UL
Landing field length	**Known**	s_{LFL}	**1430**	m		
Approach speed	**Known**	V_{APP}	**67,00**	m/s	67,0	67,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2200**	m	2200	2200
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**1813**	NM		
Cruise Mach number		M_{CR}	**0,78**			
Wing area		S_W	**122**	m²		
Wing span	**Known**	b_W	**34,09**	m²	34,09	34,09
Aspect ratio		A	9,49			
Maximum take-off mass		m_{MTO}	**75500**	kg		
Maximum payload mass		m_{PL}	**17900**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,237			
Maximum landing mass		m_{ML}	**61000**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,808			
Operating empty mass		m_{OE}	**41200**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,546			
Wing loading		m_{MTO}/S_W	616,8	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**104,5**	kN		
Total take-off thrust		T_{TO}	209	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,282			
Bypass ratio		μ	**6,2**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed	V_{CR}	**230**	m/s			
Cruise altitude	h_{CR}	**11278**	m			
Speed ratio	V/V_{md}	**1,053**	-		1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**24,967**	°		
Mean aerodynamic chord		c_{MAC}	**4,2**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,6**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1430	1430	m	0,00%
Approach speed	V_{APP}	67,00	67,0	m/s	0,00%
Take-off field length	s_{TOFL}	2200	2200	m	0,00%
Span	b_W	34,09	34,09	m	0,00%
Aspect ratio	A	9,49	9,49		0,00%
Cruise speed	V_{CR}	230,0	230	m/s	0,08%
Cruise altitude	h_{CR}	11278	11278	m	0,00%
Squared Sum					**6,90E-07**
Absolute maximum deviation					0,1%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,26**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,33**	
Maximum aerodynamic efficiency	E_{max}	**17,65**	
Specific fuel consumption	SFC	**1,62E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1430	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	67,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,81	
Wing loading at maximum take-off mass	m_{MTO}/S_W	616,8	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,26**	

Take-off

Take-off field length	s_{TOFL}	2200	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,282	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,33**	

2nd Segment

Aspect ratio	A	9,495
Lift coefficient, take-off	$C_{L,TO}$	1,61
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,026
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,046
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	9,47
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,259

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,93
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,041
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,076
Glide ratio in landing configuration	E_L	7,58
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,247

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,78	
Aspect ratio	A	9,49	
Bypass ratio	μ	6,20	
Wing loading	m_{MTO}/S_W	617	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,282	

Variables		
	V/V_{md}	**1,1**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,020
Lift coefficient at E_{max}	$C_{L,md}$	0,72
Ratio, lift coefficient	$C_L/C_{L,md}$	0,902
Lift coefficient, cruise	C_L	0,648
Actual aerodynamic efficiency, cruise	E	17,55
Max. glide ratio, cruise	E_{max}	**17,65**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,18	-0,01	0,00
f'(x)	-0,11	-0,11	-0,11
E_{max}	16	17,70	17,65

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	1813	NM
Mach number, cruise	M_{CR}	0,78	
Bypass ratio	μ	6,20	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,282	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	75500	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,237	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,546	

Calculated values			
Actual aerodynamic efficiency, cruise	E	17,55	
Cruise altitude	h_{CR}	11278	m
Cruise speed	V_{CR}	230	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,217	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,783	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,253	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,762	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,62E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 4 digit**	
Wing span	b_W	34,09	m
Structural wing span	$b_{W,struct}$	37,60	m
Wing area	S_W	122,4	m²
Aspect ratio	A	9,49	
Sweep	φ_{25}	24,967	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,6	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	67,00	m/s
Mach number, landing	M_{APP}	0,20	
Mach number, cruise	M_{CR}	0,78	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	3,0	%c
Leading edge sweep	φ_{LE}	28,7	°
Reynoldsnumber	Re	2,0E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,58	
Correction term, camber	$\Delta_1 c_{L,max}$	0,18	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,076	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,829	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,80	
Correction term, Mach number	$\Delta C_{L,max}$	0,00	
Lift coefficient, wing	$C_{L,max}$	1,46	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_φ	0,87	
• Flap group A			
0,3c Single-slotted fowler flap	$\Delta c_{L,max,fA}$	1,73	
Use flapped span	b_W,fA	**26,6**	m
Percentage of flaps allong the wing		71%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	1,06	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,75	
Use flapped span	b_W,fB	0	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	1,06	

Calculations increase of lift coefficient due to slats			**2 slat types**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**27**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,90	
Use slatted span	b_W,sA	**7,5**	m
Percentage of slats allong the wing		20%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,16	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**21,8**	m
Percentage of slats allong the wing		58%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,47	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,63	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**3,10**
RE value maximum lift coefficient, landing		3,26
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,21**
RE value maximum lift coefficient, take-off		2,33

-5%

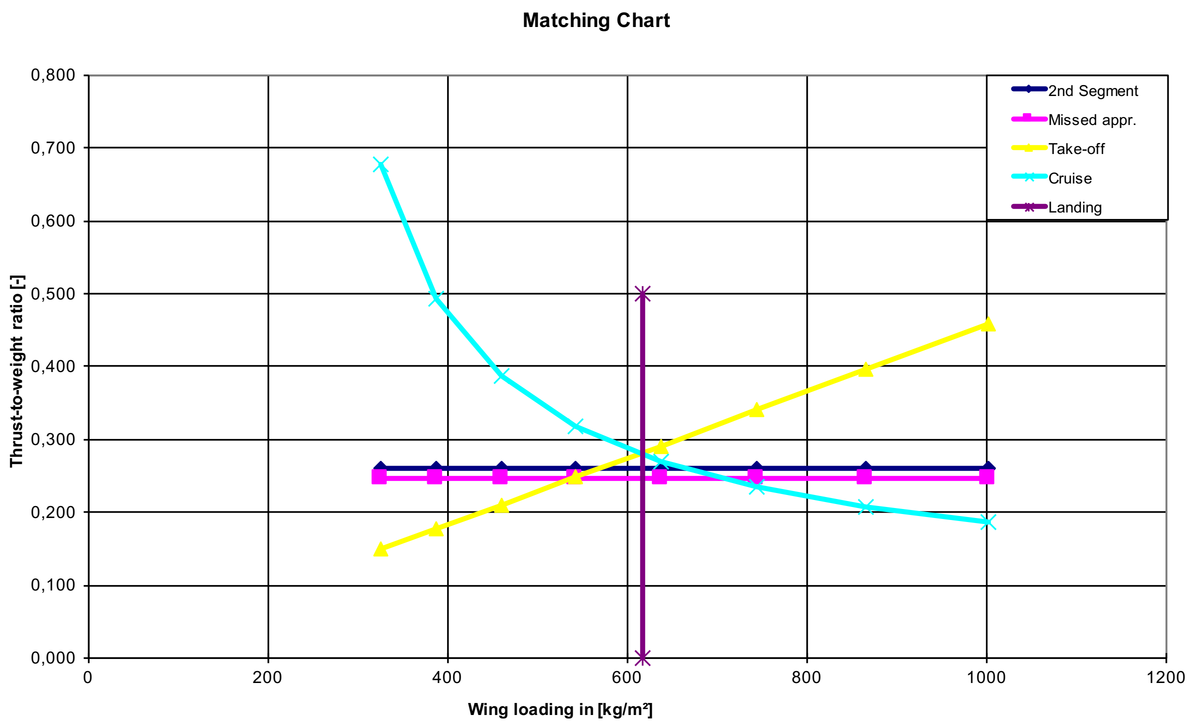
Aerodynamic efficiency

Real aircraft average	k_{WL}	**2,83**	
End plate	$k_{e,WL}$	1,05	
Span	b_W	34,09	m
Winglet height	h	**1,1**	m
Aspect ratio	A	9,49	
Effective aspect ratio	A_{eff}	9,93	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**18,9**	
RE value maximum aerodynamic efficiency		17,65	

7%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,780	
Cruise altitude	h_{CR}	11278	m
By Pass Ratio	μ	6,20	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	104,50	kN
Overall Pressure ratio	OAPR	**24,10**	
Turbine entry temperature	TET	**1443,44**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,94	
Ventilator efficiency	$\eta_{ventilator}$	0,86	
Compressor efficiency	$\eta_{compresor}$	0,86	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,98	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,66	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,66	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,18	
Verification value specific fuel consumption	SFC	0,60	kg/daN/h
Verification value specific fuel consumption	SFC	**1,66E-05**	kg/N/s
RE value specific fuel consumption (2%)	SFC	1,62E-05	kg/N/s


Matching Chart
Thrust-to-weight ratio [-]
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
200
400
600
800
1000
1200
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix H Boeing 737-700

Data Collection			737-700	Source:	1			2		3	4	5	6	7	8	9
					Aircraft characteristics for airport planning			Jane's		Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collectior	Webs
Parameter	Symbol	Units	Chosen value					A	B							
PAX			149			128-148		126-149		149-128			149	149-126		
Landing field length	s_{LFL}	m	1400			1510		1418	1433	1356			1356	1356	1400	
Approach speed	V_{APP}	m/s	67					66,3633333	66,8777778				66,94		70,478889	
Temperature above ISA (288,15K)	ΔT_L	K	0					0		0			0			
Relative density	s															
Take-off field length	s_{TOFL}	m	1800			2840		1744	1677	2042					1800	2480
Temperature above ISA (288,15K)	ΔT_{TO}	K	0			0		15		20						
Relative density	s															
Range (max payload)	R	km	2852			3920		2852	5648				6009	631		6230
Cruise Mach number	M_{CR}		0,785					0,785			0,8			0,79	0,785	0,785
Wing area	S_W	m²	124,6					125		124,6			125	124,6		
Wing span	b_W	m	34,32			34,32-35,79		34,31	35,79	34,3			34,31	34,32	34,3	35,7
Aspect ratio	A		9,45					9,4		9,44213483			9,4	9,45		
Maximum take-off mass	m_{MTO}	kg	69400		60328	69400	70080	60330	70080	69400			69399	60326	66320	70000
Payload mass	m_{PL}	kg	17010		17010		17554			11610				17010		
Mass ratio, payload - take-off	m_{PL}/m_{MTO}									0,16729107				0,282		
Maximum landing mass	m_{ML}	kg	58060		58060	58060	58604	58060	58605	58060			58059	58060		58600
Mass ratio, landing - take-off	m_{ML}/m_{MTO}									0,83659942						
Operating empty mass	m_{OE}	kg	38147			37648		38147		37585				37648		38150
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}									0,54157061				0,624		
Wing loading	m_{MTO}/S_W	kg/m²	484					482,6	560,6	556,982343				484		
Maximum zero fuel mass	m_{MZF}	kg	54658		54658		55202	54655	55200	54650				54658		
Number of engines	n_E		2							2				2	2	2
Engine type	CFM56-7B		CFM56-7B24			CFM56-7B20/-7B22/-7B24		CFM56-7B20	CFM56-7B24	CFM56-7B20	CFM56-7B20			CFM56-7B20	CFM56-7	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	101			88,9056		91,6	101	89	91,63337			91,633	89	116
Total take-off thrust	T_{TO}	kN														
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,31					0,31015446	0,29406575	0,26145173				0,31		
Bypass ratio	μ		5,6								5,6			5,6		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	1,02E-05								1,02E-05			1,02E-05		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s	1,79E-05								1,79E-05			1,79E-05		
Available fuel volume	$V_{fuel,available}$	m³	26,022			26,022		26,025		26,024				26,022		26,02
Cruise speed	V_{CR}	m/s	232							232,53					236,64444	230
Cruise altitude	h_{CR}	m	11887					12500	11700	11887,2	10668			11887		
Sweep angle	ϕ_{25}	°	25							25				25		25,02
Mean aerodynamic chord	c_{MAC}	m	4,17							4,17				4,17		
Position of maximum camber	$x_{(y\_c),max}$	%c	10													10
Camber	$(y_c)_{max}/c$	%c	0,8													0,8
Position of maximum thickness	$x_{t,max}$	%c	29,7													29,7
Relative thickness	t/c	%	12,5													12,5
Taper	λ		0,219					0,218914186		0,278				0,219		
Overall pressure ratio	OAPR		22,7								22,7					
Turbine entry temperature	TET	K														

Aeroplane Specifications

Data to apply reverse engineering

					LL	*UL*
Landing field length	**Known**	s_{LFL}	**1400**	m		
Approach speed	**Known**	V_{APP}	**67,00**	m/s	67,0	67,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**1800**	m	1800	1800
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**1540**	NM		
Cruise Mach number		M_{CR}	**0,785**			
Wing area		S_W	**125**	m²		
Wing span	**Known**	b_W	**34,32**	m²	34,32	34,32
Aspect ratio		A	9,45			
Maximum take-off mass		m_{MTO}	**69400**	kg		
Maximum payload mass		m_{PL}	**17010**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,245			
Maximum landing mass		m_{ML}	**58060**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,837			
Operating empty mass		m_{OE}	**38147**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,550			
Wing loading		m_{MTO}/S_W	557,0	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**101**	kN		
Total take-off thrust		T_{TO}	202	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,297			
Bypass ratio		μ	**5,6**			
Available fuel volume		$V_{fuel,available}$	**26,022**	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed	V_{CR}	232	m/s			
Cruise altitude	h_{CR}	11887	m			
Speed ratio	V/V_{md}	1,049	-		1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	25	°		
Mean aerodynamic chord		c_{MAC}	4,17	m		
Position of maximum camber		$x_{(y\_c),max}$	30	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	4	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	30	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	11,5	%		
Taper		λ	0,219			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1400	1400	m	0,00%
Approach speed	V_{APP}	67,00	67,0	m/s	0,00%
Take-off field length	s_{TOFL}	1800	1800	m	0,00%
Span	b_W	34,32	34,32	m	0,00%
Aspect ratio	A	9,45	9,45		0,00%
Cruise speed	V_{CR}	232,0	232	m/s	-0,14%
Cruise altitude	h_{CR}	11887	11887	m	0,00%
Squared Sum					**2,07E-06**
Absolute maximum deviation					0,1%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	3,11	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	2,44	
Maximum aerodynamic efficiency	E_{max}	17,99	
Specific fuel consumption	SFC	1,72E-05	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1400	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	67,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,84	
Wing loading at maximum take-off mass	m_{MTO}/S_W	557,0	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,11**	

Take-off

Take-off field length	s_{TOFL}	1800	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,297	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,44**	

2nd Segment

Aspect ratio	A	9,453
Lift coefficient, take-off	$C_{L,TO}$	1,69
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,030
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,050
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	9,02
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,270

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,84
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,037
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,072
Glide ratio in landing configuration	E_L	7,83
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,249

2) Maximum Aerodynamic Efficiency

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications

Mach number, cruise	M_{CR}	0,785	
Aspect ratio	A	9,45	
Bypass ratio	μ	5,60	
Wing loading	m_{MTO}/S_W	557	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,297	

Variables

	V/V_{md}	**1,0**

Calculations

Zero-lift drag coefficient	$C_{D,0}$	0,020
Lift coefficient at E_{max}	$C_{L,md}$	0,70
Ratio, lift coefficient	$C_L/C_{L,md}$	0,908
Lift coefficient, cruise	C_L	0,637
Actual aerodynamic efficiency, cruise	E	17,90
Max. glide ratio, cruise	E_{max}	**17,99**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,22	-0,01	0,00
f'(x)	-0,11	-0,12	-0,11
E_{max}	16	18,06	17,99

3) Specific Fuel Consumption

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications

Range	R	1540	NM
Mach number, cruise	M_{CR}	0,785	
Bypass ratio	μ	5,60	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,297	
Available fuel volume	$V_{fuel,available}$	26,022	m³
Maximum take-off mass	m_{MTO}	69400	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,245	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,550	

Calculated values

Actual aerodynamic efficiency, cruise	E	17,90	
Cruise altitude	h_{CR}	11887	m
Cruise speed	V_{CR}	232	m/s

Mission fuel fraction

Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations

Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,205	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,795	
Available fuel mass	$m_{F,available}$	20817,6	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,300	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,714	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,72E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	34,32	m
Structural wing span	$b_{W,struct}$	37,87	m
Wing area	S_W	124,6	m²
Aspect ratio	A	9,45	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	4,17	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,5	%
Taper	λ	0,219	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	67,00	m/s
Mach number, landing	M_{APP}	0,20	
Mach number, cruise	M_{CR}	0,785	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,1	%c
Leading edge sweep	φ_{LE}	28,9	°
Reynoldsnumber	Re	2,0E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,25	
Correction term, camber	$\Delta_1 c_{L,max}$	0,40	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,036	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,693	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,87	
Correction term, Mach number	$\Delta C_{L,max}$	0,00	
Lift coefficient, wing	$C_{L,max}$	1,47	

Calculations increase of lift coefficient due to flaps		**2 flap types**
Correction factor, sweep	K_φ	0,87
• Flap group A		
Double-slotted flap	$\Delta c_{L,max,fA}$	1,44
Use flapped span	b_W,fA	**6,9** m
Percentage of flaps allong the wing		18%
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,23
• Flap group B		
Double-slotted flap	$\Delta c_{L,max,fB}$	1,44
Use flapped span	b_W,fB	**11,8** m
Percentage of flaps allong the wing		31%
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,39
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,62

Calculations increase of lift coefficient due to slats		**2 slat types**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**27** °
• Slat group A		
0,1c Kruger flap	$\Delta c_{L,max,sA}$	0,67
Use slatted span	b_W,sA	**4,5** m
Percentage of slats allong the wing		12%
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,07
• Slat group B		
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,91
Use slatted span	b_W,sB	**25,4** m
Percentage of slats allong the wing		67%
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,54
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,61

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,67**
RE value maximum lift coefficient, landing		3,11
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,09**
RE value maximum lift coefficient, take-off		2,44

-14%

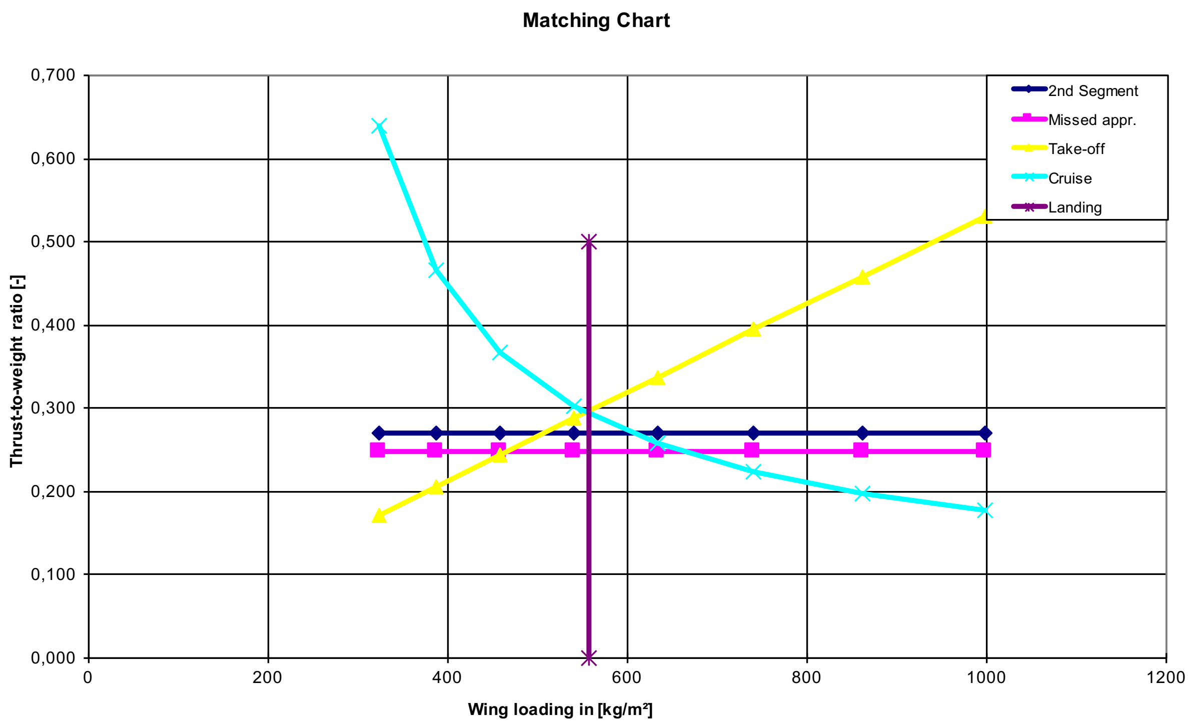
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83
End plate	$k_{e,WL}$	1,11
Span	b_W	34,32 m
Winglet height	h	**2,49** m
Aspect ratio	A	9,45
Effective aspect ratio	A_{eff}	10,45
Efficiency factor, short range	k_E	15,15
Relative wetted area	S_{wet}/S_W	**6,35**
Verification value maximum aerodynamic efficiency	E_{max}	**19,4**
RE value maximum aerodynamic efficiency		17,99

8%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,785	
Cruise altitude	h_{CR}	11887	m
By Pass Ratio	μ	5,60	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	101,00	kN
Overall Pressure ratio	OAPR	**22,70**	
Turbine entry temperature	TET	**1440,79**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,86	
Compressor efficiency	$\eta_{compresor}$	0,86	
Turbine efficiency	$\eta_{turbine}$	0,89	
Nozzle efficiency	η_{nozzle}	0,98	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,65	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,62	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,18	
Verification value specific fuel consumption	SFC	0,62	kg/daN/h
Verification value specific fuel consumption	SFC	**1,71E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,72E-05	kg/N/s
0%			


Matching Chart
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix I Boeing 777-300ER

Data Collection			777-300ER	1	2	3	4		5	6	7	8	9
			Source:	Aircraft characteristics for airport planning	Jane's	Jenkinson	Engine		Scholz	Paul Müller	Elodie Roux	Data collectior	Webs
Parameter	Symbol	Units	Chosen value										
PAX			370	339-370	339-370						550-370		
Landing field length	s_{LFL}	m	1844	1770	1844							1800	
Approach speed	V_{APP}	m/s	77		77,17							76,652222	
Temperature above ISA (288,15K)	ΔT_L	K	0	0									
Relative density	s												
Take-off field length	s_{TOFL}	m	3050	3048	3200							3000	3200
Temperature above ISA (288,15K)	ΔT_{TO}	K	0	0	15								
Relative density	s												
Range (max payload)	R	km	9275	10510	11556						9275		14690
Cruise Mach number	M_{CR}		0,84	0,84	0,84						0,84	0,84	0,84
Wing area	S_W	m²	427,8		427,8								
Wing span	b_W	m	64,79	64,8	64,8						64,79	64,8	64,8
Aspect ratio	A		8,7		8,7								
Maximum take-off mass	m_{MTO}	kg	351535	351535	345050						345047	351530	351500
Payload mass	m_{PL}	kg	69853	69853							69853		
Mass ratio, payload - take-off	m_{PL}/m_{MTO}										0,202		
Maximum landing mass	m_{ML}	kg	251290	251290	251290						251290		251290
Mass ratio, landing - take-off	m_{ML}/m_{MTO}												
Operating empty mass	m_{OE}	kg	167829	167829	167830						167829		167800
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}										0,486		
Wing loading	m_{MTO}/S_W	kg/m²	615		614,9								
Maximum zero fuel mass	m_{MZF}	kg	237682	237683	237680						237682		
Number of engines	n_E		2								2	2	2
Engine type	GE90		GE90-115B	GE90-115B1	GE90-115B1		GE90-115B	Trent 892-17			GE90-115B	GE90-115B	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	511,5	512,5302	512		511,54553	406,7899			511,543	511	514
Total take-off thrust	T_{TO}	kN											
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,3		0,30279174						0,3		
Bypass ratio	μ		7,2					5,79			7,2		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s											
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s											
Available fuel volume	$V_{fuel,available}$	m³	181,283	181,283	181,283						181,264		181,283
Cruise speed	V_{CR}	m/s	252									252,07778	251,39
Cruise altitude	h_{CR}	m	10668		9845						10668		
Sweep angle	ϕ_{25}	°	31,64										31,64
Mean aerodynamic chord	c_{MAC}	m											
Position of maximum camber	$x_{(y\_c),max}$	%c	30										30
Camber	$(y_c)_{max}/c$	%c	5,9										5,9
Position of maximum thickness	$x_{t,max}$	%c	30										30
Relative thickness	t/c	%	22										22
Taper	λ												
Overall pressure ratio	OAPR		42				42	40,8					
Turbine entry temperature	TET	K											

Aeroplane Specifications

Data to apply reverse engineering

					LL	*UL*
Landing field length	**Known**	s_{LFL}	**1844**	m		
Approach speed	**Known**	V_{APP}	**77,00**	m/s	77,0	77,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**3050**	m	3050	3050
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**5008**	NM		
Cruise Mach number		M_{CR}	**0,84**			
Wing area		S_W	**428**	m²		
Wing span	**Known**	b_W	**64,79**	m²	64,79	64,79
Aspect ratio		A	9,81			
Maximum take-off mass		m_{MTO}	**351535**	kg		
Maximum payload mass		m_{PL}	**69853**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,199			
Maximum landing mass		m_{ML}	**251290**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,715			
Operating empty mass		m_{OE}	**167829**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,477			
Wing loading		m_{MTO}/S_W	821,7	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**511,5**	kN		
Total take-off thrust		T_{TO}	1023	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,297			
Bypass ratio		μ	**7,2**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	**252**	m/s		
Cruise altitude	h_{CR}	**10668**	m		
Speed ratio	V/V_{md}	**1,094**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**31,64**	°		
Mean aerodynamic chord		c_{MAC}	**4,2**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**5,9**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**10,8**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1844	1844	m	0,00%
Approach speed	V_{APP}	77,00	77,0	m/s	0,00%
Take-off field length	s_{TOFL}	3050	3050	m	0,00%
Span	b_W	64,79	64,79	m	0,00%
Aspect ratio	A	9,81	9,81		0,00%
Cruise speed	V_{CR}	252,0	249	m/s	-1,11%
Cruise altitude	h_{CR}	10668	10649	m	-0,17%
Squared Sum					**1,27E-04**
Absolute maximum deviation					1,1%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,98**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,13**	
Maximum aerodynamic efficiency	E_{max}	**16,25**	
Specific fuel consumption	SFC	**1,22E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1844	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	77,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,71	
Wing loading at maximum take-off mass	m_{MTO}/S_W	821,7	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,98**	

Take-off

Take-off field length	s_{TOFL}	3050	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,297	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,13**	

2nd Segment

Aspect ratio	A	9,812
Lift coefficient, take-off	$C_{L,TO}$	1,48
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,019
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,039
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	10,56
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,237

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,76
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,033
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,068
Glide ratio in landing configuration	E_L	8,31
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,202

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,84	
Aspect ratio	A	9,81	
Bypass ratio	μ	7,20	
Wing loading	m_{MTO}/S_W	822	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,297	

Variables		
	V/V_{md}	**1,1**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,025
Lift coefficient at E_{max}	$C_{L,md}$	0,81
Ratio, lift coefficient	$C_L/C_{L,md}$	0,836
Lift coefficient, cruise	C_L	0,674
Actual aerodynamic efficiency, cruise	E	15,99
Max. glide ratio, cruise	E_{max}	**16,25**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,03	0,00	0,00
f'(x)	-0,12	-0,12	-0,12
E_{max}	16	16,25	16,25

3) Specific Fuel Consumption

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications

Range	R	5008	NM
Mach number, cruise	M_{CR}	0,84	
Bypass ratio	μ	7,20	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,297	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	351535	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,199	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,477	

Calculated values

Actual aerodynamic efficiency, cruise	E	15,99	
Cruise altitude	h_{CR}	10649	m
Cruise speed	V_{CR}	249	m/s

Mission fuel fraction

Type of aeroplane (according to Roskam)	**Transport jet**	
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980
Fuel-Fraction, descent	$M_{ff,DES}$	0,990
Fuel-Fraction, landing	$M_{ff,L}$	0,992

Calculations

Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,324	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,676	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,054	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,965	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**no**	
	international	**yes**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	834141	m
Loiter time	t_{loiter}	1800	s
Specific fuel consumption	SFC	**1,22E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	64,79	m
Structural wing span	$b_{W,struct}$	76,10	m
Wing area	S_W	427,8	m²
Aspect ratio	A	9,81	
Sweep	φ_{25}	31,64	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	5,9	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	10,8	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	77,00	m/s
Mach number, landing	M_{APP}	0,23	
Mach number, cruise	M_{CR}	0,84	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,0	%c
Leading edge sweep	φ_{LE}	35,2	°
Reynoldsnumber	Re	2,3E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,19	
Correction term, camber	$\Delta_1 c_{L,max}$	0,55	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,066	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,805	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,90	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,61	

Calculations increase of lift coefficient due to flaps		**2 flap types**	
Correction factor, sweep	K_{φ}	0,83	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,57	
Use flapped span	b_W,fA	**11,4**	m
Percentage of flaps allong the wing		15%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,20	
• Flap group B			
Single-slotted flap	$\Delta c_{L,max,fB}$	0,86	
Use flapped span	b_W,fB	**26,7**	m
Percentage of flaps allong the wing		35%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,25	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,45	

Calculations increase of lift coefficient due to slats		**2 slat types**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**34**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	1,00	
Use slatted span	b_W,sA	**12,2**	m
Percentage of slats allong the wing		16%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,13	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	1,00	
Use slatted span	b_W,sB	**45,2**	m
Percentage of slats allong the wing		59%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,49	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,62	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,65**
RE value maximum lift coefficient, landing		2,98
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,89**
RE value maximum lift coefficient, take-off		2,13
-11%		

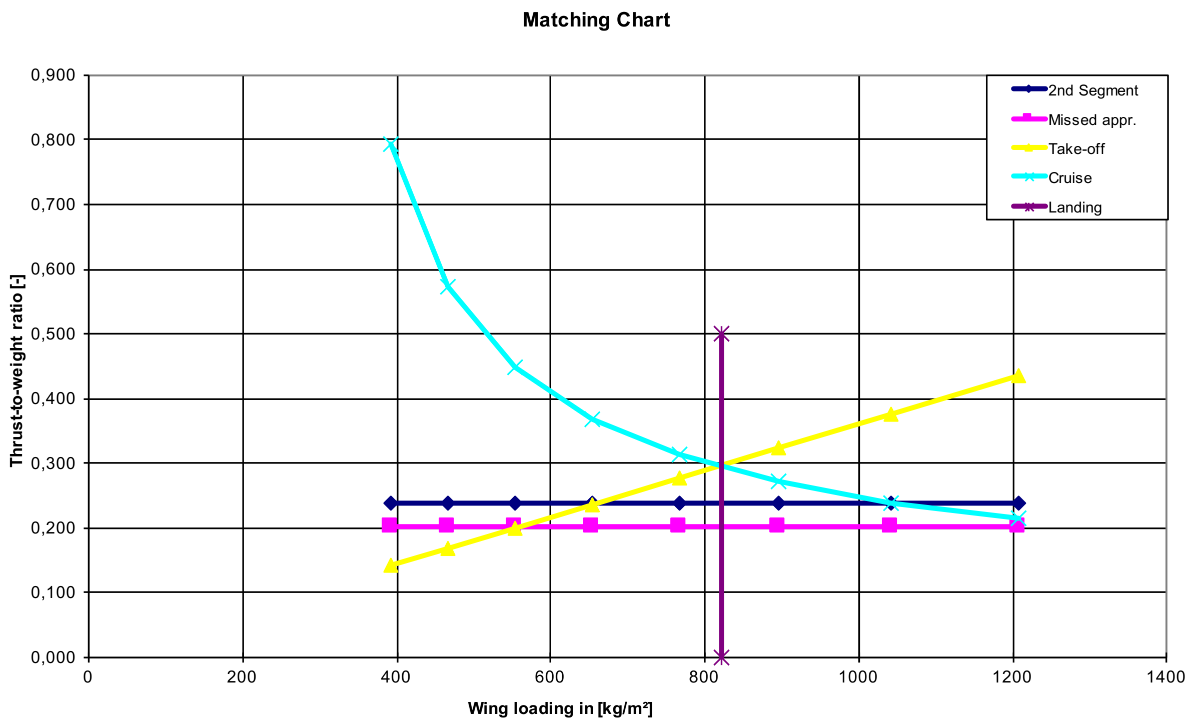
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,04	
Span	b_W	64,79	m
Winglet height	h	**2**	m
Aspect ratio	A	9,81	
Effective aspect ratio	A_{eff}	10,25	
Efficiency factor, short range	k_E	16,19	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**20,6**	
RE value maximum aerodynamic efficiency		16,25	
27%			

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,840	
Cruise altitude	h_{CR}	10668	m
By Pass Ratio	μ	7,20	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	511,50	kN
Overall Pressure ratio	OAPR	**42,00**	
Turbine entry temperature	TET	**1504,36**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,94	
Ventilator efficiency	$\eta_{ventilator}$	0,90	
Compressor efficiency	$\eta_{compresor}$	0,88	
Turbine efficiency	$\eta_{turbine}$	0,91	
Nozzle efficiency	η_{nozzle}	1,00	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,81	K
Dimensionless turbine entry temperature	ϕ	6,88	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,14	
Temperature function	χ	2,18	
Gas generator efficiency	η_{gasgen}	0,97	
Gas generator function	G	2,15	
Verification value specific fuel consumption	SFC	0,54	kg/daN/h
Verification value specific fuel consumption	SFC	**1,49E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,22E-05	kg/N/s

22%



Matching Chart
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
1400
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix J Airbus A330-300

Data Collection			A330-300	Source:	1		2		3	4	5	6	7		8	9
					Aircraft characteristics for airport planning		Jane's		Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux		Data collectior	Webs
Parameter	Symbol	Units	Chosen value		WV026	WV082	Basic	Option								
PAX			375		300		375-379		440-335-295			412	375-295			
Landing field length	s_{LFL}	m	1750		1750	1820			1600			1815	1600		1700	
Approach speed	V_{APP}	m/s	70		70,5				69,96			72,22			66,877778	
Temperature above ISA (288,15K)	ΔT_L	K	0		0				0			0				
Relative density	s															
Take-off field length	s_{TOFL}	m	2320		2300	3660	2515	2606	2320				2320		2300	2500
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0		15		0							
Relative density	s															
Range (max payload)	R	km	7000		7700		10371		7200,6			6500	6297			11750
Cruise Mach number	M_{CR}		0,82				0,82						0,82		0,81	0,82
Wing area	S_W	m²	361,6				361,6		363,1			363,1	363,1			361,6
Wing span	b_W	m	60,3		60,3		63,68		58			60,3	60,3		60,3	60,3
Aspect ratio	A		10,01						9,26466538			10	10,02			
Maximum take-off mass	m_{MTO}	kg	242000		217000	242000	230000	233000	217000			230000	230000		230000	242000
Payload mass	m_{PL}	kg	48400		45300		48400		48400				53269			45900
Mass ratio, payload - take-off	m_{PL}/m_{MTO}								0,22304147				0,232			
Maximum landing mass	m_{ML}	kg	185000		185000	187000	185000	187000	179000			177000	185000			187000
Mass ratio, landing - take-off	m_{ML}/m_{MTO}								0,82488479							
Operating empty mass	m_{OE}	kg	124600				124600		118189				119731			124000
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}								0,54464977				0,521			
Wing loading	m_{MTO}/S_W	kg/m²	633				633,4	644,4	597,631506				633			
Maximum zero fuel mass	m_{MZF}	kg	173000		173000	175000	173000	175000	169000				173000			175000
Number of engines	n_E		2						2				2			2
Engine type	GE CF6 (17%), PW4000		Trent 772-60		RR TRENT 700 Series		R-R Trent 772-60/772B-60A		CF6-80E1A2	Trent 768-60			CF6-80E1A2	Trent 772-60	GE CF6-80E1	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	316,267				316		300	300,255			287,055	316,267	306	320
Total take-off thrust	T_{TO}	kN														
Thrust to weight ratio	$T_{TO}/(m_{MTO}{*}g)$		0,28						0,2818529				0,25	0,28		
Bypass ratio	μ		4,89							4,97			5,3	4,89		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s											0,00000935			
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s	1,60E-05										0,0000159	1,60E-05		
Available fuel volume	$V_{fuel,available}$	m³	97,53		97,53		97,885		98,25				97,53			139,09
Cruise speed	V_{CR}	m/s					185,2		239,2-257,2						244,36111	241,94
Cruise altitude	h_{CR}	m	11887						11887,2-10058,4				11887			
Sweep angle	ϕ_{25}	°	29,7						29,7				29,7			30
Mean aerodynamic chord	c_{MAC}	m	7,28						7,26				7,28			
Position of maximum camber	$x_{(y\_c),max}$	%c														
Camber	$(y_c)_{max}/c$	%c														
Position of maximum thickness	$x_{t,max}$	%c														
Relative thickness	t/c	%	15,3-11,3-10,6										15,3-11,3-10,6			
Taper	λ		0,235						0,251				0,235			
Overall pressure ratio	OAPR		36,8							35,2				36,8		
Turbine entry temperature	TET	K														

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1750**	m		
Approach speed	**Known**	V_{APP}	**70,00**	m/s	70,0	70,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2320**	m	2320	2320
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**3780**	NM		
Cruise Mach number		M_{CR}	**0,82**			
Wing area		S_W	**362**	m²		
Wing span	**Known**	b_W	**60,3**	m²	60,3	60,3
Aspect ratio		A	10,06			
Maximum take-off mass		m_{MTO}	**242000**	kg		
Maximum payload mass		m_{PL}	**48400**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,200			
Maximum landing mass		m_{ML}	**185000**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,764			
Operating empty mass		m_{OE}	**124600**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,515			
Wing loading		m_{MTO}/S_W	669,2	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**316,267**	kN		
Total take-off thrust		T_{TO}	632,534	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,266			
Bypass ratio		μ	**4,89**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed		V_{CR}	**242**	m/s		
Cruise altitude		h_{CR}	**11887**	m		
Speed ratio		V/V_{md}	**1,000**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**25**	°		
Mean aerodynamic chord		c_{MAC}	**4,2**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,1**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1750	1750	m	0,00%
Approach speed	V_{APP}	70,00	70,0	m/s	0,00%
Take-off field length	s_{TOFL}	2320	2320	m	0,00%
Span	b_W	60,3	60,3	m	0,00%
Aspect ratio	A	10,06	10,06		0,00%
Cruise speed	V_{CR}	242,0	242	m/s	0,00%
Cruise altitude	h_{CR}	11887	11867	m	-0,17%
Squared Sum					**2,97E-06**
Absolute maximum deviation					0,2%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,73**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,53**	
Maximum aerodynamic efficiency	E_{max}	**19,19**	
Specific fuel consumption	SFC	**1,55E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing			
Landing field length	s_{LFL}	1750	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	70,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,76	
Wing loading at maximum take-off mass	m_{MTO}/S_W	669,2	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,73**	

Take-off			
Take-off field length	s_{TOFL}	2320	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,266	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,53**	

2nd Segment		
Aspect ratio	A	10,056
Lift coefficient, take-off	$C_{L,TO}$	1,76
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,033
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,053
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	9,12
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,267

Missed approach		
Lift coefficient, landing	$C_{L,L}$	1,62
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,026
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,061
Glide ratio in landing configuration	E_L	9,03
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,201

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,82	
Aspect ratio	A	10,06	
Bypass ratio	μ	4,89	
Wing loading	m_{MTO}/S_W	669	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,266	

Variables		
	V/V_{md}	**1,0**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,018
Lift coefficient at E_{max}	$C_{L,md}$	0,70
Ratio, lift coefficient	$C_L/C_{L,md}$	1,000
Lift coefficient, cruise	C_L	0,700
Actual aerodynamic efficiency, cruise	E	19,19
Max. glide ratio, cruise	E_{max}	**19,19**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,32	-0,02	0,00
f'(x)	-0,10	-0,11	-0,11
E_{max}	16	19,39	19,19

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	3780	NM
Mach number, cruise	M_{CR}	0,82	
Bypass ratio	μ	4,89	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,266	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	242000	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,200	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,515	

Calculated values			
Actual aerodynamic efficiency, cruise	E	19,19	
Cruise altitude	h_{CR}	11867	m
Cruise speed	V_{CR}	242	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,285	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,715	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,079	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,940	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,55E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 4 digit**	
Wing span	b_W	60,3	m
Structural wing span	$b_{W,struct}$	66,53	m
Wing area	S_W	361,6	m²
Aspect ratio	A	10,06	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,1	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	70,00	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,82	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,9	%c
Leading edge sweep	φ_{LE}	28,5	°
Reynoldsnumber	Re	2,1E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,55	
Correction term, camber	$\Delta_1 c_{L,max}$	0,22	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,060	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,825	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,80	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,45	

Calculations increase of lift coefficient due to flaps			1 flap type
Correction factor, sweep	K_φ	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,42	
Use flapped span	b_W,fA	40,1	m
Percentage of flaps allong the wing		60%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,74	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,74	
Use flapped span	b_W,fB	0	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,74	

Calculations increase of lift coefficient due to slats			2 slat types
Sweep angle of the hinge line	$\varphi_{H.L.}$	32	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,90	
Use slatted span	b_W,sA	10,3	m
Percentage of slats allong the wing		15%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,12	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	43,1	m
Percentage of slats allong the wing		65%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,49	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,61	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	2,77
RE value maximum lift coefficient, landing		2,73
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	2,57
RE value maximum lift coefficient, take-off		2,53

1%

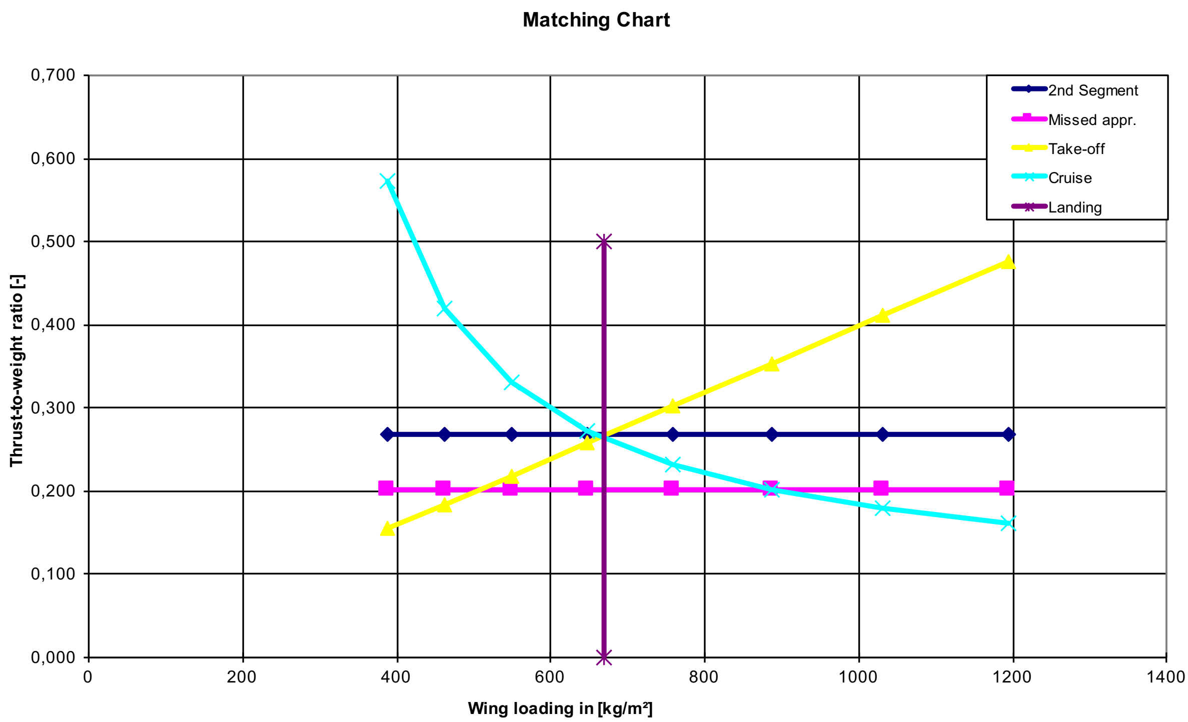
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,07	
Span	b_W	60,3	m
Winglet height	h	2,74	m
Aspect ratio	A	10,06	
Effective aspect ratio	A_{eff}	10,71	
Efficiency factor, short range	k_E	16,19	
Relative wetted area	S_{wet}/S_W	6,35	
Verification value maximum aerodynamic efficiency	E_{max}	21,0	
RE value maximum aerodynamic efficiency		19,19	

10%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,820	
Cruise altitude	h_{CR}	11887	m
By Pass Ratio	μ	4,89	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	316,27	kN
Overall Pressure ratio	OAPR	**36,80**	
Turbine entry temperature	TET	**1494,70**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,89	
Compressor efficiency	$\eta_{compresor}$	0,87	
Turbine efficiency	$\eta_{turbine}$	0,91	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,90	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,13	
Temperature function	χ	2,04	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,22	
Verification value specific fuel consumption	SFC	0,56	kg/daN/h
Verification value specific fuel consumption	SFC	**1,57E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,55E-05	kg/N/s
1%			


Matching Chart
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
1400
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix K Boeing 787-9

Data Collection			787-9		1		2	3	4		5	6	7	8	9	
				Source:	Aircraft characteristics for airport planning		Jane's	Jenkinson	Engine		Scholz	Paul Müller	Elodie Roux	Data collection	Webs	
Parameter	Symbol	Units	Chosen value		GE	RR										
PAX			420		290-406-420		280									389-222
Landing field length	s_{LFL}	m	1870		1870											
Approach speed	V_{APP}	m/s														
Temperature above ISA (288,15K)	ΔT_L	K	0		0											
Relative density	s															
Take-off field length	s_{TOFL}	m	3140		3020											3140
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0											
Relative density	s															
Range (max payload)	R	km	9720		9720		15927									15750
Cruise Mach number	M_{CR}		0,85		0,85		0,85							0,85		0,85
Wing area	S_W	m²	325													325
Wing span	b_W	m	60,12		60,12		63,35							60,1		60,1
Aspect ratio	A		11,1													
Maximum take-off mass	m_{MTO}	kg	254011		254011		244950							253000		250836
Payload mass	m_{PL}	kg	65325		66086		65325									
Mass ratio, payload - take-off	m_{PL}/m_{MTO}															
Maximum landing mass	m_{ML}	kg	192776		192776		190950									192777
Mass ratio, landing - take-off	m_{ML}/m_{MTO}															
Operating empty mass	m_{OE}	kg	115350				115350									
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}															
Wing loading	m_{MTO}/S_W	kg/m²														
Maximum zero fuel mass	m_{MZF}	kg	181436		181436		179625									181437
Number of engines	n_E		2						2					2		2
Engine type	GE GEnx-1B (49%), RR		GEnx-1B74				Genx/Trent 1000		GEnx 72A1	Trent 1000				GEnx-1B	GEnx-1B74/75	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	330				235-311		235,7558	235,756				320	329,61325	320
Total take-off thrust	T_{TO}	kN														
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$															
Bypass ratio	μ		9				9,0-12,0			11					8,8-8,1	
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s														
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s														
Available fuel volume	$V_{fuel,available}$	m³	126,429		126,429		126,917									138,7
Cruise speed	V_{CR}	m/s	252											252,07778		253,61
Cruise altitude	h_{CR}	m														
Sweep angle	ϕ_{25}	°	32,2													32,2
Mean aerodynamic chord	c_{MAC}	m														
Position of maximum camber	$x_{(y\_c),max}$	%c														
Camber	$(y_c)_{max}/c$	%c														
Position of maximum thickness	$x_{t,max}$	%c														
Relative thickness	t/c	%														
Taper	λ															
Overall pressure ratio	OAPR		55,4												46,3-55,4	
Turbine entry temperature	TET	K														

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1870**	m		
Approach speed	**Unknown**	V_{APP}	70,00	m/s	73,6	73,6
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**3140**	m	3140	3140
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**5248**	NM		
Cruise Mach number		M_{CR}	**0,85**			
Wing area		S_W	**325**	m²		
Wing span	**Known**	b_W	**60,12**	m²	60,12	60,12
Aspect ratio		A	11,12			
Maximum take-off mass		m_{MTO}	**254011**	kg		
Maximum payload mass		m_{PL}	**65325**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,257			
Maximum landing mass		m_{ML}	**192776**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,759			
Operating empty mass		m_{OE}	**115350**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,454			
Wing loading		m_{MTO}/S_W	781,6	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**330**	kN		
Total take-off thrust		T_{TO}	660	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,265			
Bypass ratio		μ	**9**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	**252**	m/s		
Cruise altitude	h_{CR}	**10668**	m		
Speed ratio	V/V_{md}	**1,086**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**25**	°		
Mean aerodynamic chord		c_{MAC}	**4,2**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**10,6**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1870	1870	m	0,00%
Approach speed	V_{APP}	Unknown	**73,6**	m/s	0,00%
Take-off field length	s_{TOFL}	3140	3140	m	0,00%
Span	b_W	60,12	60,12	m	0,00%
Aspect ratio	A	11,12	11,12		0,00%
Cruise speed	V_{CR}	252,0	252	m/s	0,04%
Cruise altitude	h_{CR}	10668	10669	m	0,01%
Squared Sum					**1,40E-07**
Absolute maximum deviation					0,0%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,96**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,20**	
Maximum aerodynamic efficiency	E_{max}	**20,08**	
Specific fuel consumption	SFC	**1,23E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing			
Landing field length	s_{LFL}	1870	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	73,59	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,76	
Wing loading at maximum take-off mass	m_{MTO}/S_W	781,6	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,96**	

Take-off			
Take-off field length	s_{TOFL}	3140	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,265	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,20**	

2nd Segment		
Aspect ratio	A	11,121
Lift coefficient, take-off	$C_{L,TO}$	1,53
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,021
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,041
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	11,17
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,227

Missed approach		
Lift coefficient, landing	$C_{L,L}$	1,75
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,033
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,068
Glide ratio in landing configuration	E_L	9,06
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,199

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,85	
Aspect ratio	A	11,12	
Bypass ratio	μ	9,00	
Wing loading	m_{MTO}/S_W	782	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,265	

Variables		
	V/V_{md}	**1,1**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,018
Lift coefficient at E_{max}	$C_{L,md}$	0,74
Ratio, lift coefficient	$C_L/C_{L,md}$	0,848
Lift coefficient, cruise	C_L	0,627
Actual aerodynamic efficiency, cruise	E	19,81
Max. glide ratio, cruise	E_{max}	**20,08**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,37	-0,03	0,00
f'(x)	-0,08	-0,10	-0,10
E_{max}	16	20,39	20,08

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	5248	NM
Mach number, cruise	M_{CR}	0,85	
Bypass ratio	μ	9,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,265	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	254011	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,257	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,454	

Calculated values			
Actual aerodynamic efficiency, cruise	E	19,81	
Cruise altitude	h_{CR}	10669	m
Cruise speed	V_{CR}	252	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,289	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,711	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,075	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,944	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**no**	
	international	**yes**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	856365	m
Loiter time	t_{loiter}	1800	s
Specific fuel consumption	SFC	**1,23E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 4 digit**	
Wing span	b_W	60,12	m
Structural wing span	$b_{W,struct}$	66,34	m
Wing area	S_W	325,0	m²
Aspect ratio	A	11,12	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	10,6	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	73,59	m/s
Mach number, landing	M_{APP}	0,22	
Mach number, cruise	M_{CR}	0,85	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,8	%c
Leading edge sweep	φ_{LE}	28,2	°
Reynoldsnumber	Re	2,2E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,52	
Correction term, camber	$\Delta_1 c_{L,max}$	0,25	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,045	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,816	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,80	
Correction term, Mach number	$\Delta C_{L,max}$	-0,02	
Lift coefficient, wing	$C_{L,max}$	1,44	

Calculations increase of lift coefficient due to flaps		**1 flap type**	
Correction factor, sweep	K_{φ}	0,87	
• Flap group A			
0,4c Single-slotted fowler flap	$\Delta c_{L,max,fA}$	2,01	
Use flapped span	b_W,fA	**40,7**	m
Percentage of flaps allong the wing		61%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	1,07	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,74	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	1,07	
Calculations increase of lift coefficient due to slats		**2 slat types**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**34,5**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,89	
Use slatted span	b_W,sA	**13,36**	m
Percentage of slats allong the wing		20%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,15	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,89	
Use slatted span	b_W,sB	**40,08**	m
Percentage of slats allong the wing		60%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,44	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,59	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**3,04**
RE value maximum lift coefficient, landing		2,96
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,26**
RE value maximum lift coefficient, take-off		2,20

3%

Aerodynamic efficiency

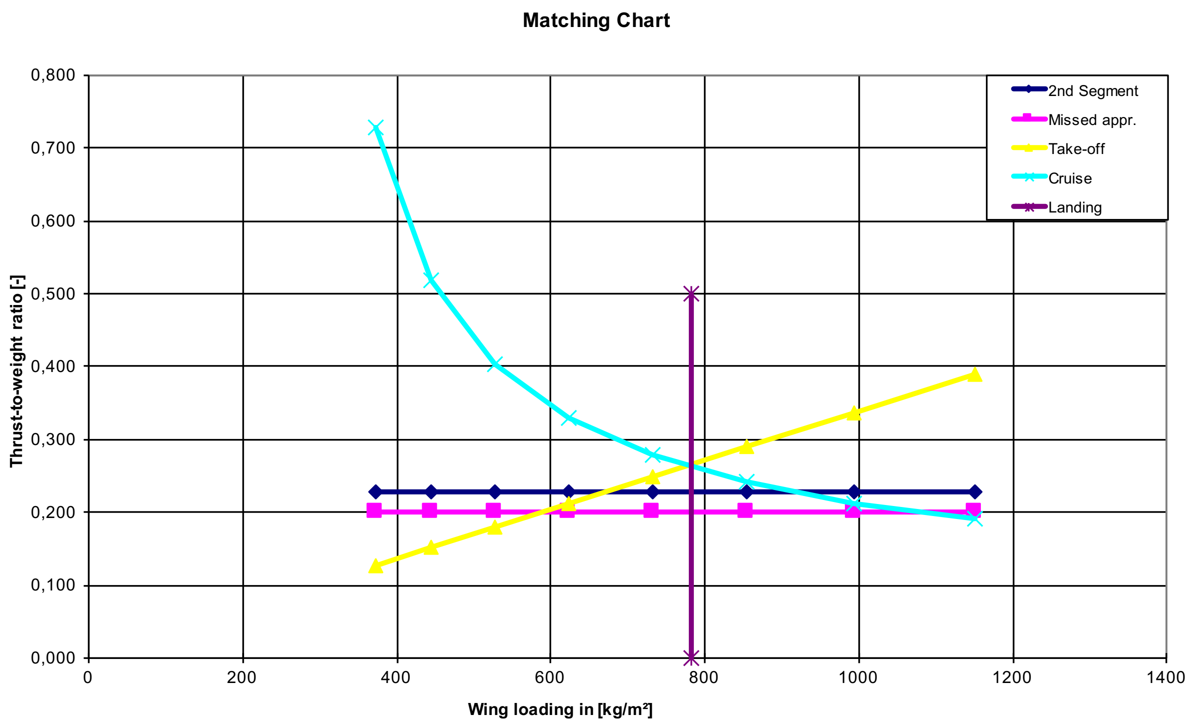
Real aircraft average	k_{WL}	2,83	
End plate (kWL = 2,13)	$k_{e,WL}$	1,41	
Span	b_W	60,12	m
Winglet height	h	**2,7**	m
Aspect ratio	A	11,12	
Effective aspect ratio	A_{eff}	15,68	
Efficiency factor, short range	k_E	16,19	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**25,4**	
RE value maximum aerodynamic efficiency		20,08	

27%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,850	
Cruise altitude	h_{CR}	10668	m
By Pass Ratio	μ	9,00	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	330,00	kN
Overall Pressure ratio	OAPR	**55,40**	
Turbine entry temperature	TET	**1495,76**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,93	
Ventilator efficiency	$\eta_{ventilator}$	0,90	
Compressor efficiency	$\eta_{compresor}$	0,88	
Turbine efficiency	$\eta_{turbine}$	0,91	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,81	K
Dimensionless turbine entry temperature	ϕ	6,84	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,14	
Temperature function	χ	2,46	
Gas generator efficiency	η_{gasgen}	0,97	
Gas generator function	G	1,94	
Verification value specific fuel consumption	SFC	0,54	kg/daN/h
Verification value specific fuel consumption	SFC	**1,50E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,23E-05	kg/N/s

21%


Matching Chart
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
1400
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix L Airbus A350-900

Data Collection			A350-900		1		2	3	4	5	6	7	8	9
				Source:	Aircraft characteristics for airport planning		Jane's	Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collectior	Webs
Parameter	Symbol	Units	Chosen value		WV000	WV022								
PAX			315		315							314		
Landing field length	s_{LFL}	m	1960		1960								888	
Approach speed	V_{APP}	m/s	72		72								79,738889	
Temperature above ISA (288,15K)	ΔT_L	K	0		0									
Relative density	s													
Take-off field length	s_{TOFL}	m	2830		2830									
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0									
Relative density	s													
Range (max payload)	R	km	10000		10800		15000					8900		15000
Cruise Mach number	M_{CR}		0,85				0,85					0,85	0,85	0,85
Wing area	S_W	m²	443				443					443		443
Wing span	b_W	m	64,75		64,75		64					64	64,75	64,75
Aspect ratio	A		9,25									9,25		
Maximum take-off mass	m_{MTO}	kg	265000		268000	280000	265000					265000	268000	280000
Payload mass	m_{PL}	kg	49800			54000						49800		
Mass ratio, payload - take-off	m_{PL}/m_{MTO}											0,188		
Maximum landing mass	m_{ML}	kg	202500		205000		202500					202500		207000
Mass ratio, landing - take-off	m_{ML}/m_{MTO}													
Operating empty mass	m_{OE}	kg	130700									130700		115700
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}											0,493		
Wing loading	m_{MTO}/S_W	kg/m²	598				598,2					598		
Maximum zero fuel mass	m_{MZF}	kg	189500		192000	194000	189500					180500		195700
Number of engines	n_E		2				2		2			2	2	2
Engine type	RR Trent XWB		Trent XWB-83				RR Trent XWB-74/-83/-92		Trent 1000			GEnx 1A72	Trent XWB	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	369				329/369/409		235,7558			320	374	374
Total take-off thrust	T_{TO}	kN												
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,25						0,18			0,25		
Bypass ratio	μ		8,9						10,8			8,9		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s												
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s												
Available fuel volume	$V_{fuel,available}$	m³	138		138		138					150		141
Cruise speed	V_{CR}	m/s	250,5										250,53444	250,83
Cruise altitude	h_{CR}	m	13100									13100		
Sweep angle	ϕ_{25}	°	35				35					28		
Mean aerodynamic chord	c_{MAC}	m	8,35									8,35		
Position of maximum camber	$x_{(y\_c),max}$	%c	15											15
Camber	$(y_c)_{max}/c$	%c	1,8											1,8
Position of maximum thickness	$x_{t,max}$	%c	30											30
Relative thickness	t/c	%	15											15
Taper	λ		0,113									0,113		
Overall pressure ratio	OAPR													
Turbine entry temperature	TET	K												

Aeroplane Specifications

Data to apply reverse engineering

					LL	*UL*
Landing field length	**Known**	s_{LFL}	**1960**	m		
Approach speed	**Known**	V_{APP}	**72,00**	m/s	72,0	72,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2830**	m	2830	2830
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**5400**	NM		
Cruise Mach number		M_{CR}	**0,85**			
Wing area		S_W	**443**	m²		
Wing span	**Known**	b_W	**64,75**	m²	64,75	64,75
Aspect ratio		A	9,46			
Maximum take-off mass		m_{MTO}	**265000**	kg		
Maximum payload mass		m_{PL}	**49800**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,188			
Maximum landing mass		m_{ML}	**207000**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,781			
Operating empty mass		m_{OE}	**130700**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,493			
Wing loading		m_{MTO}/S_W	598,2	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**369**	kN		
Total take-off thrust		T_{TO}	738	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,284			
Bypass ratio		μ	**8,9**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed	V_{CR}	**251**	m/s			
Cruise altitude	h_{CR}	**11887**	m			
Speed ratio	V/V_{md}	**1,000**	-		1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**35**	°		
Mean aerodynamic chord		c_{MAC}	**8,35**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**10,6**	%		
Taper		λ	**0,113**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1960	1960	m	0,00%
Approach speed	V_{APP}	72,00	72,0	m/s	0,00%
Take-off field length	s_{TOFL}	2830	2830	m	0,00%
Span	b_W	64,75	64,75	m	0,00%
Aspect ratio	A	9,46	9,46		0,00%
Cruise speed	V_{CR}	250,5	251	m/s	0,14%
Cruise altitude	h_{CR}	11887	11795	m	-0,77%
Squared Sum					**6,14E-05**
Absolute maximum deviation					0,8%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,23**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,74**	
Maximum aerodynamic efficiency	E_{max}	**22,02**	
Specific fuel consumption	SFC	**1,54E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1960	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	72,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,78	
Wing loading at maximum take-off mass	m_{MTO}/S_W	598,2	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,23**	

Take-off

Take-off field length	s_{TOFL}	2830	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,284	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,74**	

2nd Segment

Aspect ratio	A	9,464
Lift coefficient, take-off	$C_{L,TO}$	1,21
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,005
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,025
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	12,62
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,206

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,32
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,011
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,046
Glide ratio in landing configuration	E_L	10,19
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,186

2) Maximum Aerodynamic Efficiency

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications

Mach number, cruise	M_{CR}	0,85	
Aspect ratio	A	9,46	
Bypass ratio	μ	8,90	
Wing loading	m_{MTO}/S_W	598	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,284	

Variables

	V/V_{md}	**1,0**

Calculations

Zero-lift drag coefficient	$C_{D,0}$	0,013
Lift coefficient at E_{max}	$C_{L,md}$	0,57
Ratio, lift coefficient	$C_L/C_{L,md}$	1,000
Lift coefficient, cruise	C_L	0,574
Actual aerodynamic efficiency, cruise	E	22,02
Max. glide ratio, cruise	E_{max}	**22,02**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,52	-0,07	0,00
f'(x)	-0,08	-0,10	-0,10
E_{max}	16	22,77	22,03

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	5400	NM
Mach number, cruise	M_{CR}	0,85	
Bypass ratio	μ	8,90	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,284	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	265000	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,188	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,493	

Calculated values			
Actual aerodynamic efficiency, cruise	E	22,02	
Cruise altitude	h_{CR}	11795	m
Cruise speed	V_{CR}	251	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,319	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,681	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,072	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,947	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**no**	
	international	**yes**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	870440	m
Loiter time	t_{loiter}	1800	s
Specific fuel consumption	SFC	**1,54E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 64 series**	
Wing span	b_W	64,75	m
Structural wing span	$b_{W,struct}$	79,05	m
Wing area	S_W	443,0	m²
Aspect ratio	A	9,46	
Sweep	φ_{25}	35	°
Mean aerodynamic chord	c_{MAC}	8,35	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	10,6	%
Taper	λ	0,113	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	72,00	m/s
Mach number, landing	M_{APP}	0,22	
Mach number, cruise	M_{CR}	0,85	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,3	%c
Leading edge sweep	φ_{LE}	39,8	°
Reynoldsnumber	Re	4,3E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,33	
Correction term, camber	$\Delta_1 c_{L,max}$	0,39	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,028	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,749	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,80	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,39	

Calculations increase of lift coefficient due to flaps		**2 flap types**	
Correction factor, sweep	K_{φ}	0,81	
• Flap group A			
Single-slotted flap	$\Delta c_{L,max,fA}$	0,74	
Use flapped span	b_W,fA	**15,2**	m
Percentage of flaps allong the wing		19%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,12	
• Flap group B			
Single-slotted flap	$\Delta c_{L,max,fB}$	0,74	
Use flapped span	b_W,fB	**22,9**	m
Percentage of flaps allong the wing		29%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,18	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,29	
Calculations increase of lift coefficient due to slats		**2 slat types**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**36**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,86	
Use slatted span	b_W,sA	**14,2**	m
Percentage of slats allong the wing		18%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,12	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,86	
Use slatted span	b_W,sB	**39,5**	m
Percentage of slats allong the wing		50%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,35	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,47	
Wing			
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,14**	
RE value maximum lift coefficient, landing		2,23	
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,67**	
RE value maximum lift coefficient, take-off		1,74	

-4%

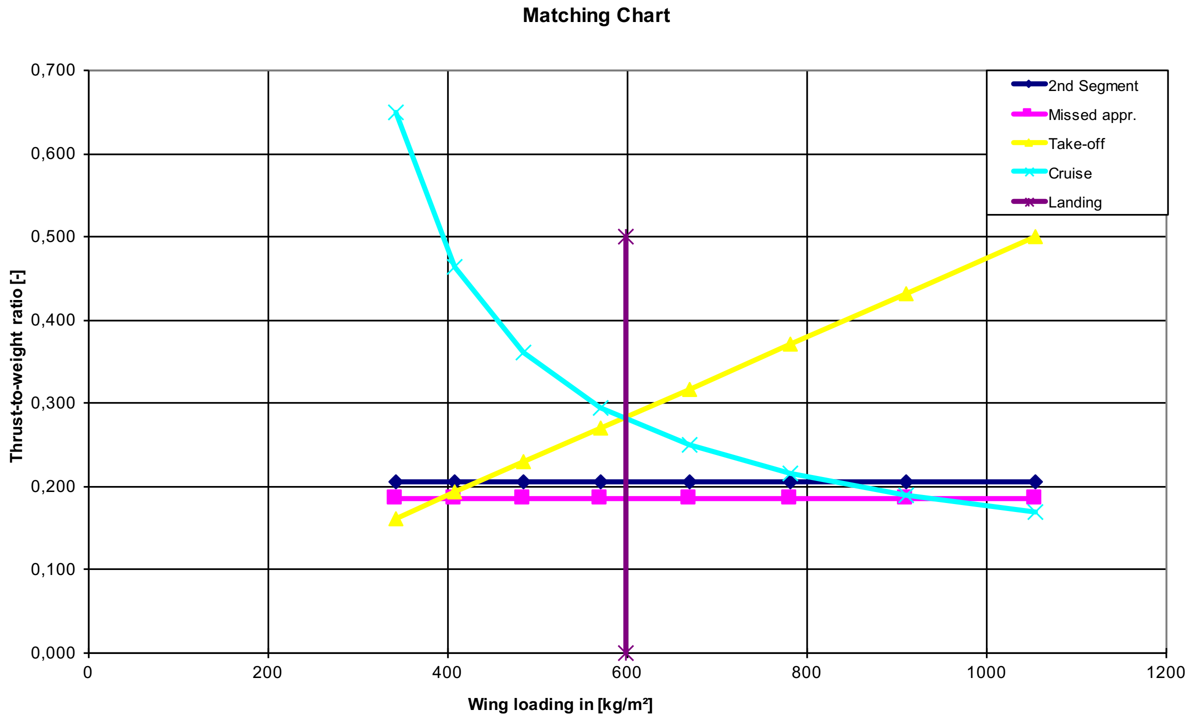
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate (kWL = 2,13)	$k_{e,WL}$	1,41	
Span	b_W	64,75	m
Winglet height	h	2,43	m
Aspect ratio	A	9,46	
Effective aspect ratio	A_{eff}	13,34	
Efficiency factor, short range	k_E	16,19	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**23,5**	
RE value maximum aerodynamic efficiency		22,02	

7%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,850	
Cruise altitude	h_{CR}	11887	m
By Pass Ratio	μ	8,90	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	369,00	kN
Overall Pressure ratio	OAPR	**31,36**	
Turbine entry temperature	TET	**1498,32**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,93	
Ventilator efficiency	$\eta_{ventilator}$	0,90	
Compressor efficiency	$\eta_{compresor}$	0,88	
Turbine efficiency	$\eta_{turbine}$	0,91	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,92	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,14	
Temperature function	χ	1,92	
Gas generator efficiency	η_{gasgen}	0,97	
Gas generator function	G	2,31	
Verification value specific fuel consumption	SFC	0,56	kg/daN/h
Verification value specific fuel consumption	SFC	**1,54E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,54E-05	kg/N/s
0%			


Matching Chart
Thrust-to-weight ratio [-]
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
200
400
600
800
1000
1200
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix M Airbus A330-200

Data Collection			A330-200	Source:	1		2		3	4		5	6	7	8	9
					Aircraft characteristics for airport planning		Jane's		Jenkinson	Engine		Scholz	Paul Müller	Elodie Roux	Data collectior	Webs
Parameter	Symbol	Units	Chosen value		WV050	WV082	Basic	Option								
PAX			375		247		375-379		380-293-253					375-253		
Landing field length	s_{LFL}	m	1750		1740	1750	1722	1753	1750					1750	1800	
Approach speed	V_{APP}	m/s	70		70				69,45						72,02	
Temperature above ISA (288,15K)	ΔT_L	K	0		0		15		0							
Relative density	s															
Take-off field length	s_{TOFL}	m	2500		2740	3660	2530	2652	2470					2470	2300	2220
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0		15		0							
Relative density	s															
Range (max payload)	R	km	7400		8500		12315		7797					7400		13450
Cruise Mach number	M_{CR}		0,82				0,82				0,82			0,82	0,81	0,82
Wing area	S_W	m²	361,6				361,6		363,1					363,1		361,6
Wing span	b_W	m	60,3		60,3		63,68		58					60,3	60,3	60,3
Aspect ratio	A		10,01						9,26466538					10,02		
Maximum take-off mass	m_{MTO}	kg	242000		230000	242000	230000	233000	230000					230000	230000	242000
Payload mass	m_{PL}	kg	47400		45300		47400		36400					49052		36400
Mass ratio, payload - take-off	m_{PL}/m_{MTO}								0,15826087					0,213		
Maximum landing mass	m_{ML}	kg	180000		180000	182000	180000	182000	177150					180000		182000
Mass ratio, landing - take-off	m_{ML}/m_{MTO}								0,77021739							
Operating empty mass	m_{OE}	kg	120600				120600		120200					120948		120000
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}								0,5226087					0,526		
Wing loading	m_{MTO}/S_W	kg/m²	633				633,4	644,4	633,434316					633		
Maximum zero fuel mass	m_{MZF}	kg	168000		168000	170000	168000	170000	165142					170000		170000
Number of engines	n_E		2						2					2	2	2
Engine type	GE CF6 (29%), PW4000		Trent 772B-60		RR TRENT 700 Series		R-R Trent 772-60/772B-60A		CF6-80E1A4	CF6-80E1A4	Trent 772-60			CF6-80E1A4	CF6-80E1	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	316,279				316		310	297,452605	316,26858			297,451	306	320
Total take-off thrust	T_{TO}	kN														
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,28						0,27478615		0,28			0,26		
Bypass ratio	μ		4,89							5	4,89			5		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s								9,5654E-06				0,00000957		
Specific Fuel Comsumption (cruise)	SFC (cruise)	kg/N s	1,60E-05								1,60E-05					
Available fuel volume	$V_{fuel,available}$	m³	139,09		139,09		139,09		139,09					139,09		139,09
Cruise speed	V_{CR}	m/s	241,79				185,2		241,8						241,79	241,94
Cruise altitude	h_{CR}	m	11887						11887,2		10668			11887		
Sweep angle	ϕ_{25}	°	29,7						29,7					29,7		30
Mean aerodynamic chord	c_{MAC}	m	7,28						7,26					7,28		
Position of maximum camber	$x_{(y\_c),max}$	%c														
Camber	$(y_c)_{max}/c$	%c														
Position of maximum thickness	$x_{t,max}$	%c														
Relative thickness	t/c	%	15,3-11,3-10,6											15,3-11,3-10,6		
Taper	λ		0,235						0,251					0,235		
Overall pressure ratio	OAPR		36,8							33,7	36,8					
Turbine entry temperature	TET	K														

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1750**	m		
Approach speed	**Known**	V_{APP}	**70,00**	m/s	70,0	70,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2500**	m	2500	2500
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**3996**	NM		
Cruise Mach number		M_{CR}	**0,82**			
Wing area		S_W	**362**	m²		
Wing span	**Known**	b_W	**60,3**	m²	60,3	60,3
Aspect ratio		A	10,06			
Maximum take-off mass		m_{MTO}	**242000**	kg		
Maximum payload mass		m_{PL}	**47400**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,196			
Maximum landing mass		m_{ML}	**180000**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,744			
Operating empty mass		m_{OE}	**120600**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,498			
Wing loading		m_{MTO}/S_W	669,2	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**316,279**	kN		
Total take-off thrust		T_{TO}	632,558	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,266			
Bypass ratio		μ	**4,89**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	**242**	m/s		
Cruise altitude	h_{CR}	**11887**	m		
Speed ratio	V/V_{md}	**1,000**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**29,7**	°		
Mean aerodynamic chord		c_{MAC}	**7,28**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,1**	%		
Taper		λ	**0,235**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1750	1750	m	0,00%
Approach speed	V_{APP}	70,00	70,0	m/s	0,00%
Take-off field length	s_{TOFL}	2500	2500	m	0,00%
Span	b_W	60,3	60,3	m	0,00%
Aspect ratio	A	10,06	10,06		0,00%
Cruise speed	V_{CR}	241,8	242	m/s	0,09%
Cruise altitude	h_{CR}	11887	11867	m	-0,17%
Squared Sum					**3,66E-06**
Absolute maximum deviation					0,2%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,66**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,35**	
Maximum aerodynamic efficiency	E_{max}	**19,19**	
Specific fuel consumption	SFC	**1,64E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing			
Landing field length	s_{LFL}	1750	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	(m/s²)$^{0.5}$
Approach speed	V_{APP}	70,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,74	
Wing loading at maximum take-off mass	m_{MTO}/S_W	669,2	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,66**	

Take-off			
Take-off field length	s_{TOFL}	2500	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,266	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,35**	

2nd Segment		
Aspect ratio	A	10,056
Lift coefficient, take-off	$C_{L,TO}$	1,63
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,027
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,047
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	9,77
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,253

Missed approach		
Lift coefficient, landing	$C_{L,L}$	1,57
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,024
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,059
Glide ratio in landing configuration	E_L	9,22
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,193

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,82	
Aspect ratio	A	10,06	
Bypass ratio	μ	4,89	
Wing loading	m_{MTO}/S_W	669	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,266	

Variables		
	V/V_{md}	**1,0**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,018
Lift coefficient at E_{max}	$C_{L,md}$	0,70
Ratio, lift coefficient	$C_L/C_{L,md}$	1,000
Lift coefficient, cruise	C_L	0,700
Actual aerodynamic efficiency, cruise	E	19,19
Max. glide ratio, cruise	E_{max}	**19,19**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,32	-0,02	0,00
f'(x)	-0,10	-0,11	-0,11
E_{max}	16	19,39	19,19

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	3996	NM
Mach number, cruise	M_{CR}	0,82	
Bypass ratio	μ	4,89	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,266	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	242000	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,196	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,498	

Calculated values			
Actual aerodynamic efficiency, cruise	E	19,19	
Cruise altitude	h_{CR}	11867	m
Cruise speed	V_{CR}	242	m/s

Mission fuel fraction		
Type of aeroplane (according to Roskam)	**Transport jet**	
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980
Fuel-Fraction, descent	$M_{ff,DES}$	0,990
Fuel-Fraction, landing	$M_{ff,L}$	0,992

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,306	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,694	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,079	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,940	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,64E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	NACA 4 digit	
Wing span	b_W	60,3	m
Structural wing span	$b_{W,struct}$	69,42	m
Wing area	S_W	361,6	m²
Aspect ratio	A	10,06	
Sweep	φ_{25}	29,7	°
Mean aerodynamic chord	c_{MAC}	7,28	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,1	%
Taper	λ	0,235	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	70,00	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,82	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,9	%c
Leading edge sweep	φ_{LE}	33,2	°
Reynoldsnumber	Re	3,6E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,55	
Correction term, camber	$\Delta_1 c_{L,max}$	0,22	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,080	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,845	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,78	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,42	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_{φ}	0,85	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,40	
Use flapped span	b_W,fA	**40,1**	m
Percentage of flaps allong the wing		58%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,68	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,73	
Use flapped span	b_W,fB	0	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,68	
Calculations increase of lift coefficient due to slats			**2 slat types**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**32**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,88	
Use slatted span	b_W,sA	**10,3**	m
Percentage of slats allong the wing		15%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,11	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,88	
Use slatted span	b_W,sB	**43,1**	m
Percentage of slats allong the wing		62%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,46	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,58	

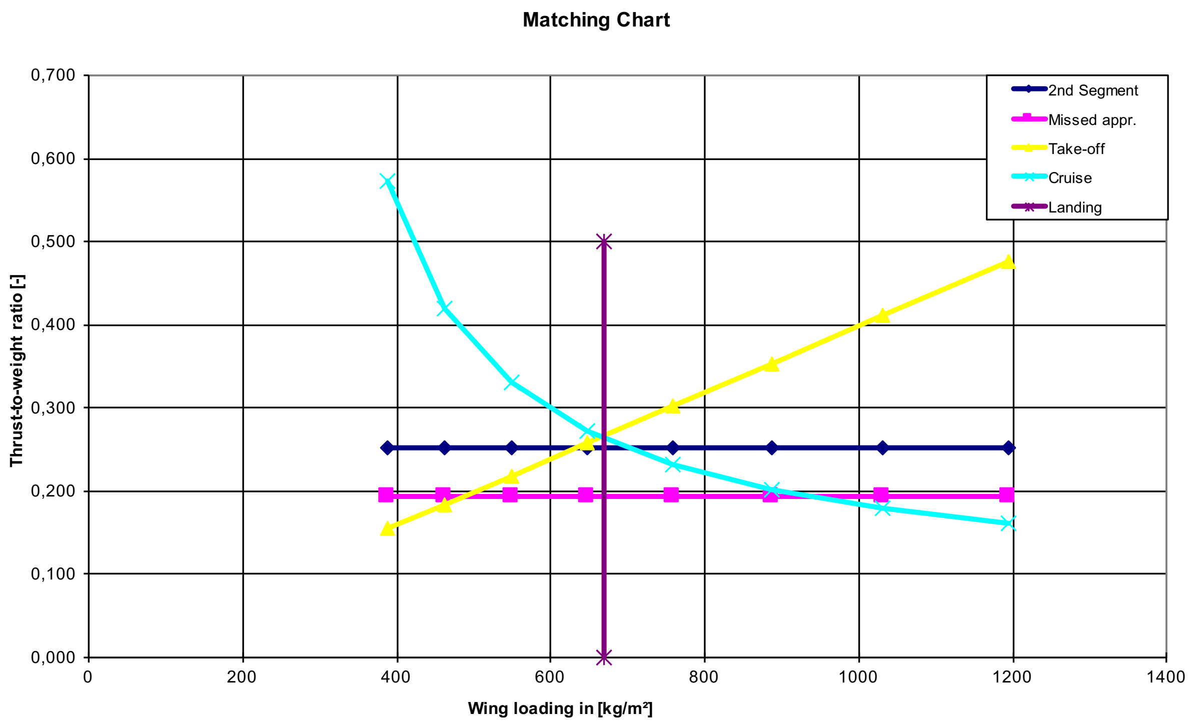
Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,65**
RE value maximum lift coefficient, landing		2,66
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,34**
RE value maximum lift coefficient, take-off		2,35
0%		

Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,07	
Span	b_W	60,3	m
Winglet height	h	**2,74**	m
Aspect ratio	A	10,06	
Effective aspect ratio	A_{eff}	10,71	
Efficiency factor, short range	k_E	16,19	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**21,0**	
RE value maximum aerodynamic efficiency		19,19	
10%			

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,820	
Cruise altitude	h_{CR}	11887	m
By Pass Ratio	μ	4,89	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	316,28	kN
Overall Pressure ratio	OAPR	**36,80**	
Turbine entry temperature	TET	**1494,71**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,89	
Compressor efficiency	$\eta_{compresor}$	0,87	
Turbine efficiency	$\eta_{turbine}$	0,91	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,90	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,13	
Temperature function	χ	2,04	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,22	
Verification value specific fuel consumption	SFC	0,56	kg/daN/h
Verification value specific fuel consumption	SFC	**1,57E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,64E-05	kg/N/s
-4%			



Matching Chart
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
1400
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix N Embraer 190

Data Collection			Embraer 190		1			2			3	4	5	6	7	8	9
				Source:	Aircraft characteristics for airport planning			Jane's			Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collection	Webs
Parameter	Symbol	Units	Chosen value		STD	LR	AR	Standard	Long-Range	IGW							
PAX			106			106		98-106							104-94		
Landing field length	s_{LFL}	m	1323			1250			1392						1323	1286	
Approach speed	V_{APP}	m/s															
Temperature above ISA (288,15K)	ΔT_L	K	0			0											
Relative density	s																
Take-off field length	s_{TOFL}	m	2076		2000	2200	2300		2107						2076	1190	
Temperature above ISA (288,15K)	ΔT_{TO}	K	0			0											
Relative density	s																
Range (max payload)	R	km	1852		1852	2778	3333,6			4259					1926		4260
Cruise Mach number	M_{CR}		0,78			0,78			0,82						0,78	0,82	
Wing area	S_W	m²	92,53			92,5			92,53						92,5		
Wing span	b_W	m	28,72			28,72			28,72						28,72	33,7	28,72
Aspect ratio	A		8,92			8,1									8,92		
Maximum take-off mass	m_{MTO}	kg	51800		47790	50300	51800	47790	50300	51800					47790	56400	51800
Payload mass	m_{PL}	kg	12900		12900		13000		13530						12900		
Mass ratio, payload - take-off	m_{PL}/m_{MTO}														0,27		
Maximum landing mass	m_{ML}	kg	43000		43000		44000	43000		44000					43000		
Mass ratio, landing - take-off	m_{ML}/m_{MTO}																
Operating empty mass	m_{OE}	kg	27900			27900		28080		28180					27900		28080
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}														0,584		
Wing loading	m_{MTO}/S_W	kg/m²	516,5					516,5	543,6	559,8					517		
Maximum zero fuel mass	m_{MZF}	kg	40800		40800		40900	40800		40900					40800		
Number of engines	n_E		2				2								2	2	2
Engine type	GE CF34		CF34-10E5		CF34 −10E5A, −10E5A1, −10E6A, −10E6A1			CF34-10E, -10E6, -10E6A1, -10E5, -10E5A1							CF34-10E5	PW1900G	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	82,292				82,3		88,9						82,292	85-102	82,3
Total take-off thrust	T_{TO}	kN															
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,35					0,380749315	0,361846866	0,350655726					0,35		
Bypass ratio	μ		5												5		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	1,08E-05												1,08E-05		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s															
Available fuel volume	$V_{fuel,available}$	m³	16,029			16,029			16,153						16,029		
Cruise speed	V_{CR}	m/s	236														236,11
Cruise altitude	h_{CR}	m	10669			10668											
Sweep angle	ϕ_{25}	°															
Mean aerodynamic chord	c_{MAC}	m	3,68						3,68								
Position of maximum camber	$x_{(y\_c),max}$	%c															
Camber	$(y_c)_{max}/c$	%c															
Position of maximum thickness	$x_{t,max}$	%c															
Relative thickness	t/c	%															
Taper	λ																
Overall pressure ratio	OAPR																
Turbine entry temperature	TET	K															

Aeroplane Specifications

Data to apply reverse engineering

					LL	*UL*
Landing field length	**Known**	s_{LFL}	**1323**	m		
Approach speed	**Unknown**	V_{APP}	70,00	m/s	61,9	61,9
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2076**	m	2076	2076
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**1000**	NM		
Cruise Mach number		M_{CR}	**0,78**			
Wing area		S_W	**93**	m²		
Wing span	**Known**	b_W	**28,72**	m²	28,72	28,72
Aspect ratio		A	8,91			
Maximum take-off mass		m_{MTO}	**51800**	kg		
Maximum payload mass		m_{PL}	**12900**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,249			
Maximum landing mass		m_{ML}	**43000**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,830			
Operating empty mass		m_{OE}	**27900**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,539			
Wing loading		m_{MTO}/S_W	559,8	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**82,292**	kN		
Total take-off thrust		T_{TO}	164,584	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,324			
Bypass ratio		μ	**5**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed		V_{CR}	**236**	m/s		
Cruise altitude		h_{CR}	**10669**	m		
Speed ratio		V/V_{md}	**1,246**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**25**	°		
Mean aerodynamic chord		c_{MAC}	**3,68**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,6**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1323	1323	m	0,00%
Approach speed	V_{APP}	Unknown	**61,9**	m/s	0,00%
Take-off field length	s_{TOFL}	2076	2076	m	0,00%
Span	b_W	28,72	28,72	m	0,00%
Aspect ratio	A	8,91	8,91		0,00%
Cruise speed	V_{CR}	236,0	231	m/s	-1,93%
Cruise altitude	h_{CR}	10669	10637	m	-0,30%
Squared Sum					**3,82E-04**
Absolute maximum deviation					1,9%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,28**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,95**	
Maximum aerodynamic efficiency	E_{max}	**14,41**	
Specific fuel consumption	SFC	**1,80E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1323	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	61,90	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,83	
Wing loading at maximum take-off mass	m_{MTO}/S_W	559,8	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,28**	

Take-off

Take-off field length	s_{TOFL}	2076	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,324	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,95**	

2nd Segment

Aspect ratio	A	8,914
Lift coefficient, take-off	$C_{L,TO}$	1,35
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,013
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,033
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	10,74
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,234

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,94
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,042
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,077
Glide ratio in landing configuration	E_L	7,21
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,265

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,78	
Aspect ratio	A	8,91	
Bypass ratio	μ	5,00	
Wing loading	m_{MTO}/S_W	560	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,324	

Variables		
	V/V_{md}	**1,2**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,029
Lift coefficient at E_{max}	$C_{L,md}$	0,83
Ratio, lift coefficient	$C_L/C_{L,md}$	0,644
Lift coefficient, cruise	C_L	0,532
Actual aerodynamic efficiency, cruise	E	13,12
Max. glide ratio, cruise	E_{max}	**14,41**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,22	-0,01	0,00
f'(x)	-0,14	-0,13	-0,13
E_{max}	16	14,45	14,41

3) Specific Fuel Consumption

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications

Range	R	1000	NM
Mach number, cruise	M_{CR}	0,78	
Bypass ratio	μ	5,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,324	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	51800	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,249	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,539	

Calculated values

Actual aerodynamic efficiency, cruise	E	13,12	
Cruise altitude	h_{CR}	10637	m
Cruise speed	V_{CR}	231	m/s

Mission fuel fraction

Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations

Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,212	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,788	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,368	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,644	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,80E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 65 series**	
Wing span	b_W	28,72	m
Structural wing span	$b_{W,struct}$	31,69	m
Wing area	S_W	92,5	m²
Aspect ratio	A	8,91	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	3,68	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,6	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	61,90	m/s
Mach number, landing	M_{APP}	0,19	
Mach number, cruise	M_{CR}	0,78	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,2	%c
Leading edge sweep	φ_{LE}	28,9	°
Reynoldsnumber	Re	1,6E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,32	
Correction term, camber	$\Delta_1 c_{L,max}$	0,40	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,015	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,726	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,85	
Correction term, Mach number	$\Delta C_{L,max}$	0,00	
Lift coefficient, wing	$C_{L,max}$	1,46	

Calculations increase of lift coefficient due to flaps		**2 flap types**
Correction factor, sweep	K_{φ}	0,87
• Flap group A		
Double-slotted flap	$\Delta c_{L,max,fA}$	1,43
Use flapped span	b_W,fA	**8,5** m
Percentage of flaps allong the wing		27%
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,33
• Flap group B		
Double-slotted flap	$\Delta c_{L,max,fB}$	1,43
Use flapped span	b_W,fB	**12,8** m
Percentage of flaps allong the wing		40%
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,50
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,83

Calculations increase of lift coefficient due to slats		**2 slat types**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**29** °
• Slat group A		
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,90
Use slatted span	b_W,sA	**4,8** m
Percentage of slats allong the wing		15%
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,12
• Slat group B		
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90
Use slatted span	b_W,sB	**20,1** m
Percentage of slats allong the wing		63%
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,50
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,62

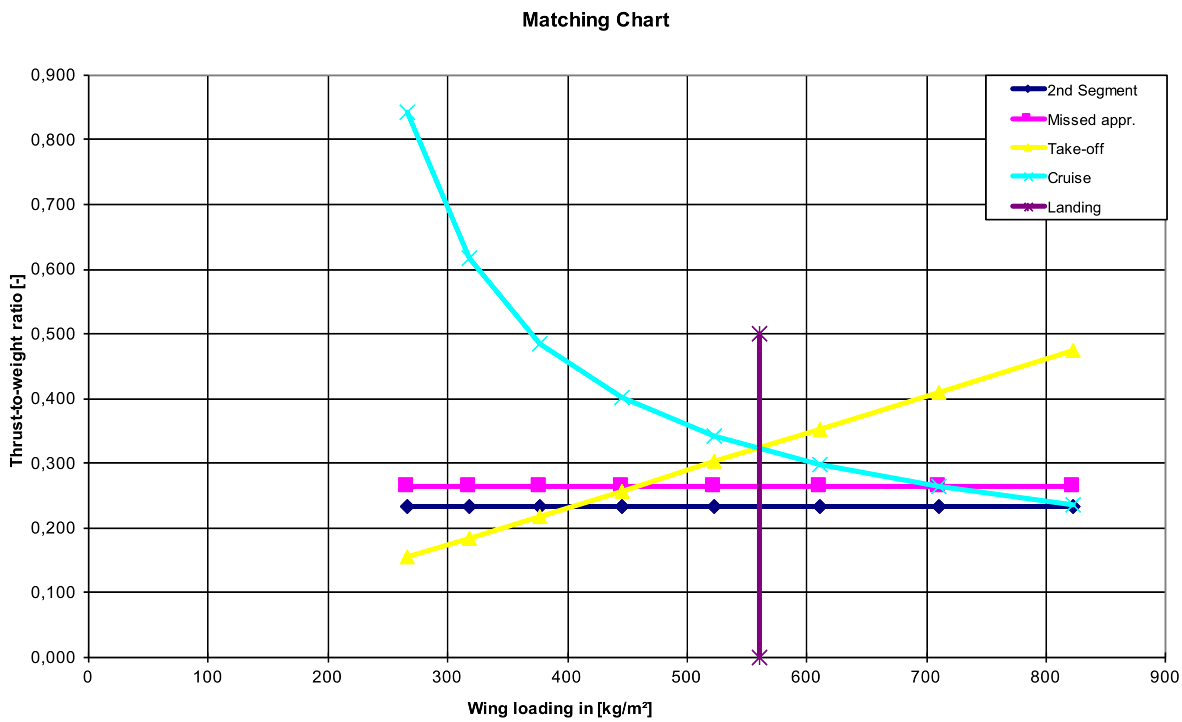
Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,87**
RE value maximum lift coefficient, landing		3,28
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,71**
RE value maximum lift coefficient, take-off		1,95
-12%		

Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83
End plate	$k_{e,WL}$	1,08
Span	b_W	28,72 m
Winglet height	h	**1,59** m
Aspect ratio	A	8,91
Effective aspect ratio	A_{eff}	9,63
Efficiency factor, short range	k_E	15,15
Relative wetted area	S_{wet}/S_W	**6,35**
Verification value maximum aerodynamic efficiency	E_{max}	**18,7**
RE value maximum aerodynamic efficiency		14,41
29%		

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,780	
Cruise altitude	h_{CR}	10669	m
By Pass Ratio	μ	5,00	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	82,29	kN
Overall Pressure ratio	OAPR	**29,00**	
Turbine entry temperature	TET	**1422,79**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,85	
Compressor efficiency	$\eta_{compresor}$	0,85	
Turbine efficiency	$\eta_{turbine}$	0,89	
Nozzle efficiency	η_{nozzle}	0,98	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,80	K
Dimensionless turbine entry temperature	ϕ	6,50	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,81	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	1,98	
Verification value specific fuel consumption	SFC	0,62	kg/daN/h
Verification value specific fuel consumption	SFC	**1,72E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,80E-05	kg/N/s
-4%			


Matching Chart
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
100
200
300
400
500
600
700
800
900
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix O Embraer 175

Data Collection			Embraer 175		1				2		3	4	5	6	7	8	9
				Source:	Aircraft characteristics for airport planning				Jane's		Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collectior	Webs
Parameter	Symbol	Units	Chosen value		STD	LR	LL	AR	Standard	Long-Range							
PAX			86		84		70	86	78-86						86-78		
Landing field length	s_{LFL}	m	1294		1270					1309					1294	1350	1261
Approach speed	V_{APP}	m/s															
Temperature above ISA (288,15K)	ΔT_L	K	0					0									
Relative density	s																
Take-off field length	s_{TOFL}	m	1714		1600	1650		2360		1734					1714	1370	2244
Temperature above ISA (288,15K)	ΔT_{TO}	K	0					0									
Relative density	s																
Range (max payload)	R	km	1815		1852	2400				3518					1815		4074
Cruise Mach number	M_{CR}		0,78					0,78	0,82						0,78		0,75
Wing area	S_W	m²	72,72		72,72				72,72						72,72		72,72
Wing span	b_W	m	26		26				26						26	31	26
Aspect ratio	A		9,3		8,6										9,3		9,3
Maximum take-off mass	m_{MTO}	kg	40370		37500	38790	38600	40370	37500	38790					37500	44800	40370
Payload mass	m_{PL}	kg	10200		10200				9890						10200		10094
Mass ratio, payload - take-off	m_{PL}/m_{MTO}														0,272		
Maximum landing mass	m_{ML}	kg	34100		34000			34100	34000						34000		34100
Mass ratio, landing - take-off	m_{ML}/m_{MTO}																
Operating empty mass	m_{OE}	kg	21500		21500			22500	21810						21500		21810
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}														0,573		
Wing loading	m_{MTO}/S_W	kg/m²	515,7						515,7	533,4					516		
Maximum zero fuel mass	m_{MZF}	kg	31700		31700		31510	32000	31700						31700		
Number of engines	n_E		2												2	2	2
Engine type	GE CF34		CF34-8E2		CF34 – 8E5A1, – 8E5				CF34-8E5, -8E5A1						CF34-8E2	PW1700G	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	62,275		63,2				63,2						62,275	67	62,3
Total take-off thrust	T_{TO}	kN															
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,34						0,343571772	0,332380509					0,34		
Bypass ratio	μ		5												5		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	1,11E-05												1,11E-05		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s															
Available fuel volume	$V_{fuel,available}$	m³	11,625		11,625				11,625						11,625		11,625
Cruise speed	V_{CR}	m/s	221,4														221,39
Cruise altitude	h_{CR}	m	10668		10668												
Sweep angle	ϕ_{25}	°															
Mean aerodynamic chord	c_{MAC}	m	3,195						3,195								
Position of maximum camber	$x_{(y\_c),max}$	%c															
Camber	$(y_c)_{max}/c$	%c															
Position of maximum thickness	$x_{t,max}$	%c															
Relative thickness	t/c	%															
Taper	λ																
Overall pressure ratio	OAPR																
Turbine entry temperature	TET	K															

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1294**	m		
Approach speed	**Unknown**	V_{APP}	70,00	m/s	61,2	61,2
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**1714**	m	1714	1714
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**980**	NM		
Cruise Mach number		M_{CR}	**0,78**			
Wing area		S_W	**73**	m²		
Wing span	**Known**	b_W	**26**	m²	26	26
Aspect ratio		A	9,30			
Maximum take-off mass		m_{MTO}	**40370**	kg		
Maximum payload mass		m_{PL}	**10200**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,253			
Maximum landing mass		m_{ML}	**34100**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,845			
Operating empty mass		m_{OE}	**21500**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,533			
Wing loading		m_{MTO}/S_W	555,1	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**62,275**	kN		
Total take-off thrust		T_{TO}	124,55	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,314			
Bypass ratio		μ	**5**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed		V_{CR}	221	m/s		
Cruise altitude		h_{CR}	10668	m		
Speed ratio		V/V_{md}	1,241	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	25	°		
Mean aerodynamic chord		c_{MAC}	3,195	m		
Position of maximum camber		$x_{(y\_c),max}$	30	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	4	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	30	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	11,6	%		
Taper		λ	0,24			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1294	1294	m	0,00%
Approach speed	V_{APP}	Unknown	61,2	m/s	0,00%
Take-off field length	s_{TOFL}	1714	1714	m	0,00%
Span	b_W	26	26	m	0,00%
Aspect ratio	A	9,30	9,30		0,00%
Cruise speed	V_{CR}	221,4	231	m/s	4,37%
Cruise altitude	h_{CR}	10668	10745	m	0,72%
Squared Sum					**1,96E-03**
Absolute maximum deviation					4,4%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	3,39	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	2,41	
Maximum aerodynamic efficiency	E_{max}	15,02	
Specific fuel consumption	SFC	1,94E-05	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1294	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	61,22	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,84	
Wing loading at maximum take-off mass	m_{MTO}/S_W	555,1	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,39**	

Take-off

Take-off field length	s_{TOFL}	1714	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,314	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,41**	

2nd Segment

Aspect ratio	A	9,296
Lift coefficient, take-off	$C_{L,TO}$	1,67
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,029
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,049
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	9,01
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,270

Missed approach

Lift coefficient, landing	$C_{L,L}$	2,00
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,045
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,080
Glide ratio in landing configuration	E_L	7,24
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,269

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,78	
Aspect ratio	A	9,30	
Bypass ratio	μ	5,00	
Wing loading	m_{MTO}/S_W	555	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,314	

Variables		
	V/V_{md}	**1,2**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,028
Lift coefficient at E_{max}	$C_{L,md}$	0,83
Ratio, lift coefficient	$C_L/C_{L,md}$	0,649
Lift coefficient, cruise	C_L	0,537
Actual aerodynamic efficiency, cruise	E	13,72
Max. glide ratio, cruise	E_{max}	**15,02**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,13	0,00	0,00
f'(x)	-0,13	-0,13	-0,13
E_{max}	16	15,04	15,02

3) Specific Fuel Consumption

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications

Range	R	980	NM
Mach number, cruise	M_{CR}	0,78	
Bypass ratio	µ	5,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,314	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	40370	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,253	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,533	

Calculated values

Actual aerodynamic efficiency, cruise	E	13,72	
Cruise altitude	h_{CR}	10745	m
Cruise speed	V_{CR}	231	m/s

Mission fuel fraction

Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations

Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,215	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,785	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,473	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,538	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,94E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 65 series**	
Wing span	b_W	26	m
Structural wing span	$b_{W,struct}$	28,69	m
Wing area	S_W	72,7	m²
Aspect ratio	A	9,30	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	3,195	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,6	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	61,22	m/s
Mach number, landing	M_{APP}	0,18	
Mach number, cruise	M_{CR}	0,78	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,2	%c
Leading edge sweep	φ_{LE}	28,8	°
Reynoldsnumber	Re	1,4E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,32	
Correction term, camber	$\Delta_1 c_{L,max}$	0,40	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,010	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,722	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,85	
Correction term, Mach number	$\Delta C_{L,max}$	0,00	
Lift coefficient, wing	$C_{L,max}$	1,46	

Calculations increase of lift coefficient due to flaps		**2 flap types**	
Correction factor, sweep	K_φ	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,43	
Use flapped span	b_W,fA	**7,7**	m
Percentage of flaps allong the wing		27%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,33	
• Flap group B			
Double-slotted flap	$\Delta c_{L,max,fB}$	1,43	
Use flapped span	b_W,fB	**11,6**	m
Percentage of flaps allong the wing		40%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,50	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,83	

Calculations increase of lift coefficient due to slats		**2 slat types**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**27**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,90	
Use slatted span	b_W,sA	**4,3**	m
Percentage of slats allong the wing		15%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,12	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**18,2**	m
Percentage of slats allong the wing		63%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,51	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,63	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,88**
RE value maximum lift coefficient, landing		3,39
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,05**
RE value maximum lift coefficient, take-off		2,41

-15%

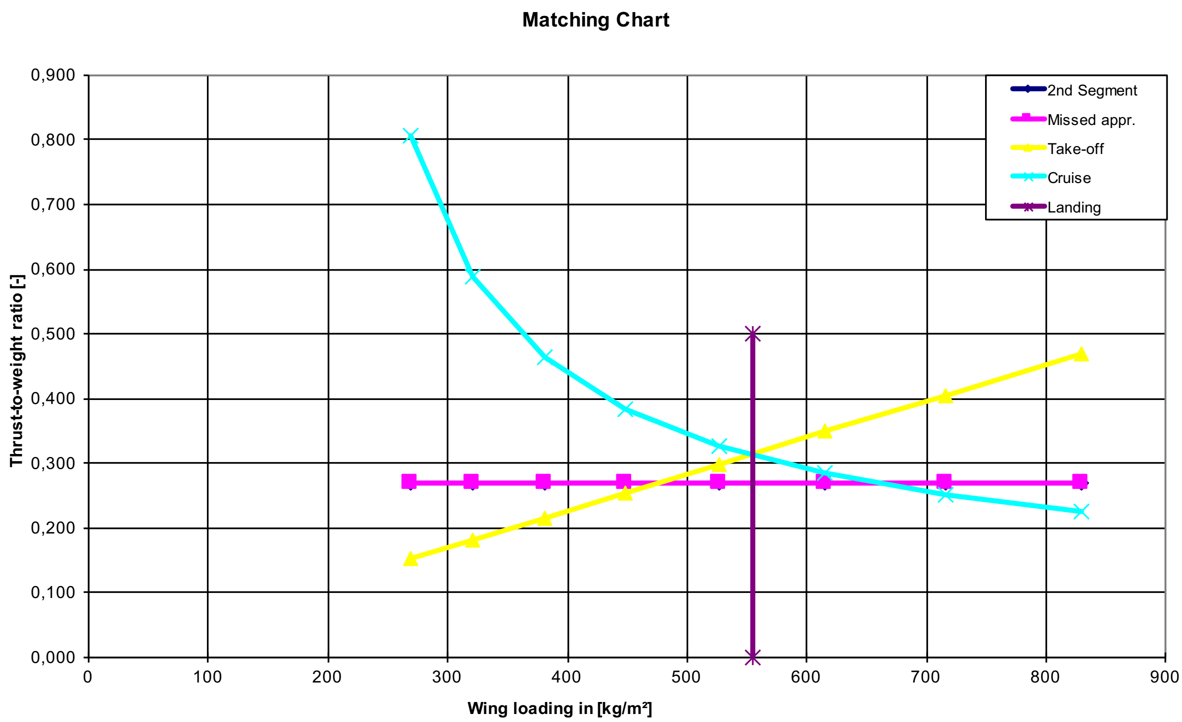
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,09	
Span	b_W	26	m
Winglet height	h	**1,57**	m
Aspect ratio	A	9,30	
Effective aspect ratio	A_{eff}	10,11	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**19,1**	
RE value maximum aerodynamic efficiency		15,02	

27%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,780	
Cruise altitude	h_{CR}	10668	m
By Pass Ratio	μ	5,00	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	62,28	kN
Overall Pressure ratio	OAPR	**28,50**	
Turbine entry temperature	TET	**1391,54**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,83	
Compressor efficiency	$\eta_{compresor}$	0,84	
Turbine efficiency	$\eta_{turbine}$	0,88	
Nozzle efficiency	η_{nozzle}	0,97	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,81	K
Dimensionless turbine entry temperature	ϕ	6,36	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,80	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	1,85	
Verification value specific fuel consumption	SFC	0,66	kg/daN/h
Verification value specific fuel consumption	SFC	**1,82E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,94E-05	kg/N/s
-6%			


Matching Chart
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
100
200
300
400
500
600
700
800
900
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix P Boeing 737-900ER

Data Collection			737-900ER	Source:	1		2		3	4	5	6	7	8	9
					Aircraft characteristics for airport planning		Jane's		Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collectior	Webs
Parameter	Symbol	Units	Chosen value				A	B							
PAX			215		177-186-215		189-215						215-180		
Landing field length	s_{LFL}	m	1660		1700		1662								
Approach speed	V_{APP}	m/s	72				72,53666667								
Temperature above ISA (288,15K)	ΔT_L	K	0		0										
Relative density	s														
Take-off field length	s_{TOFL}	m	2600		2990		2591	2439							2450
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0		30								
Relative density	s														
Range (max payload)	R	km	3120		3120-3890		3815	5083					4800		4995-5925
Cruise Mach number	M_{CR}		0,785				0,785			0,8					0,78
Wing area	S_W	m²	125				125						124,6 (B737-900)		
Wing span	b_W	m	34,32		34,32-35,79		34,31	35,79					34,32		35,7
Aspect ratio	A		9,4				9,4								
Maximum take-off mass	m_{MTO}	kg	79015		74389	85139	74840	79015					85139		76900-85100
Payload mass	m_{PL}	kg	17830		17830	23045							23045		
Mass ratio, payload - take-off	m_{PL}/m_{MTO}												0,271		
Maximum landing mass	m_{ML}	kg	66360		66361	71350	66360	66810					71350		66350
Mass ratio, landing - take-off	m_{ML}/m_{MTO}														
Operating empty mass	m_{OE}	kg	42493		44677		42493						44676		44675
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}												0,525		
Wing loading	m_{MTO}/S_W	kg/m²	595,1				595,1	632,1							
Maximum zero fuel mass	m_{MZF}	kg	62730		62732	67721	62730	63640					67721		
Number of engines	n_E												2		2
Engine type	CFM56-7B		CFM56-7B26		CFM56-7B26/-7B27		CFM56-7B26	CFM56-7B27		CFM56-7B26			CFM56-7B20		
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	117,433		115,5714		117	121,4		117,433061			91,633		121,4
Total take-off thrust	T_{TO}	kN													
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,32				0,32088307	0,31397174					0,22		
Bypass ratio	μ		5,6							5,1			5,6		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	1,08E-05							1,08E-05			1,02E-05		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s											1,79E-05		
Available fuel volume	$V_{fuel,available}$	m³	29,663		27,974	29,666	29,665						29,663		29,66
Cruise speed	V_{CR}	m/s	228,61												228,61
Cruise altitude	h_{CR}	m	11215				11215	10820		10668					
Sweep angle	ϕ_{25}	°	25,02												25,02
Mean aerodynamic chord	c_{MAC}	m													
Position of maximum camber	$x_{(y\_c),max}$	%c	10												10
Camber	$(y_c)_{max}/c$	%c	0,8												0,8
Position of maximum thickness	$x_{t,max}$	%c	29,7												29,7
Relative thickness	t/c	%	12,5												12,5
Taper	λ		0,219				0,218914186						0,219		
Overall pressure ratio	OAPR		27,9							27,9					
Turbine entry temperature	TET	K													

Aeroplane Specifications

Data to apply reverse engineering

					LL	*UL*
Landing field length	**Known**	s_{LFL}	**1660**	m		
Approach speed	**Known**	V_{APP}	**72,00**	m/s	72,0	72,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2600**	m	2600	2600
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**1685**	NM		
Cruise Mach number		M_{CR}	**0,785**			
Wing area		S_W	**125**	m²		
Wing span	**Known**	b_W	**34,32**	m²	34,32	34,32
Aspect ratio		A	9,42			
Maximum take-off mass		m_{MTO}	**79015**	kg		
Maximum payload mass		m_{PL}	**17830**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,226			
Maximum landing mass		m_{ML}	**66360**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,840			
Operating empty mass		m_{OE}	**42493**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,538			
Wing loading		m_{MTO}/S_W	632,1	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**117,433**	kN		
Total take-off thrust		T_{TO}	234,866	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,303			
Bypass ratio		μ	**5,6**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	**229**	m/s		
Cruise altitude	h_{CR}	**11215**	m		
Speed ratio	V/V_{md}	**1,100**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**25**	°		
Mean aerodynamic chord		c_{MAC}	**4,2**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,5**	%		
Taper		λ	**0,219**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1660	1660	m	0,00%
Approach speed	V_{APP}	72,00	72,0	m/s	0,00%
Take-off field length	s_{TOFL}	2600	2600	m	0,00%
Span	b_W	34,32	34,32	m	0,00%
Aspect ratio	A	9,42	9,42		0,00%
Cruise speed	V_{CR}	228,6	232	m/s	1,34%
Cruise altitude	h_{CR}	11215	11215	m	0,00%
Squared Sum					**1,79E-04**
Absolute maximum deviation					1,3%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,99**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,88**	
Maximum aerodynamic efficiency	E_{max}	**16,00**	
Specific fuel consumption	SFC	**1,77E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1660	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	72,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,84	
Wing loading at maximum take-off mass	m_{MTO}/S_W	632,1	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,99**	

Take-off

Take-off field length	s_{TOFL}	2600	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,303	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,88**	

2nd Segment

Aspect ratio	A	9,423
Lift coefficient, take-off	$C_{L,TO}$	1,30
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,010
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,030
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	11,62
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,220

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,77
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,033
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,068
Glide ratio in landing configuration	E_L	8,06
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,244

2) Maximum Aerodynamic Efficiency

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications

Mach number, cruise	M_{CR}	0,785	
Aspect ratio	A	9,42	
Bypass ratio	μ	5,60	
Wing loading	m_{MTO}/S_W	632	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,303	

Variables

	V/V_{md}	**1,1**

Calculations

Zero-lift drag coefficient	$C_{D,0}$	0,025
Lift coefficient at E_{max}	$C_{L,md}$	0,79
Ratio, lift coefficient	$C_L/C_{L,md}$	0,826
Lift coefficient, cruise	C_L	0,649
Actual aerodynamic efficiency, cruise	E	15,71
Max. glide ratio, cruise	E_{max}	**16,00**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,00	0,00	0,00
f'(x)	-0,12	-0,12	-0,12
E_{max}	16	16,00	16,00

3) Specific Fuel Consumption

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications

Range	R	1685	NM
Mach number, cruise	M_{CR}	0,785	
Bypass ratio	μ	5,60	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,303	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	79015	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,226	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,538	

Calculated values

Actual aerodynamic efficiency, cruise	E	15,71	
Cruise altitude	h_{CR}	11215	m
Cruise speed	V_{CR}	232	m/s

Mission fuel fraction

Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations

Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,237	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,763	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,242	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,774	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,77E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 4 digit**	
Wing span	b_W	34,32	m
Structural wing span	$b_{W,struct}$	37,87	m
Wing area	S_W	125,0	m²
Aspect ratio	A	9,42	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,5	%
Taper	λ	0,219	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	72,00	m/s
Mach number, landing	M_{APP}	0,22	
Mach number, cruise	M_{CR}	0,785	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	3,0	%c
Leading edge sweep	φ_{LE}	28,9	°
Reynoldsnumber	Re	2,2E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,57	
Correction term, camber	$\Delta_1 c_{L,max}$	0,18	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,084	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,838	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,80	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,45	

Calculations increase of lift coefficient due to flaps		**2 flap types**	
Correction factor, sweep	K_{φ}	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,42	
Use flapped span	b_W,fA	**6,9**	m
Percentage of flaps allong the wing		18%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,23	
• Flap group B			
Double-slotted flap	$\Delta c_{L,max,fB}$	1,42	
Use flapped span	b_W,fB	**11,8**	m
Percentage of flaps allong the wing		31%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,39	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,61	

Calculations increase of lift coefficient due to slats		**2 slat types**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**27**	°
• Slat group A			
0,1c Kruger flap	$\Delta c_{L,max,sA}$	0,66	
Use slatted span	b_W,sA	**4,5**	m
Percentage of slats allong the wing		12%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,07	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**25,4**	m
Percentage of slats allong the wing		67%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,54	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,61	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,64**
RE value maximum lift coefficient, landing		2,99
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,66**
RE value maximum lift coefficient, take-off		1,88

-12%

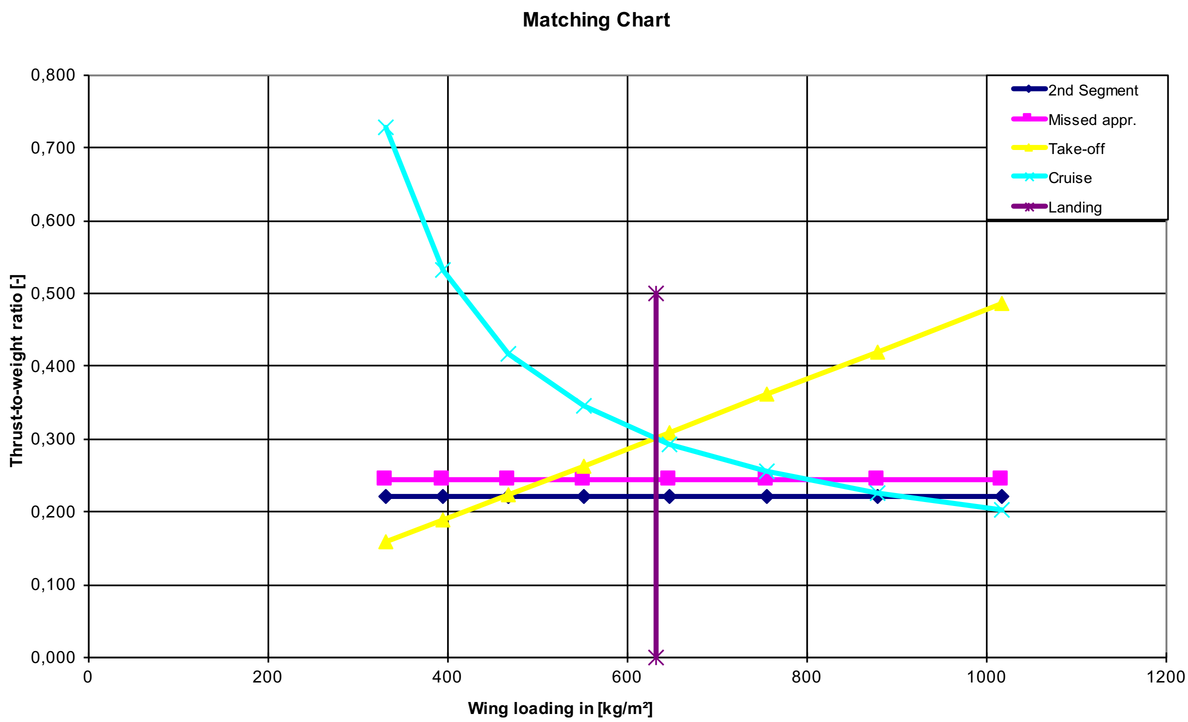
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
No winglets	$k_{e,WL}$	1,00	
Span	b_W	34,32	m
Winglet height	h	**2,49**	m
Aspect ratio	A	9,42	
Effective aspect ratio	A_{eff}	9,42	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**18,5**	
RE value maximum aerodynamic efficiency		16,00	

15%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,785	
Cruise altitude	h_{CR}	11215	m
By Pass Ratio	μ	5,60	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	117,43	kN
Overall Pressure ratio	OAPR	**27,90**	
Turbine entry temperature	TET	**1451,88**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,87	
Compressor efficiency	$\eta_{compresor}$	0,86	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,98	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,70	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,78	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,16	
Verification value specific fuel consumption	SFC	0,59	kg/daN/h
Verification value specific fuel consumption	SFC	**1,64E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,77E-05	kg/N/s
-8%			


Matching Chart
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix Q Bombardier CRJ200

Data Collection			CRJ200		1			2			3	4	5	6	7		8	9
				Source:	Aircraft characteristics for airport planning			Jane's			Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux		Data collectior	Webs
Parameter	Symbol	Units	Chosen value		200	200ER	200LR	200	200ER	200LR								
PAX			50			50			50 - 52						50			
Landing field length	s_{LFL}	m	1478		1440	1490		1423	1478						1478			
Approach speed	V_{APP}	m/s	70		70	72			69,45									
Temperature above ISA (288,15K)	ΔT_L	K	0															
Relative density	s																	
Take-off field length	s_{TOFL}	m	1768		1500	1720	1870	1527	1768	1917					1768			
Temperature above ISA (288,15K)	ΔT_{TO}	K																
Relative density	s																	
Range (max payload)	R	km	1064,9		1064,9	1620,5	2222,4	1787	3046	3713					1833			3045-3713
Cruise Mach number	M_{CR}		0,74						0,74						0,74			0,78
Wing area	S_W	m²	57,07						48,35 - 54,54						57,07			48,35
Wing span	b_W	m	21,21			21,23			21,21						21,21			21,21
Aspect ratio	A		7,88						8,9						7,88			
Maximum take-off mass	m_{MTO}	kg	24041		21523	23133	24041	21523	23133	24040					21530			24091
Payload mass	m_{PL}	kg	6125		5307	6124		5411	6124						6125			6124
Mass ratio, payload - take-off	m_{PL}/m_{MTO}														0,284			
Maximum landing mass	m_{ML}	kg	21320		20276	21319		20275	21319						21320			
Mass ratio, landing - take-off	m_{ML}/m_{MTO}																	
Operating empty mass	m_{OE}	kg	13835			13835		13730	13835						13835			
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}														0,643			
Wing loading	m_{MTO}/S_W	kg/m²	424					394,6	424,1	440,8					377			
Maximum zero fuel mass	m_{MZF}	kg	19960		19142	19958		19141	19958						19960			19958
Number of engines	n_E		2		2	2	2								2			
Engine type	GE CF34		CF34-3B1		CF34-3A1/3B	CF34-3B1	CF34-3B1		CF34-3B1						CF34-3B1	CF34-8C5		GE CF34-3B1
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	41,012						38,8 - 41						41,012	64,499		38,83-41,01
Total take-off thrust	T_{TO}	kN																
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,39					0,38799	0,36185	0,34826					0,39	0,61		
Bypass ratio	μ		6,3												6,3	4,9		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	9,80E-06												9,80E-06	1,11E-05		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s																
Available fuel volume	$V_{fuel,available}$	m³	8,081		5,3	8,081	8,081		5,3 - 8,08						8			
Cruise speed	V_{CR}	m/s	225						218,1									224,812222
Cruise altitude	h_{CR}	m	11278												11278			
Sweep angle	ϕ_{25}	°	24,9												24,9			
Mean aerodynamic chord	c_{MAC}	m																
Position of maximum camber	$x_{(y\_c),max}$	%c																
Camber	$(y_c)_{max}/c$	%c																
Position of maximum thickness	$x_{t,max}$	%c																
Relative thickness	t/c	%																
Taper	λ		0,248						0,247563353									
Overall pressure ratio	OAPR																	
Turbine entry temperature	TET	K																

Aeroplane Specifications

Data to apply reverse engineering					LL	UL
Landing field length	**Known**	s_{LFL}	**1660**	m		
Approach speed	**Known**	V_{APP}	**72,00**	m/s	72,0	72,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2600**	m	2600	2600
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**1685**	NM		
Cruise Mach number		M_{CR}	**0,785**			
Wing area		S_W	**125**	m²		
Wing span	**Known**	b_W	**34,32**	m²	34,32	34,32
Aspect ratio		A	9,42			
Maximum take-off mass		m_{MTO}	**79015**	kg		
Maximum payload mass		m_{PL}	**17830**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,226			
Maximum landing mass		m_{ML}	**66360**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,840			
Operating empty mass		m_{OE}	**42493**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,538			
Wing loading		m_{MTO}/S_W	632,1	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**117,433**	kN		
Total take-off thrust		T_{TO}	234,866	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,303			
Bypass ratio		μ	**5,6**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	229	m/s		
Cruise altitude	h_{CR}	11215	m		
Speed ratio	V/V_{md}	1,100	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	25	°		
Mean aerodynamic chord		c_{MAC}	4,2	m		
Position of maximum camber		$x_{(y\_c),max}$	30	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	4	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	30	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	11,5	%		
Taper		λ	0,219			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1660	1660	m	0,00%
Approach speed	V_{APP}	72,00	72,0	m/s	0,00%
Take-off field length	s_{TOFL}	2600	2600	m	0,00%
Span	b_W	34,32	34,32	m	0,00%
Aspect ratio	A	9,42	9,42		0,00%
Cruise speed	V_{CR}	228,6	232	m/s	1,34%
Cruise altitude	h_{CR}	11215	11215	m	0,00%
Squared Sum					**1,79E-04**
Absolute maximum deviation					1,3%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	2,99	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	1,88	
Maximum aerodynamic efficiency	E_{max}	16,00	
Specific fuel consumption	SFC	1,77E-05	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1660	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	72,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,84	
Wing loading at maximum take-off mass	m_{MTO}/S_W	632,1	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,99**	

Take-off

Take-off field length	s_{TOFL}	2600	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,303	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,88**	

2nd Segment

Aspect ratio	A	9,423
Lift coefficient, take-off	$C_{L,TO}$	1,30
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,010
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,030
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	11,62
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,220

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,77
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,033
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,068
Glide ratio in landing configuration	E_L	8,06
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,244

2) Maximum Aerodynamic Efficiency

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications

Mach number, cruise	M_{CR}	0,785	
Aspect ratio	A	9,42	
Bypass ratio	μ	5,60	
Wing loading	m_{MTO}/S_W	632	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,303	

Variables

	V/V_{md}	**1,1**

Calculations

Zero-lift drag coefficient	$C_{D,0}$	0,025
Lift coefficient at E_{max}	$C_{L,md}$	0,79
Ratio, lift coefficient	$C_L/C_{L,md}$	0,826
Lift coefficient, cruise	C_L	0,649
Actual aerodynamic efficiency, cruise	E	15,71
Max. glide ratio, cruise	E_{max}	**16,00**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,00	0,00	0,00
f'(x)	-0,12	-0,12	-0,12
E_{max}	16	16,00	16,00

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	1685	NM
Mach number, cruise	M_{CR}	0,785	
Bypass ratio	μ	5,60	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,303	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	79015	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,226	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,538	

Calculated values			
Actual aerodynamic efficiency, cruise	E	15,71	
Cruise altitude	h_{CR}	11215	m
Cruise speed	V_{CR}	232	m/s

Mission fuel fraction		
Type of aeroplane (according to Roskam)	**Transport jet**	
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980
Fuel-Fraction, descent	$M_{ff,DES}$	0,990
Fuel-Fraction, landing	$M_{ff,L}$	0,992

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,237	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,763	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,242	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,774	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,77E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 4 digit**	
Wing span	b_W	34,32	m
Structural wing span	$b_{W,struct}$	37,87	m
Wing area	S_W	125,0	m²
Aspect ratio	A	9,42	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,5	%
Taper	λ	0,219	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	72,00	m/s
Mach number, landing	M_{APP}	0,22	
Mach number, cruise	M_{CR}	0,785	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	3,0	%c
Leading edge sweep	φ_{LE}	28,9	°
Reynoldsnumber	Re	2,2E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,57	
Correction term, camber	$\Delta_1 c_{L,max}$	0,18	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,084	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,838	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,80	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,45	

Calculations increase of lift coefficient due to flaps		**2 flap types**	
Correction factor, sweep	K_φ	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,42	
Use flapped span	b_W,fA	**6,9**	m
Percentage of flaps allong the wing		18%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,23	
• Flap group B			
Double-slotted flap	$\Delta c_{L,max,fB}$	1,42	
Use flapped span	b_W,fB	**11,8**	m
Percentage of flaps allong the wing		31%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,39	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,61	

Calculations increase of lift coefficient due to slats		**2 slat types**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**27**	°
• Slat group A			
0,1c Kruger flap	$\Delta c_{L,max,sA}$	0,66	
Use slatted span	b_W,sA	**4,5**	m
Percentage of slats allong the wing		12%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,07	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**25,4**	m
Percentage of slats allong the wing		67%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,54	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,61	

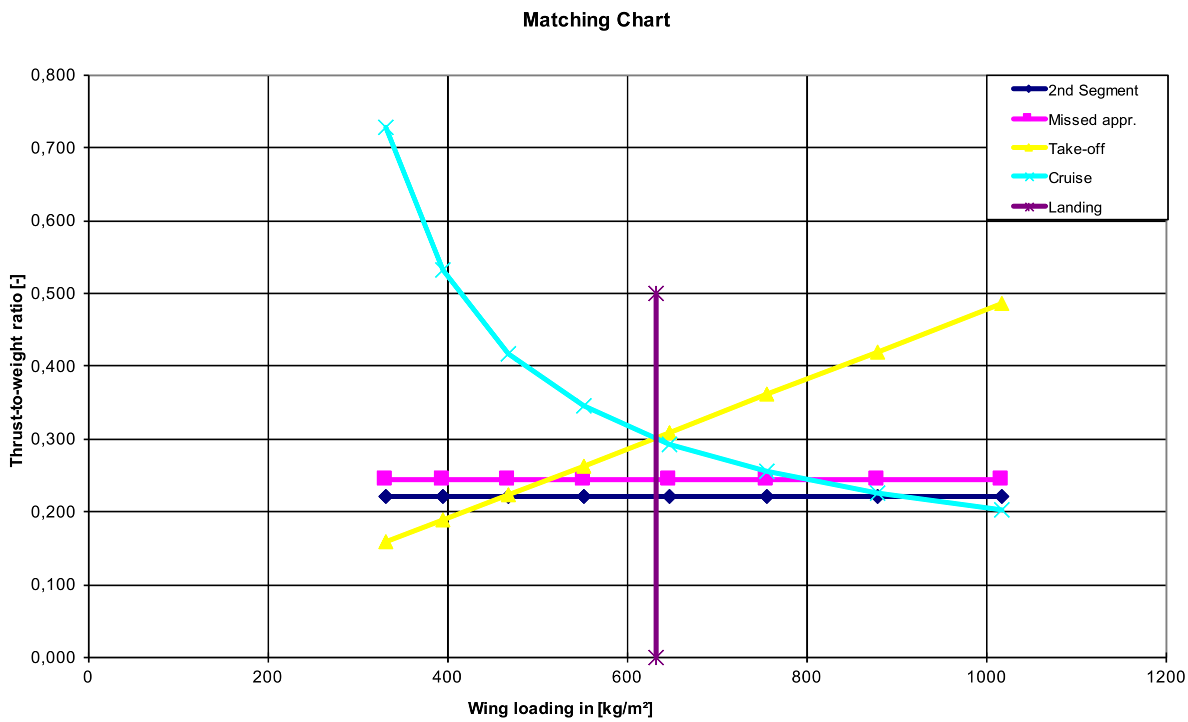
Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,64**
RE value maximum lift coefficient, landing		2,99
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,66**
RE value maximum lift coefficient, take-off		1,88
-12%		

Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
No winglets	$k_{e,WL}$	1,00	
Span	b_W	34,32	m
Winglet height	h	**2,49**	m
Aspect ratio	A	9,42	
Effective aspect ratio	A_{eff}	9,42	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**18,5**	
RE value maximum aerodynamic efficiency		16,00	
15%			

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,785	
Cruise altitude	h_{CR}	11215	m
By Pass Ratio	μ	5,60	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	117,43	kN
Overall Pressure ratio	OAPR	**27,90**	
Turbine entry temperature	TET	**1451,88**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,87	
Compressor efficiency	$\eta_{compresor}$	0,86	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,98	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,70	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,78	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,16	
Verification value specific fuel consumption	SFC	0,59	kg/daN/h
Verification value specific fuel consumption	SFC	**1,64E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,77E-05	kg/N/s
-8%			



Matching Chart
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
200
400
600
800
1000
1200
Thrust-to-weight ratio [-]
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix R Boeing 767-300

Data Collection			767-300	Source:	1			2			3	4		5	6	7	8	9
					Aircraft characteristics for airport planning			Jane's			Jenkinson	Engine		Scholz	Paul Müller	Elodie Roux	Data collection	Webs
Parameter	Symbol	Units	Chosen value					3GB	3PB	3RB								
PAX			290		261-290				269-350		290-261-216				316	290-261		
Landing field length	s_{LFL}	m	1646		1500			1677		1707	1646				1646	1646		
Approach speed	V_{APP}	m/s	74,6					74,6		76,14	72,54				72,5			
Temperature above ISA (288,15K)	ΔT_L	K	0		0						0				0			
Relative density	s																	
Take-off field length	s_{TOFL}	m	2545		2400			2530	2485	2500	2545					2545		2410
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0				15		0							
Relative density	s																	
Range (max payload)	R	km	3873		4260			9056	8926	8435	5965,3				7600	3873		10300
Cruise Mach number	M_{CR}		0,8		0,8				0,8			0,8				0,8		0,8
Wing area	S_W	m²	283,3						283,3		283,3				283,3	283,3		283,3
Wing span	b_W	m	47,57		47,57				47,57		47,57				47,57	47,57		47,6
Aspect ratio	A		7,99						8		7,987662902				8	7,99		
Maximum take-off mass	m_{MTO}	kg	156490		156490-158758				172365		156489				156490	156490		158760
Payload mass	m_{PL}	kg	39140		41558-40230						39140					41558		
Mass ratio, payload - take-off	m_{PL}/m_{MTO}										0,250113427					0,266		
Maximum landing mass	m_{ML}	kg	136078		136078				145150		136078				136080	136078		
Mass ratio, landing - take-off	m_{ML}/m_{MTO}										0,869569107							
Operating empty mass	m_{OE}	kg	84541		84541-86069			90130	90175	90945	87135					84541		86070
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}										0,5568123					0,54		
Wing loading	m_{MTO}/S_W	kg/m²	552						608,3		552,3791034					552		
Maximum zero fuel mass	m_{MZF}	kg	126099		126099				133810		126099					126099		
Number of engines	n_E		2		2						2					2		2
Engine type	GE CF6-80 (63%), PW J		CF6-80C2B2F		CF6-80C2-B2	PW4052	JT9D-7R4E	CF6-80C2B4F	PW4056	RB211-524G4	CF6-802C2B2F	CF6-80C2B2	CF6-80C2B4			CF6-80C2B2F		
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	231,351		233,373274	223,1493	222,26026	251	254	251	223,5	229,483773	254,349334			231,351		220
Total take-off thrust	T_{TO}	kN																
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,3					0,297495091	0,30101	0,29663028	0,291175413					0,3		
Bypass ratio	μ		5,3									5,31	5,15			5,3		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	9,00E-06									8,9994E-06	9,2258E-06					
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s	1,63E-05									1,6301E-05						
Available fuel volume	$V_{fuel,available}$	m³	63,216		63,216				63,216		63,216					63,216		
Cruise speed	V_{CR}	m/s	236,5								236,64-251,56							236,39
Cruise altitude	h_{CR}	m	11887		10668-11887			10700		10730	11887,2	10668				11887		
Sweep angle	ϕ_{25}	°	31,5								31,5					31,5		
Mean aerodynamic chord	c_{MAC}	m	6,98								6,98					6,98		
Position of maximum camber	$x_{(y\_c),max}$	%c	20															20
Camber	$(y_c)_{max}/c$	%c	1,5															1,5
Position of maximum thickness	$x_{t,max}$	%c	20															20
Relative thickness	t/c	%	11,5								11,5					11,5		12
Taper	λ		0,207						0,267211202		0,207					0,207		
Overall pressure ratio	OAPR		30,4									30,4	29,9					
Turbine entry temperature	TET	K																

Aeroplane Specifications

Data to apply reverse engineering

					LL	*UL*
Landing field length	**Known**	s_{LFL}	**1646**	m		
Approach speed	**Known**	V_{APP}	**74,60**	m/s	74,6	74,6
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2545**	m	2545	2545
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**2091**	NM		
Cruise Mach number		M_{CR}	**0,8**			
Wing area		S_W	**283**	m²		
Wing span	**Known**	b_W	**47,57**	m²	47,57	47,57
Aspect ratio		A	7,99			
Maximum take-off mass		m_{MTO}	**158758**	kg		
Maximum payload mass		m_{PL}	**39140**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,247			
Maximum landing mass		m_{ML}	**136078**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,857			
Operating empty mass		m_{OE}	**84541**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,533			
Wing loading		m_{MTO}/S_W	560,4	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**231,351**	kN		
Total take-off thrust		T_{TO}	462,702	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,297			
Bypass ratio		μ	**5,3**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	*UL*
Cruise speed	V_{CR}	**237**	m/s		
Cruise altitude	h_{CR}	**11887**	m		
Speed ratio	V/V_{md}	**1,000**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**31,5**	°		
Mean aerodynamic chord		c_{MAC}	**6,98**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,3**	%		
Taper		λ	**0,207**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1646	1646	m	0,00%
Approach speed	V_{APP}	74,60	74,6	m/s	0,00%
Take-off field length	s_{TOFL}	2545	2545	m	0,00%
Span	b_W	47,57	47,57	m	0,00%
Aspect ratio	A	7,99	7,99		0,00%
Cruise speed	V_{CR}	236,5	236	m/s	-0,17%
Cruise altitude	h_{CR}	11887	11828	m	-0,50%
Squared Sum					**2,77E-05**
Absolute maximum deviation					0,5%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,73**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,73**	
Maximum aerodynamic efficiency	E_{max}	**17,44**	
Specific fuel consumption	SFC	**1,52E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1646	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	74,60	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,86	
Wing loading at maximum take-off mass	m_{MTO}/S_W	560,4	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,73**	

Take-off

Take-off field length	s_{TOFL}	2545	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,297	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,73**	

2nd Segment

Aspect ratio	A	7,988
Lift coefficient, take-off	$C_{L,TO}$	1,20
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,005
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,025
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	11,17
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,227

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,61
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,026
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,061
Glide ratio in landing configuration	E_L	7,72
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,258

2) Maximum Aerodynamic Efficiency

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications

Mach number, cruise	M_{CR}	0,8	
Aspect ratio	A	7,99	
Bypass ratio	μ	5,30	
Wing loading	m_{MTO}/S_W	560	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,297	

Variables

	V/V_{md}	**1,0**

Calculations

Zero-lift drag coefficient	$C_{D,0}$	0,018
Lift coefficient at E_{max}	$C_{L,md}$	0,61
Ratio, lift coefficient	$C_L/C_{L,md}$	1,000
Lift coefficient, cruise	C_L	0,611
Actual aerodynamic efficiency, cruise	E	17,44
Max. glide ratio, cruise	E_{max}	**17,44**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,17	0,00	0,00
f'(x)	-0,11	-0,12	-0,12
E_{max}	16	17,48	17,44

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	2091	NM
Mach number, cruise	M_{CR}	0,8	
Bypass ratio	μ	5,30	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,297	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	158758	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,247	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,533	

Calculated values			
Actual aerodynamic efficiency, cruise	E	17,44	
Cruise altitude	h_{CR}	11828	m
Cruise speed	V_{CR}	236	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,221	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,779	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,120	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,898	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**no**	
	international	**yes**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	564027	m
Loiter time	t_{loiter}	1800	s
Specific fuel consumption	SFC	**1,52E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 65 series**	
Wing span	b_W	47,57	m
Structural wing span	$b_{W,struct}$	55,79	m
Wing area	S_W	283,3	m²
Aspect ratio	A	7,99	
Sweep	φ_{25}	31,5	°
Mean aerodynamic chord	c_{MAC}	6,98	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,3	%
Taper	λ	0,207	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	74,60	m/s
Mach number, landing	M_{APP}	0,23	
Mach number, cruise	M_{CR}	0,8	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,2	%c
Leading edge sweep	φ_{LE}	36,2	°
Reynoldsnumber	Re	3,7E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,29	
Correction term, camber	$\Delta_1 c_{L,max}$	0,40	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,040	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,733	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,83	
Correction term, Mach number	$\Delta C_{L,max}$	-0,03	
Lift coefficient, wing	$C_{L,max}$	1,41	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_φ	0,84	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,39	
Use flapped span	b_W,fA	**36,9**	m
Percentage of flaps allong the wing		66%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,77	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,72	
Use flapped span	b_W,fB	0	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,77	

Calculations increase of lift coefficient due to slats			**2 slat types**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**34**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,88	
Use slatted span	b_W,sA	**9,7**	m
Percentage of slats allong the wing		17%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,13	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,88	
Use slatted span	b_W,sB	**36,4**	m
Percentage of slats allong the wing		65%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,47	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,60	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,74**
RE value maximum lift coefficient, landing		2,73
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,75**
RE value maximum lift coefficient, take-off		1,73

1%

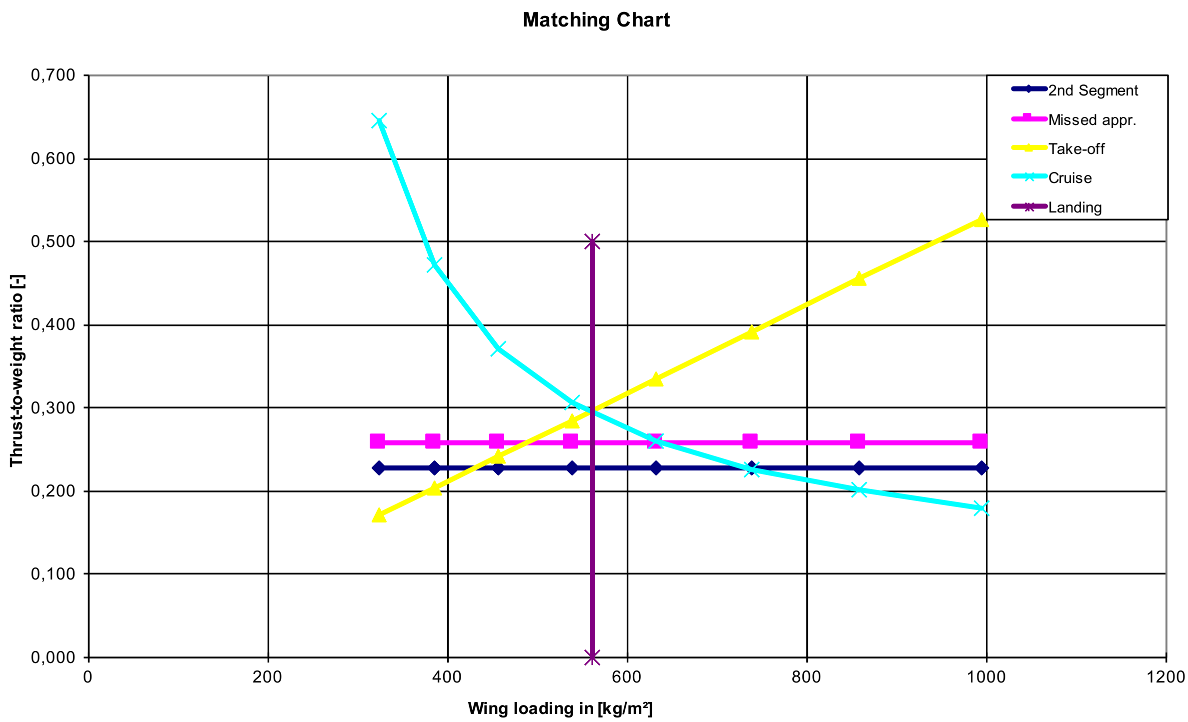
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,10	
Span	b_W	47,57	m
Winglet height	h	**3,4**	m
Aspect ratio	A	7,99	
Effective aspect ratio	A_{eff}	8,81	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**5,44**	
Verification value maximum aerodynamic efficiency	E_{max}	**19,3**	
RE value maximum aerodynamic efficiency		17,44	

11%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,800	
Cruise altitude	h_{CR}	11887	m
By Pass Ratio	μ	5,30	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	231,35	kN
Overall Pressure ratio	OAPR	**30,40**	
Turbine entry temperature	TET	**1485,42**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,89	
Compressor efficiency	$\eta_{compresor}$	0,87	
Turbine efficiency	$\eta_{turbine}$	0,91	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,86	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,13	
Temperature function	χ	1,86	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,27	
Verification value specific fuel consumption	SFC	0,57	kg/daN/h
Verification value specific fuel consumption	SFC	**1,58E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,52E-05	kg/N/s
4%			


Matching Chart
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix S Bombardier CRJ900

Data Collection			CRJ900		1	2			3	4	5	6	7	8	9
				Source:	Aircraft characteristics for airport planning	Jane's			Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collection	Webs
Parameter	Symbol	Units	Chosen value			900	900ER	900LR							
PAX			86		86		86						90-75		
Landing field length	s_{LFL}	m	1596		1670	1596		1623					1565	1660	
Approach speed	V_{APP}	m/s	71,5		71,50777778										
Temperature above ISA (288,15K)	ΔT_L	K	0		0										
Relative density	s														
Take-off field length	s_{TOFL}	m	1878		2000	1779	1861	1945					1878	1972	
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0										
Relative density	s														
Range (max payload)	R	km	1828		2440	2500	2950	1828					2774		2956
Cruise Mach number	M_{CR}		0,78				0,78						0,77	0,8	0,8
Wing area	S_W	m²	68,63				68,63						68,63		70,61
Wing span	b_W	m	23,24		23,24		24,84						23,24	23,3	24,85
Aspect ratio	A		7,87				9						7,87		
Maximum take-off mass	m_{MTO}	kg	38329		38329	36514	37421	38328					36514	36500	37995
Payload mass	m_{PL}	kg	10205			10319		10591					10205		10319
Mass ratio, payload - take-off	m_{PL}/m_{MTO}												0,279		
Maximum landing mass	m_{ML}	kg	33340		33340	33339		34019					33340		
Mass ratio, landing - take-off	m_{ML}/m_{MTO}														
Operating empty mass	m_{OE}	kg	21432		21772		21432						21546		
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}												0,59		
Wing loading	m_{MTO}/S_W	kg/m²	532			532,1	545,3	558,5					532		
Maximum zero fuel mass	m_{MZF}	kg	31751		32092		31751						31751		31751
Number of engines	n_E		2		2								2	2	2
Engine type	GE CF34		CF34-8C5		GE CF34−8C5		CF34-8C5			CF34-8C5			CF34-8C5	CF34-8C5	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	58,4				58,4 - 63,4			64,4992			64,499	58,4	58,4
Total take-off thrust	T_{TO}	kN													
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,36			0,32601	0,31888	0,3111					0,36		
Bypass ratio	μ		4,9							4,9			4,9		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	1,11E-05							1,10E-05			1,11E-05		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s													
Available fuel volume	$V_{fuel,available}$	m³	10,989		10,989		10,989						11,148		
Cruise speed	V_{CR}	m/s	244											235,615556	244,72
Cruise altitude	h_{CR}	m													
Sweep angle	ϕ_{25}	°													
Mean aerodynamic chord	c_{MAC}	m													
Position of maximum camber	$x_{(y\_c),max}$	%c													
Camber	$(y_c)_{max}/c$	%c													
Position of maximum thickness	$x_{t,max}$	%c													
Relative thickness	t/c	%													
Taper	λ														
Overall pressure ratio	OAPR														
Turbine entry temperature	TET	K													

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1596**	m		
Approach speed	**Known**	V_{APP}	**71,50**	m/s	71,5	71,5
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**1878**	m	1878	1878
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**987**	NM		
Cruise Mach number		M_{CR}	**0,78**			
Wing area		S_W	**69**	m²		
Wing span	**Known**	b_W	**23,24**	m²	23,24	23,24
Aspect ratio		A	7,87			
Maximum take-off mass		m_{MTO}	**38329**	kg		
Maximum payload mass		m_{PL}	**10205**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,266			
Maximum landing mass		m_{ML}	**33340**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,870			
Operating empty mass		m_{OE}	**21432**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,559			
Wing loading		m_{MTO}/S_W	558,5	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**58,4**	kN		
Total take-off thrust		T_{TO}	116,8	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,311			
Bypass ratio		μ	**4,9**			
Available fuel volume		$V_{fuel,available}$	**23,86**	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed		V_{CR}	**244**	m/s		
Cruise altitude		h_{CR}	**11278**	m		
Speed ratio		V/V_{md}	**1,086**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**25**	°		
Mean aerodynamic chord		c_{MAC}	**4,2**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,6**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1596	1596	m	0,00%
Approach speed	V_{APP}	71,50	71,5	m/s	0,00%
Take-off field length	s_{TOFL}	1878	1878	m	0,00%
Span	b_W	23,24	23,24	m	0,00%
Aspect ratio	A	7,87	7,87		0,00%
Cruise speed	V_{CR}	244,0	230	m/s	-5,66%
Cruise altitude	h_{CR}	11278	11278	m	0,00%
Squared Sum					**3,20E-03**
Absolute maximum deviation					*5,7%*

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,84**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,24**	
Maximum aerodynamic efficiency	E_{max}	**15,17**	
Specific fuel consumption	SFC	**1,47E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1596	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	71,50	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,87	
Wing loading at maximum take-off mass	m_{MTO}/S_W	558,5	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,84**	

Take-off

Take-off field length	s_{TOFL}	1878	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,311	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,24**	

2nd Segment

Aspect ratio	A	7,870
Lift coefficient, take-off	$C_{L,TO}$	1,56
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,023
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,043
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	8,52
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,283

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,68
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,029
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,064
Glide ratio in landing configuration	E_L	7,39
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,272

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,78	
Aspect ratio	A	7,87	
Bypass ratio	μ	4,90	
Wing loading	m_{MTO}/S_W	558	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,311	

Variables		
	V/V_{md}	**1,1**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,023
Lift coefficient at E_{max}	$C_{L,md}$	0,69
Ratio, lift coefficient	$C_L/C_{L,md}$	0,848
Lift coefficient, cruise	C_L	0,587
Actual aerodynamic efficiency, cruise	E	14,97
Max. glide ratio, cruise	E_{max}	**15,17**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,11	0,00	0,00
f'(x)	-0,13	-0,13	-0,13
E_{max}	16	15,18	15,17

3) Specific Fuel Consumption

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications

Range	R	987	NM
Mach number, cruise	M_{CR}	0,78	
Bypass ratio	μ	4,90	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,311	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	38329	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,266	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,559	

Calculated values

Actual aerodynamic efficiency, cruise	E	14,97	
Cruise altitude	h_{CR}	11278	m
Cruise speed	V_{CR}	230	m/s

Mission fuel fraction

Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations

Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,175	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,825	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,498	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,512	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,47E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 4 digit**	
Wing span	b_W	23,24	m
Structural wing span	$b_{W,struct}$	25,64	m
Wing area	S_W	68,6	m²
Aspect ratio	A	7,87	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,6	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	71,50	m/s
Mach number, landing	M_{APP}	0,22	
Mach number, cruise	M_{CR}	0,78	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	3,0	%c
Leading edge sweep	φ_{LE}	29,5	°
Reynoldsnumber	Re	2,1E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,58	
Correction term, camber	$\Delta_1 c_{L,max}$	0,18	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,086	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,838	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,79	
Correction term, Mach number	$\Delta C_{L,max}$	-0,02	
Lift coefficient, wing	$C_{L,max}$	1,45	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_{φ}	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,42	
Use flapped span	b_W,fA	**15,3**	m
Percentage of flaps allong the wing		60%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,73	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,74	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,73	

Calculations increase of lift coefficient due to slats			**1 slat type**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**30**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,90	
Use slatted span	b_W,sA	**20**	m
Percentage of slats allong the wing		78%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,61	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**0**	m
Percentage of slats allong the wing		0%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,00	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,61	

Wing

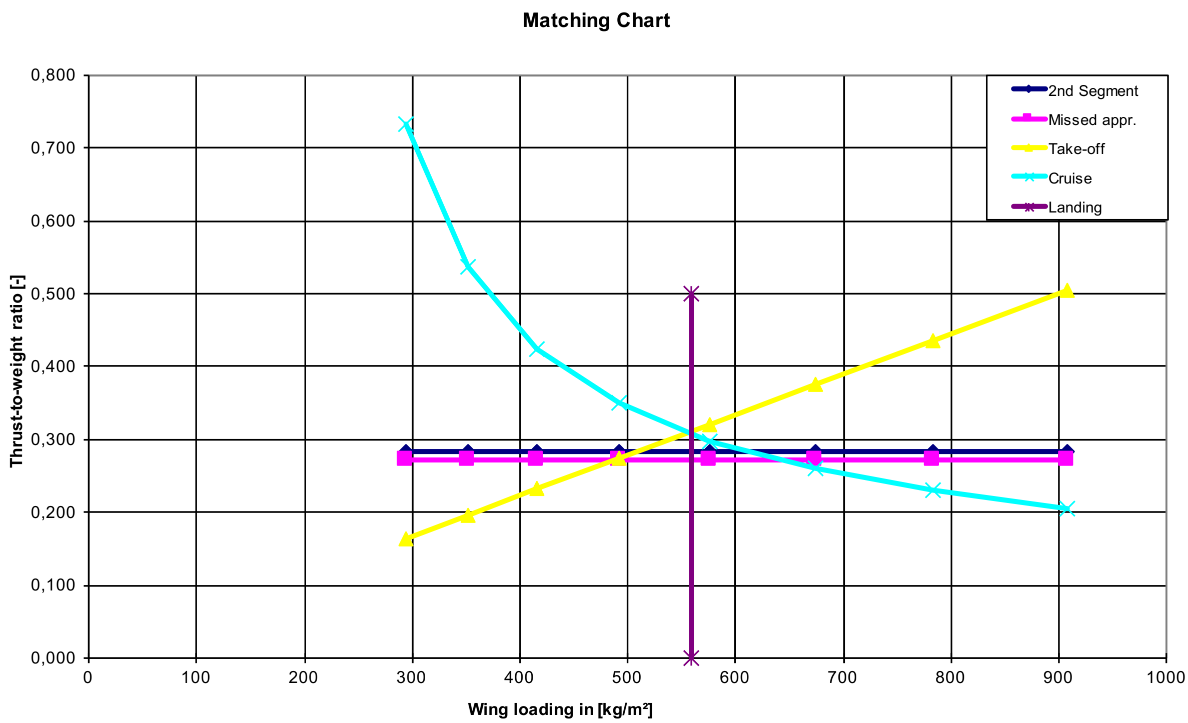
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,75**
RE value maximum lift coefficient, landing		2,84
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,16**
RE value maximum lift coefficient, take-off		2,24

-3%

Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,08	
Span	b_W	23,24	m
Winglet height	h	**1,32**	m
Aspect ratio	A	7,87	
Effective aspect ratio	A_{eff}	8,51	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**17,5**	
RE value maximum aerodynamic efficiency		15,17	

16%


Matching Chart
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
100
200
300
400
500
600
700
800
900
1000
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix T Embraer ERJ-145

Data Collection			ERJ-145		1			2			3	4	5	6	7	8	9
				Source:	Aircraft characteristics for airport planning			Jane's			Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collection	Webs
Parameter	Symbol	Units	Chosen value		ER	LR	XR	ER	LR	XR							
PAX			50			50					50			50	50		
Landing field length	s_{LFL}	m	1400		1375	1400	1450	1390		1430	1290			1290	1400	1400	1400
Approach speed	V_{APP}	m/s	65								64,8			61,11			
Temperature above ISA (288,15K)	ΔT_L	K	0			0					0			0			
Relative density	s																
Take-off field length	s_{TOFL}	m	2270		1800	2300	2050	1970		2089	1500				2270	1410	2270
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0						0						
Relative density	s																
Range (max payload)	R	km	1759		1760	2130	3333		3000	3704	1574,2			2800	1759		2900
Cruise Mach number	M_{CR}		0,78					0,78		0,8					0,64	0,78	0,78
Wing area	S_W	m²	51,18			51,18			51,18		51,18			51,18	51,18		51,2
Wing span	b_W	m	20,04		20,04		21		20,04		20,04			20,04	20,04	20,04	20,04
Aspect ratio	A		7,85			7,8			7,9		7,846846424			7,9	7,85		
Maximum take-off mass	m_{MTO}	kg	22000		20600	22000	24100	20600	22000	24100	19200			19200	20600	20990	22000
Payload mass	m_{PL}	kg	5153		5153	5786	5909	5160	5800	5920	5515				5153		5786
Mass ratio, payload - take-off	m_{PL}/m_{MTO}										0,287239583				0,25		
Maximum landing mass	m_{ML}	kg	18700		18700	19300	20000	18700	19300	20000	18700			18700	18700		19300
Mass ratio, landing - take-off	m_{ML}/m_{MTO}										0,973958333						
Operating empty mass	m_{OE}	kg	11940		11947	12114	12591	11940	12100	12580	11585				11947		11667-11740
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}										0,603385417				0,58		
Wing loading	m_{MTO}/S_W	kg/m²	402,5					402,5	429,8	470,9	375,1465416				403		
Maximum zero fuel mass	m_{MZF}	kg	17100		17100	17900	18500	17100	17900	18500	17100				17100		
Number of engines	n_E		2						2		2				2	2	2
Engine type	RR AE3007		AE3007A1/1		AE3007 A1 - A1/1		AE3007 A1E	AE 3007A - AE 3007A1P		AE 3007A1Es	AE3007A				AE3007A1/1	AE-3007A	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	33,717					33,7-37,1		39,6	31,32				33,717	31,3	33
Total take-off thrust	T_{TO}	kN															
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,33					0,3345601	0,3130086	0,334560054	0,332568807				0,33		
Bypass ratio	μ		5,3												5,3		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s															
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s															
Available fuel volume	$V_{fuel,available}$	m³	5,146		5,146	6,396	7,438	5,091	6,352	7,382	5,146				5,146		
Cruise speed	V_{CR}	m/s	231,5					231,5			188,8-210,92					231,5	231,67
Cruise altitude	h_{CR}	m	11278			11278					9753,6-11277,6				11278		
Sweep angle	ϕ_{25}	°	22,7								22,73				22,7		
Mean aerodynamic chord	c_{MAC}	m	3,13								3,13				3,13		
Position of maximum camber	$x_{(y\_c),max}$	%c															
Camber	$(y_c)_{max}/c$	%c															
Position of maximum thickness	$x_{t,max}$	%c															
Relative thickness	t/c	%	11								11				11		
Taper	λ		0,254						0,254278729		0,231				0,254		
Overall pressure ratio	OAPR		23														23
Turbine entry temperature	TET	K															

Aeroplane Specifications

Data to apply reverse engineering

					LL	*UL*
Landing field length	**Known**	s_{LFL}	**1400**	m		
Approach speed	**Known**	V_{APP}	**65,00**	m/s	65,0	65,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2270**	m	2270	2270
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**950**	NM		
Cruise Mach number		M_{CR}	**0,78**			
Wing area		S_W	**51**	m²		
Wing span	**Known**	b_W	**20,04**	m²	20,04	20,04
Aspect ratio		A	7,85			
Maximum take-off mass		m_{MTO}	**20600**	kg		
Maximum payload mass		m_{PL}	**5153**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,250			
Maximum landing mass		m_{ML}	**18700**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,908			
Operating empty mass		m_{OE}	**11940**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,580			
Wing loading		m_{MTO}/S_W	402,5	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**33,717**	kN		
Total take-off thrust		T_{TO}	67,434	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,334			
Bypass ratio		μ	**5,3**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	**232**	m/s		
Cruise altitude	h_{CR}	**11278**	m		
Speed ratio	V/V_{md}	**1,256**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**22,7**	°		
Mean aerodynamic chord		c_{MAC}	**3,13**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,6**	%		
Taper		λ	**0,254**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1400	1400	m	0,00%
Approach speed	V_{APP}	65,00	65,0	m/s	0,00%
Take-off field length	s_{TOFL}	2270	2270	m	0,00%
Span	b_W	20,04	20,04	m	0,00%
Aspect ratio	A	7,85	7,85		0,00%
Cruise speed	V_{CR}	231,5	230	m/s	-0,57%
Cruise altitude	h_{CR}	11278	11278	m	0,00%
Squared Sum					**3,20E-05**
Absolute maximum deviation					*0,6%*

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,44**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,24**	
Maximum aerodynamic efficiency	E_{max}	**15,70**	
Specific fuel consumption	SFC	**1,37E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1400	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	65,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,91	
Wing loading at maximum take-off mass	m_{MTO}/S_W	402,5	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,44**	

Take-off

Take-off field length	s_{TOFL}	2270	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,334	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,24**	

2nd Segment

Aspect ratio	A	7,847
Lift coefficient, take-off	$C_{L,TO}$	0,86
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,000
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,020
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	13,66
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,194

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,44
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,017
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,052
Glide ratio in landing configuration	E_L	8,35
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,256

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,78	
Aspect ratio	A	7,85	
Bypass ratio	μ	5,30	
Wing loading	m_{MTO}/S_W	403	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,334	

Variables		
	V/V_{md}	**1,3**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,021
Lift coefficient at E_{max}	$C_{L,md}$	0,67
Ratio, lift coefficient	$C_L/C_{L,md}$	0,634
Lift coefficient, cruise	C_L	0,423
Actual aerodynamic efficiency, cruise	E	14,20
Max. glide ratio, cruise	E_{max}	**15,70**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,04	0,00	0,00
f'(x)	-0,13	-0,13	-0,13
E_{max}	16	15,70	15,70

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	950	NM
Mach number, cruise	M_{CR}	0,78	
Bypass ratio	μ	5,30	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,334	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	20600	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,250	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,580	

Calculated values			
Actual aerodynamic efficiency, cruise	E	14,20	
Cruise altitude	h_{CR}	11278	m
Cruise speed	V_{CR}	230	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,170	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,830	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,927	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,075	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,37E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 4 digit**	
Wing span	b_W	20,04	m
Structural wing span	$b_{W,struct}$	21,72	m
Wing area	S_W	51,2	m²
Aspect ratio	A	7,85	
Sweep	φ_{25}	22,7	°
Mean aerodynamic chord	c_{MAC}	3,13	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,6	%
Taper	λ	0,254	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	65,00	m/s
Mach number, landing	M_{APP}	0,20	
Mach number, cruise	M_{CR}	0,78	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	3,0	%c
Leading edge sweep	φ_{LE}	27,0	°
Reynoldsnumber	Re	1,5E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,58	
Correction term, camber	$\Delta_1 c_{L,max}$	0,18	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,038	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,790	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,81	
Correction term, Mach number	$\Delta C_{L,max}$	0,00	
Lift coefficient, wing	$C_{L,max}$	1,44	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_φ	0,88	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,41	
Use flapped span	b_W,fA	**14,4**	m
Percentage of flaps allong the wing		66%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,82	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,74	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,82	

Calculations increase of lift coefficient due to slats			**No slats**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**26**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,90	
Use slatted span	b_W,sA	**20**	m
Percentage of slats allong the wing		92%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,74	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**0**	m
Percentage of slats allong the wing		0%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,00	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,00	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,22**
RE value maximum lift coefficient, landing		2,44
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,13**
RE value maximum lift coefficient, take-off		1,24
-9%		

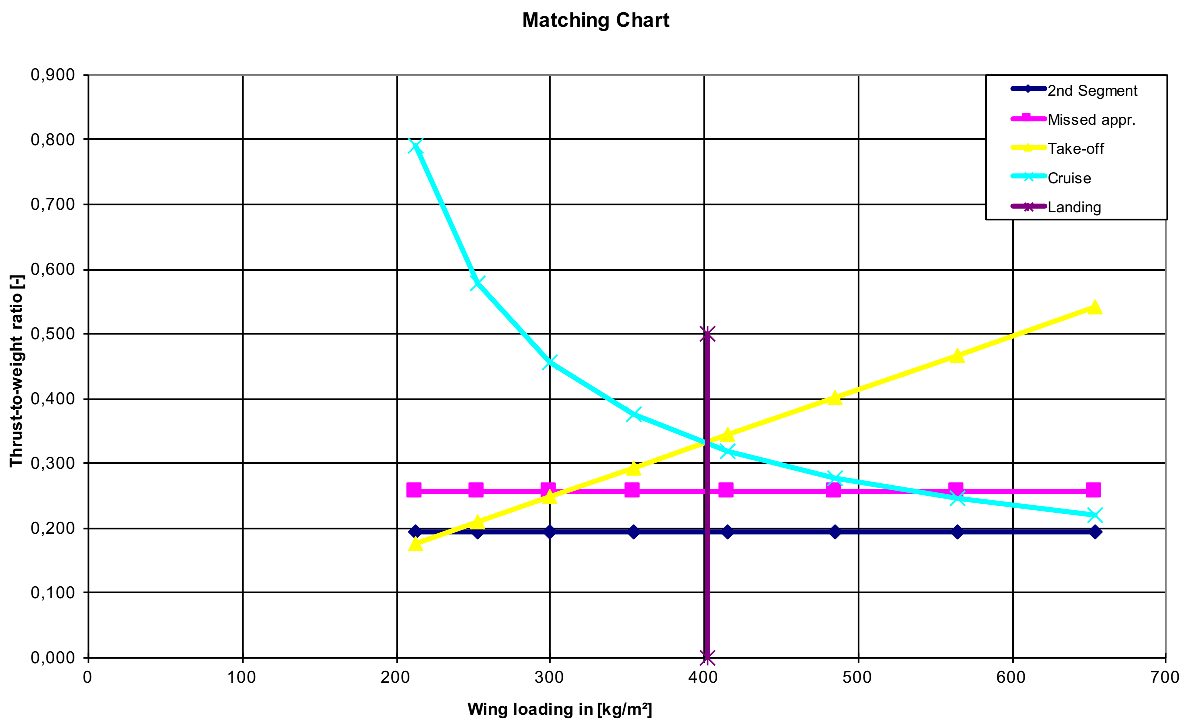
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
No winglets	$k_{e,WL}$	1,00	
Span	b_W	20,04	m
Winglet height	h	**2,7**	m
Aspect ratio	A	7,85	
Effective aspect ratio	A_{eff}	7,85	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**16,8**	
RE value maximum aerodynamic efficiency		15,70	
7%			

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,780	
Cruise altitude	h_{CR}	11278	m
By Pass Ratio	μ	5,30	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	33,72	kN
Overall Pressure ratio	OAPR	**23,00**	
Turbine entry temperature	TET	**1282,73**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,76	
Compressor efficiency	$\eta_{compresor}$	0,82	
Turbine efficiency	$\eta_{turbine}$	0,84	
Nozzle efficiency	η_{nozzle}	0,94	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	5,92	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,63	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	1,51	
Verification value specific fuel consumption	SFC	0,83	kg/daN/h
Verification value specific fuel consumption	SFC	**2,32E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,37E-05	kg/N/s

69%



Matching Chart
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
100
200
300
400
500
600
700
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix U Boeing 787-8

Data Collection			787-8	Source:	1	2	3	4		5	6	7	8	9	
Parameter	Symbol	Units	Chosen value		Aircraft characteristics for airport planning (GE / RR)	Jane's	Jenkinson	Engine		Scholz	Paul Müller	Elodie Roux	Data collection	Webs	
PAX			440		242-359-381	237-375-440									440-327
Landing field length	s_{LFL}	m	1520		1630								1520		
Approach speed	V_{APP}	m/s	72										72,022222		
Temperature above ISA (288,15K)	DT_L	K	0		0										
Relative density	s														
Take-off field length	s_{TOFL}	m	3100		3090								3100		3140
Temperature above ISA (288,15K)	DT_{TO}	K	0		0										
Relative density	s														
Range (max payload)	R	km	10180		10180	14816									15200
Cruise Mach number	M_{CR}		0,85		0,85	0,85							0,85		0,85
Wing area	S_W	m²	325												325
Wing span	b_W	m	60,12		60,12	60,12							60,1		60
Aspect ratio	A		11,1												11,0769
Maximum take-off mass	m_{MTO}	kg	227930		227930	219550							228000		227930
Payload mass	m_{PL}	kg	52165		52165	63050									
Mass ratio, payload - take-off	m_{PL}/m_{MTO}														
Maximum landing mass	m_{ML}	kg	167825		172365	167825									172365
Mass ratio, landing - take-off	m_{ML}/m_{MTO}														
Operating empty mass	m_{OE}	kg	108860			108860									117480
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}														
Wing loading	m_{MTO}/S_W	kg/m²													
Maximum zero fuel mass	m_{MZF}	kg	161025		161025	156500									161025
Number of engines	n_E		2					2					2		2
Engine type	GE GEnx-1B (60%), RR		Genx-1B70			Genx/Trent 1000		GEnx 72A1	Trent 1000				GEnx-1B	GEnx-1B70	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	310			235-311		235,7558	235,756				280	310,4859	280
Total take-off thrust	T_{TO}	kN													
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$														
Bypass ratio	μ		9			9,0-12,0			11					9-8,3	
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s													
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s													
Available fuel volume	$V_{fuel,available}$	m³	126,917		126,206	126,917									126,92
Cruise speed	V_{CR}	m/s	252										252,07778		253,61
Cruise altitude	h_{CR}	m													
Sweep angle	ϕ_{25}	°	32,2												32,2
Mean aerodynamic chord	c_{MAC}	m													
Position of maximum camber	$x_{(y\_c),max}$	%c													
Camber	$(y_c)_{max}/c$	%c													
Position of maximum thickness	$x_{t,max}$	%c													
Relative thickness	t/c	%													
Taper	λ														
Overall pressure ratio	OAPR		53,3											43,8-53,3	
Turbine entry temperature	TET	K													

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1630**	m		
Approach speed	**Known**	V_{APP}	**72,00**	m/s	72,0	72,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**3100**	m	3100	3100
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**5496**	NM		
Cruise Mach number		M_{CR}	**0,85**			
Wing area		S_W	**325**	m²		
Wing span	**Known**	b_W	**60,12**	m²	60,12	60,12
Aspect ratio		A	11,12			
Maximum take-off mass		m_{MTO}	**227930**	kg		
Maximum payload mass		m_{PL}	**52165**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,229			
Maximum landing mass		m_{ML}	**167825**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,736			
Operating empty mass		m_{OE}	**108860**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,478			
Wing loading		m_{MTO}/S_W	701,3	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**310**	kN		
Total take-off thrust		T_{TO}	620	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,277			
Bypass ratio		μ	**9**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed		V_{CR}	252	m/s		
Cruise altitude		h_{CR}	10668	m		
Speed ratio		V/V_{md}	1,156	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	32,2	°		
Mean aerodynamic chord		c_{MAC}	4,2	m		
Position of maximum camber		$x_{(y\_c),max}$	30	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	4	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	30	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	10,6	%		
Taper		λ	0,24			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1630	1630	m	0,00%
Approach speed	V_{APP}	72,00	72,0	m/s	0,00%
Take-off field length	s_{TOFL}	3100	3100	m	0,00%
Span	b_W	60,12	60,12	m	0,00%
Aspect ratio	A	11,12	11,12		0,00%
Cruise speed	V_{CR}	252,0	252	m/s	0,04%
Cruise altitude	h_{CR}	10668	10669	m	0,01%
Squared Sum					**1,40E-07**
Absolute maximum deviation					0,0%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	2,96	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	1,91	
Maximum aerodynamic efficiency	E_{max}	19,73	
Specific fuel consumption	SFC	1,16E-05	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1630	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	72,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,74	
Wing loading at maximum take-off mass	m_{MTO}/S_W	701,3	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,96**	

Take-off

Take-off field length	s_{TOFL}	3100	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,277	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,91**	

2nd Segment

Aspect ratio	A	11,121
Lift coefficient, take-off	$C_{L,TO}$	1,33
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,011
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,031
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	12,85
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,204

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,75
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,033
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,068
Glide ratio in landing configuration	E_L	9,07
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,193

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,85	
Aspect ratio	A	11,12	
Bypass ratio	μ	9,00	
Wing loading	m_{MTO}/S_W	701	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,277	

Variables		
	V/V_{md}	**1,2**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,019
Lift coefficient at E_{max}	$C_{L,md}$	0,75
Ratio, lift coefficient	$C_L/C_{L,md}$	0,748
Lift coefficient, cruise	C_L	0,563
Actual aerodynamic efficiency, cruise	E	18,92
Max. glide ratio, cruise	E_{max}	**19,73**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,35	-0,03	0,00
f'(x)	-0,09	-0,10	-0,10
E_{max}	16	19,99	19,73

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	5496	NM
Mach number, cruise	M_{CR}	0,85	
Bypass ratio	μ	9,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,277	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	227930	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,229	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,478	

Calculated values			
Actual aerodynamic efficiency, cruise	E	18,92	
Cruise altitude	h_{CR}	10669	m
Cruise speed	V_{CR}	252	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,294	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,706	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,084	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,935	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**no**	
	international	**yes**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	879330	m
Loiter time	t_{loiter}	1800	s
Specific fuel consumption	SFC	**1,16E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	60,12	m
Structural wing span	$b_{W,struct}$	71,05	m
Wing area	S_W	325,0	m²
Aspect ratio	A	11,12	
Sweep	φ_{25}	32,2	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	10,6	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	72,00	m/s
Mach number, landing	M_{APP}	0,22	
Mach number, cruise	M_{CR}	0,85	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	1,9	%c
Leading edge sweep	φ_{LE}	35,4	°
Reynoldsnumber	Re	2,2E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,17	
Correction term, camber	$\Delta_1 c_{L,max}$	0,39	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,062	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,622	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,91	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,46	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_{φ}	0,83	
• Flap group A			
0,4c Single-slotted fowler flap	$\Delta c_{L,max,fA}$	2,04	
Use flapped span	b_W,fA	**40,7**	m
Percentage of flaps allong the wing		57%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,97	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,75	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,97	

Calculations increase of lift coefficient due to slats			**2 slat types**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**34,5**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,91	
Use slatted span	b_W,sA	**13,4**	m
Percentage of slats allong the wing		19%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,14	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,91	
Use slatted span	b_W,sB	**40,1**	m
Percentage of slats allong the wing		56%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,42	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,56	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,95**
RE value maximum lift coefficient, landing		2,96
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,90**
RE value maximum lift coefficient, take-off		1,91

0%

Aerodynamic efficiency

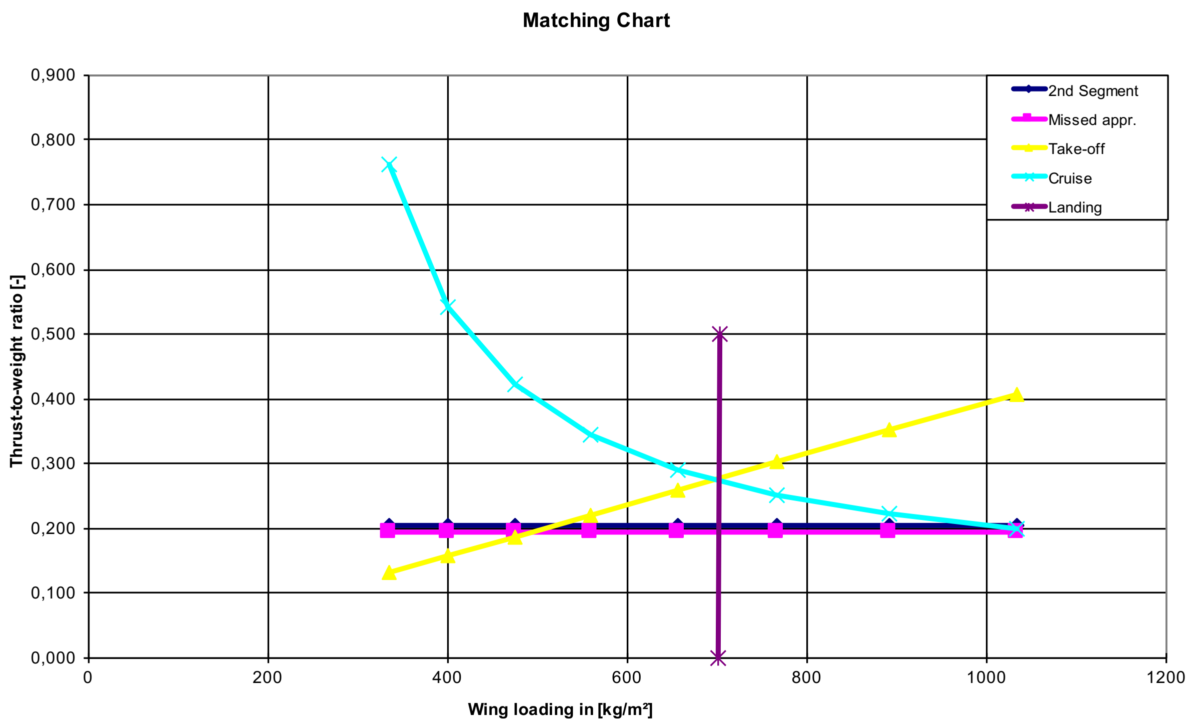
Real aircraft average	k_{WL}	2,83	
End plate (kWL = 2,13)	$k_{e,WL}$	1,41	
Span	b_W	60,12	m
Winglet height	h	**2,7**	m
Aspect ratio	A	11,12	
Effective aspect ratio	A_{eff}	15,68	
Efficiency factor, short range	k_E	16,19	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**25,4**	
RE value maximum aerodynamic efficiency		19,73	

29%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,850	
Cruise altitude	h_{CR}	10668	m
By Pass Ratio	μ	9,00	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	310,00	kN
Overall Pressure ratio	OAPR	**53,30**	
Turbine entry temperature	TET	**1494,19**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,93	
Ventilator efficiency	$\eta_{ventilator}$	0,90	
Compressor efficiency	$\eta_{compresor}$	0,88	
Turbine efficiency	$\eta_{turbine}$	0,91	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,81	K
Dimensionless turbine entry temperature	ϕ	6,83	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,14	
Temperature function	χ	2,42	
Gas generator efficiency	η_{gasgen}	0,97	
Gas generator function	G	1,96	
Verification value specific fuel consumption	SFC	0,54	kg/daN/h
Verification value specific fuel consumption	SFC	**1,50E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,16E-05	kg/N/s

30%


Matching Chart
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix V Boeing 777-200ER

Data Collection			777-200ER	Source:	1			2			3	4			5	6	7			8	9
					Aircraft characteristics for airport planning			Jane's			Jenkinson	Engine			Scholz	Paul Müller	Elodie Roux			Data collectior	Webs
Parameter	Symbol	Units	Chosen value		GE	PW	RR	GB	PB	RB											
PAX			440			305-375			305-367-375-400-440		440-375-310							440-375			
Landing field length	s_{LFL}	m	1585			1590		1616	1601		1585							1585			
Approach speed	V_{APP}	m/s	71						71		71										
Temperature above ISA (288,15K)	ΔT_L	K	0																		
Relative density	s																				
Take-off field length	s_{TOFL}	m	2135			2440		2515	2591	2545	2135							2135			
Temperature above ISA (288,15K)	ΔT_{TO}	K	0						15												
Relative density	s																				
Range (max payload)	R	km	4820			6080		10760	10547	10815								4820			
Cruise Mach number	M_{CR}		0,84			0,84			0,84			0,83						0,87			
Wing area	S_W	m²	427,8						427,8		427,8							427,8			
Wing span	b_W	m	60,93						60,93		60,9							60,93			
Aspect ratio	A		8,68						8,7		8,6694951							8,68			
Maximum take-off mass	m_{MTO}	kg	242670			229500-233600-242630			263080		242670							242670			
Payload mass	m_{PL}	kg	54635		54920	55970	57410				54635							54635			
Mass ratio, payload - take-off	m_{PL}/m_{MTO}										0,2251411							0,225			
Maximum landing mass	m_{ML}	kg	200050			200050-201800			213190		201850							201850			
Mass ratio, landing - take-off	m_{ML}/m_{MTO}										0,831788										
Operating empty mass	m_{OE}	kg	135550			135550-135850		144830	143065	141205	135875							135875			
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}										0,5599168							0,56			
Wing loading	m_{MTO}/S_W	kg/m²	567						614,9		567,25105							567			
Maximum zero fuel mass	m_{MZF}	kg	190510			190470			199580		190510							190510			
Number of engines	n_E		2								2							2			
Engine type	GE90 (39%), PW4000 (2		GE90-85B		GE 90-B4	PW 4084	TRENT 884	GE90-85B	PW4084	Trent 884	R-R/GE/PW	GE90-85B	Trent 877-1	PW4084			PW4084	Trent 877-1	GE90-85B		
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	377		376,5089	376,0644	374,7308	377	376	372	342,52	376,7644	359,0605	373,651			373,649	359,059	376,763		
Total take-off thrust	T_{TO}	kN																			
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,32					0,29238	0,29155	0,28825	0,2877603						0,33	0,3	0,32		
Bypass ratio	μ		8,4									8,4	6,15	6,41			6,4	6,2	8,4		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	9,18E-06									9,17E-06							9,18E-06		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s	1,47E-05									1,47E-05							1,47E-05		
Available fuel volume	$V_{fuel,available}$	m³	117,348			117,3			171,176		117,348							117,348			
Cruise speed	V_{CR}	m/s									244,88-256,71										
Cruise altitude	h_{CR}	m	11155					11155	10820	11005	11887,2	10668						11887			
Sweep angle	ϕ_{25}	°	31,6								31,6							31,6			
Mean aerodynamic chord	c_{MAC}	m	8,75								8,75							8,75			
Position of maximum camber	$x_{(y\_c),max}$	%c																			
Camber	$(y_c)_{max}/c$	%c																			
Position of maximum thickness	$x_{t,max}$	%c																			
Relative thickness	t/c	%	14,5-11,1-10,4															14,5-11,1-10,4			
Taper	λ		0,149								0,149							0,149			
Overall pressure ratio	OAPR											39,3	37	34,2							
Turbine entry temperature	TET	K																			

Aeroplane Specifications

Data to apply reverse engineering					LL	UL
Landing field length	Known	s_{LFL}	1585	m		
Approach speed	Known	V_{APP}	71,00	m/s	71,0	71,0
Temperature above ISA (288,15K)		ΔT_L	0	K		
Relative density		σ	1			
Take-off field length	Known	s_{TOFL}	2135	m	2135	2135
Temperature above ISA (288,15K)		ΔT_{TO}	0	K		
Relative density		σ	1,000			
Range (maximum payload)		R	2603	NM		
Cruise Mach number		M_{CR}	0,84			
Wing area		S_W	428	m²		
Wing span	Known	b_W	60,93	m²	60,93	60,93
Aspect ratio		A	8,68			
Maximum take-off mass		m_{MTO}	242670	kg		
Maximum payload mass		m_{PL}	54635	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,225			
Maximum landing mass		m_{ML}	200050	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,824			
Operating empty mass		m_{OE}	135550	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,559			
Wing loading		m_{MTO}/S_W	567,3	kg/m²		
Number of engines		n_E	2			
Take-off thrust for one engine		$T_{TO,one\ engine}$	377	kN		
Total take-off thrust		T_{TO}	754	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO} \cdot g)$	0,317			
Bypass ratio		μ	8,4			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed	V_{CR}	**252**	m/s			
Cruise altitude	h_{CR}	**11155**	m			
Speed ratio	V/V_{md}	**1,137**	-		1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**31,6**	°		
Mean aerodynamic chord		c_{MAC}	**8,75**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**10,8**	%		
Taper		λ	**0,149**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1585	1585	m	0,00%
Approach speed	V_{APP}	71,00	71,0	m/s	0,00%
Take-off field length	s_{TOFL}	2135	2135	m	0,00%
Span	b_W	60,93	60,93	m	0,00%
Aspect ratio	A	8,68	8,68		0,00%
Cruise speed	V_{CR}	252,0	248	m/s	-1,63%
Cruise altitude	h_{CR}	11155	11155	m	0,00%
Squared Sum					**2,65E-04**
Absolute maximum deviation					1,6%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,76**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,96**	
Maximum aerodynamic efficiency	E_{max}	**17,81**	
Specific fuel consumption	SFC	**1,26E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing			
Landing field length	s_{LFL}	1585	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	71,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,82	
Wing loading at maximum take-off mass	m_{MTO}/S_W	567,3	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,76**	

Take-off			
Take-off field length	s_{TOFL}	2135	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,317	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,96**	

2nd Segment		
Aspect ratio	A	8,678
Lift coefficient, take-off	$C_{L,TO}$	1,36
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,013
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,033
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	10,44
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,240

Missed approach		
Lift coefficient, landing	$C_{L,L}$	1,63
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,027
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,062
Glide ratio in landing configuration	E_L	8,11
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,238

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,84	
Aspect ratio	A	8,68	
Bypass ratio	μ	8,40	
Wing loading	m_{MTO}/S_W	567	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,317	

Variables		
	V/V_{md}	**1,1**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,018
Lift coefficient at E_{max}	$C_{L,md}$	0,65
Ratio, lift coefficient	$C_L/C_{L,md}$	0,774
Lift coefficient, cruise	C_L	0,503
Actual aerodynamic efficiency, cruise	E	17,24
Max. glide ratio, cruise	E_{max}	**17,81**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,20	-0,01	0,00
f'(x)	-0,10	-0,11	-0,11
E_{max}	16	17,87	17,81

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	2603	NM
Mach number, cruise	M_{CR}	0,84	
Bypass ratio	μ	8,40	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,317	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	242670	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,225	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,559	

Calculated values			
Actual aerodynamic efficiency, cruise	E	17,24	
Cruise altitude	h_{CR}	11155	m
Cruise speed	V_{CR}	248	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,216	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,784	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,079	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,940	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**no**	
	international	**yes**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	611438	m
Loiter time	t_{loiter}	1800	s
Specific fuel consumption	SFC	**1,26E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	60,93	m
Structural wing span	$b_{W,struct}$	71,54	m
Wing area	S_W	427,8	m²
Aspect ratio	A	8,68	
Sweep	φ_{25}	31,6	°
Mean aerodynamic chord	c_{MAC}	8,75	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	10,8	%
Taper	λ	0,149	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	71,00	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,84	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,0	%c
Leading edge sweep	φ_{LE}	36,5	°
Reynoldsnumber	Re	4,4E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,19	
Correction term, camber	$\Delta_1 c_{L,max}$	0,39	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,074	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,652	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,90	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,48	

Calculations increase of lift coefficient due to flaps			**2 flap types**
Correction factor, sweep	K_φ	0,84	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,45	
Use flapped span	b_W,fA	**10,8**	m
Percentage of flaps allong the wing		15%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,18	
• Flap group B			
Single-slotted flap	$\Delta c_{L,max,fB}$	0,79	
Use flapped span	b_W,fB	**25,1**	m
Percentage of flaps allong the wing		35%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,23	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,41	
Calculations increase of lift coefficient due to slats			**2 slat types**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**34**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,92	
Use slatted span	b_W,sA	**11,5**	m
Percentage of slats allong the wing		16%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,12	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,92	
Use slatted span	b_W,sB	**42,5**	m
Percentage of slats allong the wing		59%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,45	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,57	

Wing

Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,44**	
RE value maximum lift coefficient, landing		2,76	
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,74**	
RE value maximum lift coefficient, take-off		1,96	

-11%

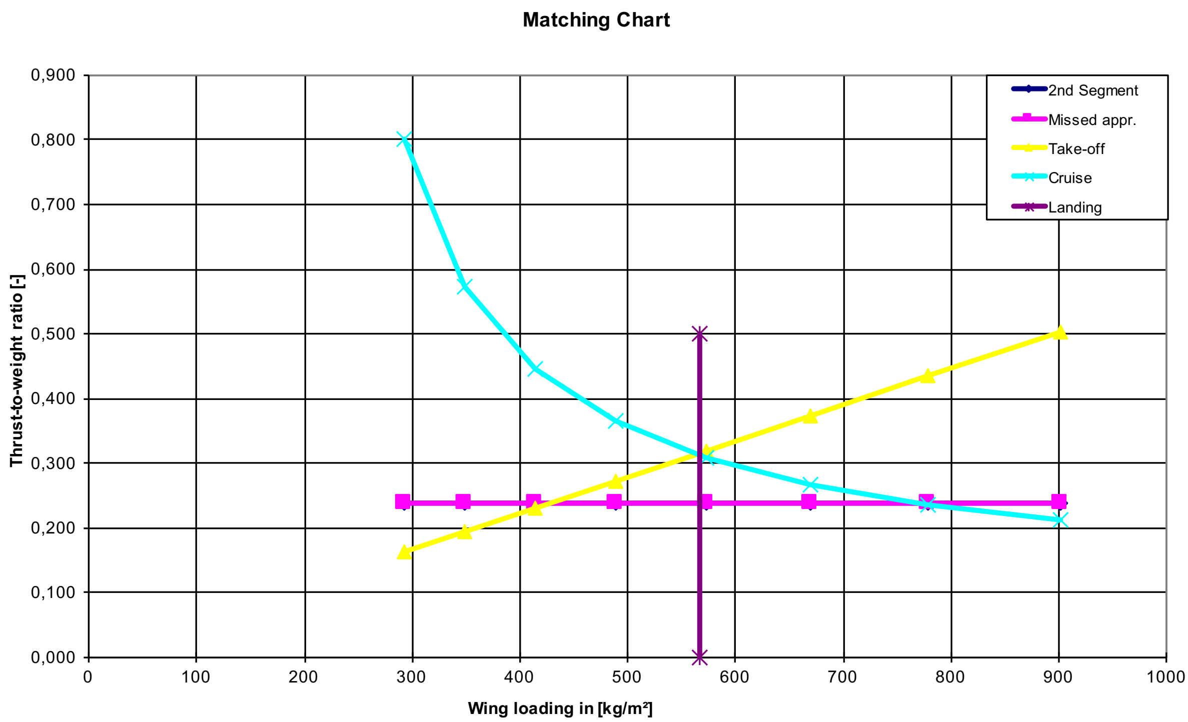
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
No winglets	$k_{e,WL}$	1,00	
Span	b_W	60,93	m
Winglet height	h	**2,7**	m
Aspect ratio	A	8,68	
Effective aspect ratio	A_{eff}	8,68	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**17,7**	
RE value maximum aerodynamic efficiency		17,81	

-1%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,840	
Cruise altitude	h_{CR}	11155	m
By Pass Ratio	μ	8,40	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	377,00	kN
Overall Pressure ratio	OAPR	**40,00**	
Turbine entry temperature	TET	**1498,78**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,93	
Ventilator efficiency	$\eta_{ventilator}$	0,90	
Compressor efficiency	$\eta_{compresor}$	0,88	
Turbine efficiency	$\eta_{turbine}$	0,91	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,92	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,14	
Temperature function	χ	2,13	
Gas generator efficiency	η_{gasgen}	0,97	
Gas generator function	G	2,21	
Verification value specific fuel consumption	SFC	0,54	kg/daN/h
Verification value specific fuel consumption	SFC	**1,49E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,26E-05	kg/N/s
	18%		


Matching Chart
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
100
200
300
400
500
600
700
800
900
1000
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix W McDonnel Douglas MD-83

Data Collection			MD-83	Source: 1	2	3	4	5	6	7	8	9
Parameter	Symbol	Units	Chosen value	Aircraft characteristics for airport planning	Jane's	Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collectior	Webs
PAX			172	172	172	172-155			172	172-155		
Landing field length	s_{LFL}	m	1585	1600	1585	1585			1540	1585		
Approach speed	V_{APP}	m/s	71,51			71,51			73,61			
Temperature above ISA (288,15K)	ΔT_L	K	0	0	0	0			0			
Relative density	s											
Take-off field length	s_{TOFL}	m	2551	2450	2552	2551				2551		
Temperature above ISA (288,15K)	ΔT_{TO}	K	0	0	0	0						
Relative density	s											
Range (max payload)	R	km	3345	3360	4635	4387,4			4200	3345		2897
Cruise Mach number	M_{CR}		0,76		0,76		0,8			0,76		
Wing area	S_W	m²	112,3		115,11	112,3			115,1	112,3		
Wing span	b_W	m	32,87	32,85	32,87	32,87			32,87	32,87		32,8
Aspect ratio	A		9,62		9,6	9,620987533			9,62	9,62		
Maximum take-off mass	m_{MTO}	kg	72575	72575	72575	72580			72575	72575		63503
Payload mass	m_{PL}	kg	18721	19193	19193	18721				19193		
Mass ratio, payload - take-off	m_{PL}/m_{MTO}					0,257936071				0,264		
Maximum landing mass	m_{ML}	kg	63276	63276	63275	63280			63276	63276		
Mass ratio, landing - take-off	m_{ML}/m_{MTO}					0,871865528						
Operating empty mass	m_{OE}	kg	35300	36145	36145	36620				36145		35300
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}					0,504546707				0,498		
Wing loading	m_{MTO}/S_W	kg/m²	646		630,5	646,3045414				646		
Maximum zero fuel mass	m_{MZF}	kg	55338	55338	55340	55340				55338		
Number of engines	n_E		2			2				2		2
Engine type	PW JT8D		JT8D-219	JT8D-219	JT8D-219	P&W JT8D-219	JT8D-219			JT8D-219		
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	96,526		93,4	96,5	93,412662			96,526		82,3
Total take-off thrust	T_{TO}	kN										
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,27		0,262992	0,271063685				0,27		
Bypass ratio	μ		1,8				1,72			1,8		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	1,47E-05				1,4688E-05			1,47E-05		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s	2,09E-05				2,0857E-05			2,09E-05		
Available fuel volume	$V_{fuel,available}$	m³	26,426	26,426	26,26	26,495				26,426		22,107
Cruise speed	V_{CR}	m/s	225			225,84-256,71						225,28
Cruise altitude	h_{CR}	m	10668	9449-10668		10668-8229,6	10668			10668		
Sweep angle	ϕ_{25}	°	24,5			24,5				24,5		
Mean aerodynamic chord	c_{MAC}	m	4,08			4,08				4,08		
Position of maximum camber	$x_{(y\_c),max}$	%c	82									82
Camber	$(y_c)_{max}/c$	%c	2,3									2,3
Position of maximum thickness	$x_{t,max}$	%c	36									36
Relative thickness	t/c	%	11			11				11		11
Taper	λ		0,195		0,156028	0,195				0,195		
Overall pressure ratio	OAPR		20,1				20,1					
Turbine entry temperature	TET	K										

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1585**	m		
Approach speed	**Known**	V_{APP}	**71,51**	m/s	71,5	71,5
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2551**	m	2551	2551
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**1806**	NM		
Cruise Mach number		M_{CR}	**0,76**			
Wing area		S_W	**112**	m²		
Wing span	**Known**	b_W	**32,87**	m²	32,87	32,87
Aspect ratio		A	9,62			
Maximum take-off mass		m_{MTO}	**72575**	kg		
Maximum payload mass		m_{PL}	**18721**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,258			
Maximum landing mass		m_{ML}	**63276**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,872			
Operating empty mass		m_{OE}	**35300**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,486			
Wing loading		m_{MTO}/S_W	646,3	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**96,526**	kN		
Total take-off thrust		T_{TO}	193,052	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,271			
Bypass ratio		μ	**1,8**			
Available fuel volume		$V_{fuel,available}$	**23,86**	m³		

Data to optimize V/V_{md}

				LL	*UL*
Cruise speed	V_{CR}	**225**	m/s		
Cruise altitude	h_{CR}	**10668**	m		
Speed ratio	V/V_{md}	**1,171**	-	1	1,316

Data to execute the verification

					Range
Sweep angle		φ_{25}	**24,5**	°	
Mean aerodynamic chord		c_{MAC}	**4,08**	m	
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50 %c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6 %c
Position of maximum thickness		$x_{t,max}$	**36**	%c	30 - 45 %c
Relative thickness	**Unknown**	t/c	**11,8**	%	
Taper		λ	**0,195**		

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1585	1585	m	0,00%
Approach speed	V_{APP}	71,51	71,5	m/s	0,00%
Take-off field length	s_{TOFL}	2551	2551	m	0,00%
Span	b_W	32,87	32,87	m	0,00%
Aspect ratio	A	9,62	9,62		0,00%
Cruise speed	V_{CR}	225,0	225	m/s	0,17%
Cruise altitude	h_{CR}	10668	10671	m	0,03%
Squared Sum					**3,13E-06**
Absolute maximum deviation					0,2%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,32**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,19**	
Maximum aerodynamic efficiency	E_{max}	**14,39**	
Specific fuel consumption	SFC	**1,61E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing			
Landing field length	s_{LFL}	1585	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	71,51	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,87	
Wing loading at maximum take-off mass	m_{MTO}/S_W	646,3	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,32**	

Take-off			
Take-off field length	s_{TOFL}	2551	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,271	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,19**	

2nd Segment		
Aspect ratio	A	9,621
Lift coefficient, take-off	$C_{L,TO}$	1,52
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,021
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,041
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	10,13
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,245

Missed approach		
Lift coefficient, landing	$C_{L,L}$	1,97
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,043
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,078
Glide ratio in landing configuration	E_L	7,53
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,268

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,76	
Aspect ratio	A	9,62	
Bypass ratio	μ	1,80	
Wing loading	m_{MTO}/S_W	646	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,271	

Variables		
	V/V_{md}	**1,2**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,031
Lift coefficient at E_{max}	$C_{L,md}$	0,89
Ratio, lift coefficient	$C_L/C_{L,md}$	0,730
Lift coefficient, cruise	C_L	0,651
Actual aerodynamic efficiency, cruise	E	13,70
Max. glide ratio, cruise	E_{max}	**14,39**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,22	-0,01	0,00
f'(x)	-0,14	-0,13	-0,13
E_{max}	16	14,43	14,39

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	1806	NM
Mach number, cruise	M_{CR}	0,76	
Bypass ratio	μ	1,80	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,271	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	72575	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,258	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,486	

Calculated values			
Actual aerodynamic efficiency, cruise	E	13,70	
Cruise altitude	h_{CR}	10671	m
Cruise speed	V_{CR}	225	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,256	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,744	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,263	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,752	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,61E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 4 digit**	
Wing span	b_W	32,87	m
Structural wing span	$b_{W,struct}$	36,12	m
Wing area	S_W	112,3	m²
Aspect ratio	A	9,62	
Sweep	φ_{25}	24,5	°
Mean aerodynamic chord	c_{MAC}	4,08	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	36	%c
Relative thickness	t/c	11,8	%
Taper	λ	0,195	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	71,51	m/s
Mach number, landing	M_{APP}	0,22	
Mach number, cruise	M_{CR}	0,76	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	3,1	%c
Leading edge sweep	φ_{LE}	28,5	°
Reynoldsnumber	Re	2,1E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,51	
Correction term, camber	$\Delta_1 c_{L,max}$	0,16	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,03	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,091	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,793	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,80	
Correction term, Mach number	$\Delta C_{L,max}$	-0,02	
Lift coefficient, wing	$C_{L,max}$	1,42	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_φ	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,39	
Use flapped span	b_W,fA	**22**	m
Percentage of flaps allong the wing		61%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,74	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,72	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,74	

Calculations increase of lift coefficient due to slats			**1 slat type**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**27**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,88	
Use slatted span	b_W,sA	**29,6**	m
Percentage of slats allong the wing		82%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,64	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,88	
Use slatted span	b_W,sB	**0**	m
Percentage of slats allong the wing		0%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,00	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,64	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,76**
RE value maximum lift coefficient, landing		3,32
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,81**
RE value maximum lift coefficient, take-off		2,19
-17%		

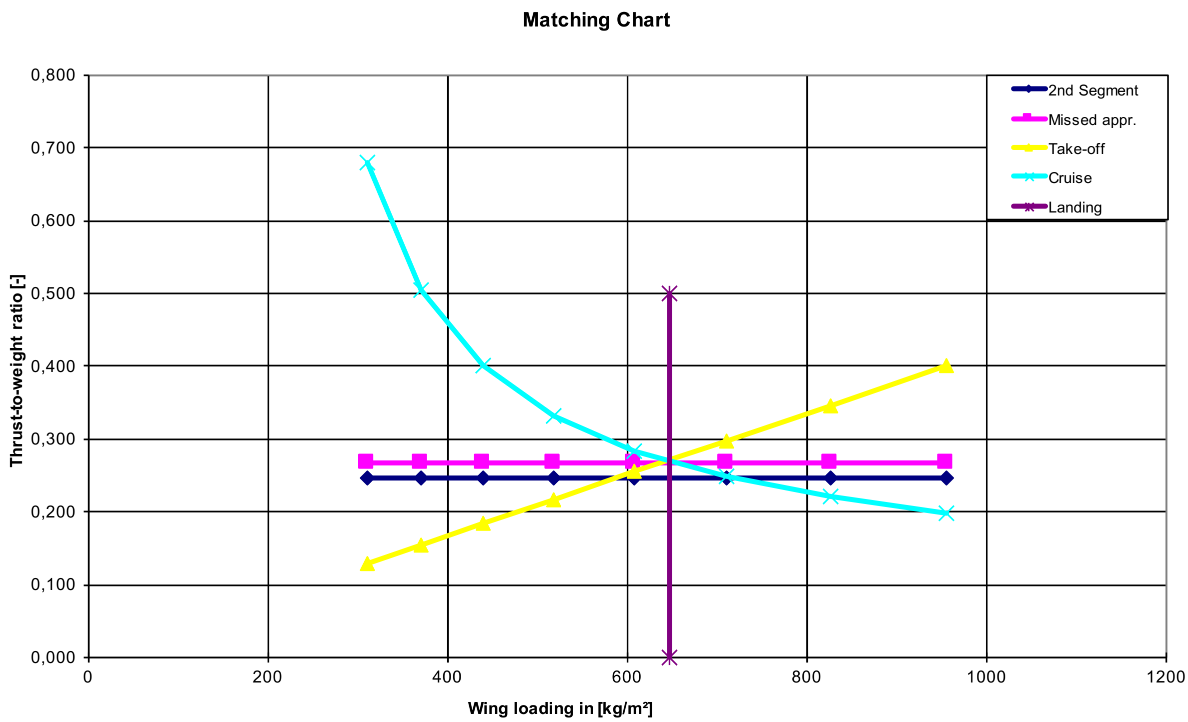
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
No winglets	$k_{e,WL}$	1,00	
Span	b_W	32,87	m
Winglet height	h	**2,7**	m
Aspect ratio	A	9,62	
Effective aspect ratio	A_{eff}	9,62	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,56**	
Verification value maximum aerodynamic efficiency	E_{max}	**18,3**	
RE value maximum aerodynamic efficiency		14,39	
28%			

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,760	
Cruise altitude	h_{CR}	10668	m
By Pass Ratio	μ	1,80	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	96,53	kN
Overall Pressure ratio	OAPR	**20,10**	
Turbine entry temperature	TET	**1437,12**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,97	
Ventilator efficiency	$\eta_{ventilator}$	0,82	
Compressor efficiency	$\eta_{compresor}$	0,82	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,98	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,81	K
Dimensionless turbine entry temperature	ϕ	6,57	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,51	
Gas generator efficiency	η_{gasgen}	0,99	
Gas generator function	G	2,07	
Verification value specific fuel consumption	SFC	0,74	kg/daN/h
Verification value specific fuel consumption	SFC	**2,04E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,61E-05	kg/N/s

27%



Matching Chart
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
200
400
600
800
1000
1200
Thrust-to-weight ratio [-]
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix X Boeing 757-200

Data Collection			757-200	Source:	1				2				3	4		6	7		8	9
					Aircraft characteristics for airport planning				Jane's				Jenkinson	Engine		Paul Müller	Elodie Roux		Data collection	Webs
Parameter	Symbol	Units	Chosen value						A	C	B	D								
PAX			224		186-224-239				195-201-224-231				239-186			239	224-186			
Landing field length	s_{LFL}	m	1550		1550		1510		1463	1418	1555	1494	1564			1460	1564		1400	
Approach speed	V_{APP}	m/s	68						67,91		70,48		70,48			68,06			70,47888889	
Temperature above ISA (288,15K)	ΔT_L	K	0		0				0				0			0				
Relative density	s																			
Take-off field length	s_{TOFL}	m	2225		2930	2290	2225	2000	1814	1677	2378	2104	2226				2226		1900	2070
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0				14				0							
Relative density	s																			
Range (max payload)	R	km	4440		4440-5740		4260-5090		4759	4398	7278	6843	7059,82			5500	2268			7222
Cruise Mach number	M_{CR}		0,8		0,8				0,8						0,8		0,8		0,8	0,8
Wing area	S_W	m²	185,25						185,25				185,25			185,25	185,25			181,25
Wing span	b_W	m	38,05		38,05				38,05				38,05			38,05	38,05		38,1	38,05
Aspect ratio	A		7,8						7,8				7,815398111			7,8	7,82			7,8
Maximum take-off mass	m_{MTO}	kg	115650		99800-115650				99790		115665		115900			104325	99800		115680	115680
Payload mass	m_{PL}	kg	22650		25250-25000		22650-21350						25690				22650			25920
Mass ratio, payload - take-off	m_{PL}/m_{MTO}												0,221656601				0,227			
Maximum landing mass	m_{ML}	kg	89800		89800-95250				89815		95255		95450			89810	89800			
Mass ratio, landing - take-off	m_{ML}/m_{MTO}												0,823554789							
Operating empty mass	m_{OE}	kg	60800		58250-59350		60800-62100		58325	58550	58390	58620	58040				60800			58390
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}												0,500776531				0,609			
Wing loading	m_{MTO}/S_W	kg/m²	538,7						538,7		624,4		625,6410256				539			
Maximum zero fuel mass	m_{MZF}	kg	83460		83450-85300				83460		84370	85275	84550				83450			
Number of engines	n_E		2										2				2		2	2
Engine type	PW2000 (43%), RR RB2		RB211-535E4		PW2037	PW 2040	RB211-535E4	RB211-535E4B	PW2037	RB211-535E4	PW2040s	RB211-535E4-B	RB211-535E4B	RB.211-535E4B-37	RB.211-535E4-37		RB.211-535E4	PW2040	RB211-535E4B	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	178,5		165,3616	185,3651	178,2522	191,588345	168,2	178,8	178,4	193,5	191,3	191,7183682	178,3737022		191,718	178,373	193,5	193
Total take-off thrust	T_{TO}	kN																		
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,37						0,3334667	0,36573769	0,3149408	0,341273633	0,336505775				0,39	0,36		
Bypass ratio	μ		4,4											4,3	4,3		4,3	5,9	4,4	
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	1,72E-05												9,1692E-06		1,72E-05	9,35E-06		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s	1,69E-05												1,69234E-05		1,69E-05	1,65E-05		
Available fuel volume	$V_{fuel,available}$	m³	42,68		42,68				42,684-43,489				42,597				42,68			43,49
Cruise speed	V_{CR}	m/s	241										236,13-263,91						241,7888889	241,11
Cruise altitude	h_{CR}	m	11795		10668-11887				11675	11795	10790	10880	11887,2-9448,8		10668		11887			
Sweep angle	φ_{25}	°	25										25				25			25
Mean aerodynamic chord	c_{MAC}	m	5,64										5,64				5,64			
Position of maximum camber	$x_{(y\_c),max}$	%c																		
Camber	$(y_c)_{max}/c$	%c																		
Position of maximum thickness	$x_{t,max}$	%c																		
Relative thickness	t/c	%																		
Taper	λ		0,243						0,21097561				0,243				0,243			
Overall pressure ratio	OAPR		25,8											25,8	25,8					
Turbine entry temperature	TET	K																		

Aeroplane Specifications

Data to apply reverse engineering

					LL	*UL*
Landing field length	**Known**	s_{LFL}	**1550**	m		
Approach speed	**Known**	V_{APP}	**68,00**	m/s	68,0	68,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2225**	m	2225	2225
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**2397**	NM		
Cruise Mach number		M_{CR}	**0,8**			
Wing area		S_W	**185**	m²		
Wing span	**Known**	b_W	**38,05**	m²	38,05	38,05
Aspect ratio		A	7,82			
Maximum take-off mass		m_{MTO}	**115650**	kg		
Maximum payload mass		m_{PL}	**22650**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,196			
Maximum landing mass		m_{ML}	**89800**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,776			
Operating empty mass		m_{OE}	**60800**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,526			
Wing loading		m_{MTO}/S_W	624,3	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**178,5**	kN		
Total take-off thrust		T_{TO}	357	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,315			
Bypass ratio		μ	**4,4**			
Available fuel volume		$V_{fuel,available}$	**23,86**	m³		

Data to optimize V/V_{md}

				LL	*UL*
Cruise speed	V_{CR}	**241**	m/s		
Cruise altitude	h_{CR}	**11795**	m		
Speed ratio	V/V_{md}	**1,000**	-	1	1,316

Data to execute the verification

					Range
Sweep angle		φ_{25}	**25**	°	
Mean aerodynamic chord		c_{MAC}	**5,64**	m	
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50 %c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6 %c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45 %c
Relative thickness	**Unknown**	t/c	**11,3**	%	
Taper		λ	**0,24**		

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1550	1550	m	0,00%
Approach speed	V_{APP}	68,00	68,0	m/s	0,00%
Take-off field length	s_{TOFL}	2225	2225	m	0,00%
Span	b_W	38,05	38,05	m	0,00%
Aspect ratio	A	7,82	7,82		0,00%
Cruise speed	V_{CR}	241,0	236	m/s	-2,04%
Cruise altitude	h_{CR}	11795	11737	m	-0,49%
Squared Sum					**4,38E-04**
Absolute maximum deviation					*2,0%*

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,92**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,09**	
Maximum aerodynamic efficiency	E_{max}	**15,54**	
Specific fuel consumption	SFC	**1,74E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing			
Landing field length	s_{LFL}	1550	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	68,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,78	
Wing loading at maximum take-off mass	m_{MTO}/S_W	624,3	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,92**	

Take-off			
Take-off field length	s_{TOFL}	2225	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,315	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,09**	

2nd Segment		
Aspect ratio	A	7,815
Lift coefficient, take-off	$C_{L,TO}$	1,45
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,017
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,037
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	9,08
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,268

Missed approach		
Lift coefficient, landing	$C_{L,L}$	1,73
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,031
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,066
Glide ratio in landing configuration	E_L	7,19
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,249

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,8	
Aspect ratio	A	7,82	
Bypass ratio	μ	4,40	
Wing loading	m_{MTO}/S_W	624	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,315	

Variables		
	V/V_{md}	**1,0**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,022
Lift coefficient at E_{max}	$C_{L,md}$	0,67
Ratio, lift coefficient	$C_L/C_{L,md}$	1,000
Lift coefficient, cruise	C_L	0,672
Actual aerodynamic efficiency, cruise	E	15,54
Max. glide ratio, cruise	E_{max}	**15,54**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,06	0,00	0,00
f'(x)	-0,13	-0,13	-0,13
E_{max}	16	15,54	15,54

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	2397	NM
Mach number, cruise	M_{CR}	0,8	
Bypass ratio	μ	4,40	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,315	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	115650	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,196	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,526	

Calculated values			
Actual aerodynamic efficiency, cruise	E	15,54	
Cruise altitude	h_{CR}	11737	m
Cruise speed	V_{CR}	236	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,278	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,722	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,165	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,852	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,74E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*		**NACA 4 digit**
Wing span	b_W	38,05	m
Structural wing span	$b_{W,struct}$	41,98	m
Wing area	S_W	185,3	m²
Aspect ratio	A	7,82	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	5,64	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,3	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	68,00	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,8	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,9	%c
Leading edge sweep	φ_{LE}	29,5	°
Reynoldsnumber	Re	2,7E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,56	
Correction term, camber	$\Delta_1 c_{L,max}$	0,20	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,096	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,855	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,79	
Correction term, Mach number	$\Delta C_{L,max}$	0,00	
Lift coefficient, wing	$C_{L,max}$	1,47	

Calculations increase of lift coefficient due to flaps		**1 flap type**	
Correction factor, sweep	K_φ	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,44	
Use flapped span	b_W,fA	**28,8**	m
Percentage of flaps allong the wing		69%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,86	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,75	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,86	

Calculations increase of lift coefficient due to slats		**2 slat types**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**28**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,91	
Use slatted span	b_W,sA	**6,9**	m
Percentage of slats allong the wing		16%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,13	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,91	
Use slatted span	b_W,sB	**25,6**	m
Percentage of slats allong the wing		61%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,49	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,62	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,91**
RE value maximum lift coefficient, landing		2,92
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,08**
RE value maximum lift coefficient, take-off		2,09

0%

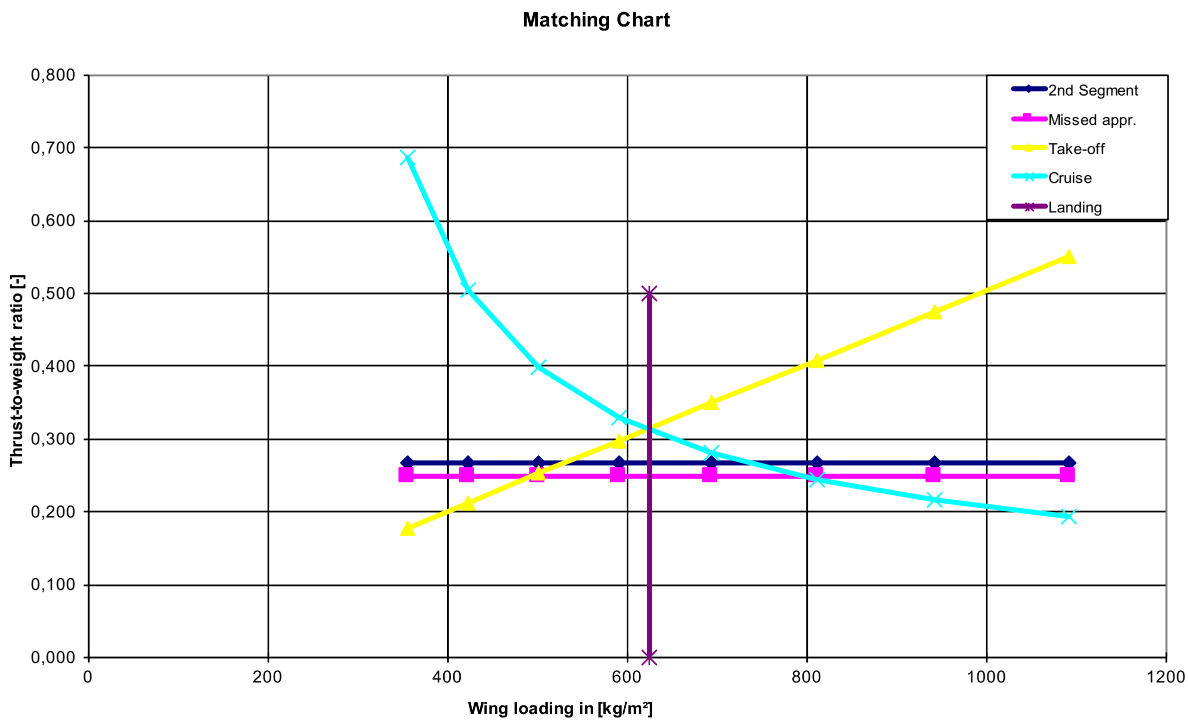
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
No winglets	$k_{e,WL}$	1,00	
Span	b_W	38,05	m
Winglet height	h	**2,5**	m
Aspect ratio	A	7,82	
Effective aspect ratio	A_{eff}	7,82	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**5,61**	
Verification value maximum aerodynamic efficiency	E_{max}	**17,9**	
RE value maximum aerodynamic efficiency		15,54	

15%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,800	
Cruise altitude	h_{CR}	11795	m
By Pass Ratio	μ	4,40	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	178,50	kN
Overall Pressure ratio	OAPR	**25,80**	
Turbine entry temperature	TET	**1475,18**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,87	
Compressor efficiency	$\eta_{compresor}$	0,86	
Turbine efficiency	$\eta_{turbine}$	0,91	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,81	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,13	
Temperature function	χ	1,73	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,27	
Verification value specific fuel consumption	SFC	0,60	kg/daN/h
Verification value specific fuel consumption	SFC	**1,68E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,74E-05	kg/N/s
-3%			


Matching Chart
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix Y Airbus A380-800

Data Collection			A380-800	Source:	1	2	3	4	5	6	7		8	9
Parameter	Symbol	Units	Chosen value		Aircraft characteristics for airport planning	Jane's	Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux		Data collectior	Webs
PAX			853		555	555					853-555			555-853
Landing field length	s_{LFL}	m	1940		1940	2103					2100		2010	
Approach speed	V_{APP}	m/s	71		71	72,5							70,993333	
Temperature above ISA (288,15K)	ΔT_L	K	0		0	15								
Relative density	s													
Take-off field length	s_{TOFL}	m	2987		2950	2987					2990		2950	2750
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0	15								
Relative density	s													
Range (max payload)	R	km	12149		12200	14816					12149			14800
Cruise Mach number	M_{CR}		0,85			0,82		0,85			0,85		0,85	0,85
Wing area	S_W	m²	845,82			845					845,82			845
Wing span	b_W	m	79,75		79,75	79,8					79,75		79,75	79,75
Aspect ratio	A		7,52			7,5					7,52			
Maximum take-off mass	m_{MTO}	kg	575000		575000	560000					560000		560000	575000
Payload mass	m_{PL}	kg	83600		83600	90985					84320			
Mass ratio, payload - take-off	m_{PL}/m_{MTO}										0,151			
Maximum landing mass	m_{ML}	kg	395000		395000	386000					386000			394000
Mass ratio, landing - take-off	m_{ML}/m_{MTO}													
Operating empty mass	m_{OE}	kg	270015			270015					276680			276000
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}										0,494			
Wing loading	m_{MTO}/S_W	kg/m²	662			662,7					662			
Maximum zero fuel mass	m_{MZF}	kg	361000		369000	361000					361000			369000
Number of engines	n_E		4								4	4	4	4
Engine type	EA GP7200 (42%), RR T		Trent 970-84			RR Trent 970		GP7270			GP7270	Trent 970-84	GP7200	GP7270-Trent 970/B
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	374			374		311,376			311,374	334,282	311	311
Total take-off thrust	T_{TO}	kN												
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,24			0,2203905					0,23	0,24		
Bypass ratio	μ		8,7					8,7			8,7	7,1		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s												
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s												
Available fuel volume	$V_{fuel,available}$	m³	324,562		323,546	310-355,85					324,562			320
Cruise speed	V_{CR}	m/s	267,5										267,51111	
Cruise altitude	h_{CR}	m	10668			10670-13100		10668			13100			
Sweep angle	ϕ_{25}	°	33,5			35					33,5			
Mean aerodynamic chord	c_{MAC}	m	12,3			12,3					12,3			
Position of maximum camber	$x_{(y\_c),max}$	%c	81											81
Camber	$(y_c)_{max}/c$	%c	2,5											2,5
Position of maximum thickness	$x_{t,max}$	%c	37											37
Relative thickness	t/c	%	13,4-9,1-9,2								13,4-9,1-9,2			14
Taper	λ		0,225								0,225			
Overall pressure ratio	OAPR		45,6					45,6						
Turbine entry temperature	TET	K												

Aeroplane Specifications

Data to apply reverse engineering

					LL	*UL*
Landing field length	**Known**	s_{LFL}	**1940**	m		
Approach speed	**Known**	V_{APP}	**71,00**	m/s	71,0	71,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2987**	m	2987	2987
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**6560**	NM		
Cruise Mach number		M_{CR}	**0,85**			
Wing area		S_W	**846**	m²		
Wing span	**Known**	b_W	**79,75**	m²	79,75	79,75
Aspect ratio		A	7,52			
Maximum take-off mass		m_{MTO}	**575000**	kg		
Maximum payload mass		m_{PL}	**83600**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,145			
Maximum landing mass		m_{ML}	**395000**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,687			
Operating empty mass		m_{OE}	**270015**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,470			
Wing loading		m_{MTO}/S_W	679,8	kg/m²		
Number of engines		n_E	**4**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**374**	kN		
Total take-off thrust		T_{TO}	1496	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,265			
Bypass ratio		μ	**8,7**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	*UL*
Cruise speed	V_{CR}	**268**	m/s		
Cruise altitude	h_{CR}	**10668**	m		
Speed ratio	V/V_{md}	**1,000**	-	1	1,316

Data to execute the verification

					Range
Sweep angle		φ_{25}	**35**	°	
Mean aerodynamic chord		c_{MAC}	**12,3**	m	
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50 %c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6 %c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45 %c
Relative thickness	**Unknown**	t/c	**10,6**	%	
Taper		λ	**0,225**		

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1940	1940	m	0,00%
Approach speed	V_{APP}	71,00	71,0	m/s	0,00%
Take-off field length	s_{TOFL}	2987	2987	m	0,00%
Span	b_W	79,75	79,75	m	0,00%
Aspect ratio	A	7,52	7,52		0,00%
Cruise speed	V_{CR}	267,5	253	m/s	-5,50%
Cruise altitude	h_{CR}	10668	10483	m	-1,73%
Squared Sum					**3,33E-03**
Absolute maximum deviation					*5,5%*

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,25**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,01**	
Maximum aerodynamic efficiency	E_{max}	**18,94**	
Specific fuel consumption	SFC	**1,48E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1940	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	71,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,69	
Wing loading at maximum take-off mass	m_{MTO}/S_W	679,8	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,25**	

Take-off

Take-off field length	s_{TOFL}	2987	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,265	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,01**	

2nd Segment

Aspect ratio	A	7,519
Lift coefficient, take-off	$C_{L,TO}$	1,39
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,015
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,035
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	9,15
Number of engines	n_E	4
Climb gradient	$\sin(\gamma)$	0,030
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,186

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,33
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,012
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,047
Glide ratio in landing configuration	E_L	8,66
Climb gradient	$\sin(\gamma)$	0,027
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,131

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,85	
Aspect ratio	A	7,52	
Bypass ratio	μ	8,70	
Wing loading	m_{MTO}/S_W	680	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,265	

Variables		
	V/V_{md}	**1,0**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,014
Lift coefficient at E_{max}	$C_{L,md}$	0,53
Ratio, lift coefficient	$C_L/C_{L,md}$	1,000
Lift coefficient, cruise	C_L	0,530
Actual aerodynamic efficiency, cruise	E	18,94
Max. glide ratio, cruise	E_{max}	**18,94**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,28	-0,02	0,00
f'(x)	-0,09	-0,10	-0,10
E_{max}	16	19,09	18,94

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	6560	NM
Mach number, cruise	M_{CR}	0,85	
Bypass ratio	μ	8,70	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,265	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	575000	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,145	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,470	

Calculated values			
Actual aerodynamic efficiency, cruise	E	18,94	
Cruise altitude	h_{CR}	10483	m
Cruise speed	V_{CR}	253	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,385	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,615	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,033	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,986	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**no**	
	international	**yes**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	977856	m
Loiter time	t_{loiter}	1800	s
Specific fuel consumption	SFC	**1,48E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 63 series**	
Wing span	b_W	79,75	m
Structural wing span	$b_{W,struct}$	97,36	m
Wing area	S_W	845,8	m²
Aspect ratio	A	7,52	
Sweep	φ_{25}	35	°
Mean aerodynamic chord	c_{MAC}	12,3	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	10,6	%
Taper	λ	0,225	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	71,00	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,85	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,3	%c
Leading edge sweep	φ_{LE}	39,8	°
Reynoldsnumber	Re	6,2E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,36	
Correction term, camber	$\Delta_1 c_{L,max}$	0,38	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,018	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,760	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,78	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,36	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_{φ}	0,81	
• Flap group A			
Single-slotted flap	$\Delta c_{L,max,fA}$	0,73	
Use flapped span	b_W,fA	**45,3**	m
Percentage of flaps allong the wing		47%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,28	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,69	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,28	

Calculations increase of lift coefficient due to slats			**1 slat type**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**37**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,84	
Use slatted span	b_W,sA	**59,3**	m
Percentage of slats allong the wing		61%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,41	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,84	
Use slatted span	b_W,sB	**0**	m
Percentage of slats allong the wing		0%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,00	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,41	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,03**
RE value maximum lift coefficient, landing		2,25
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,81**
RE value maximum lift coefficient, take-off		2,01

-10%

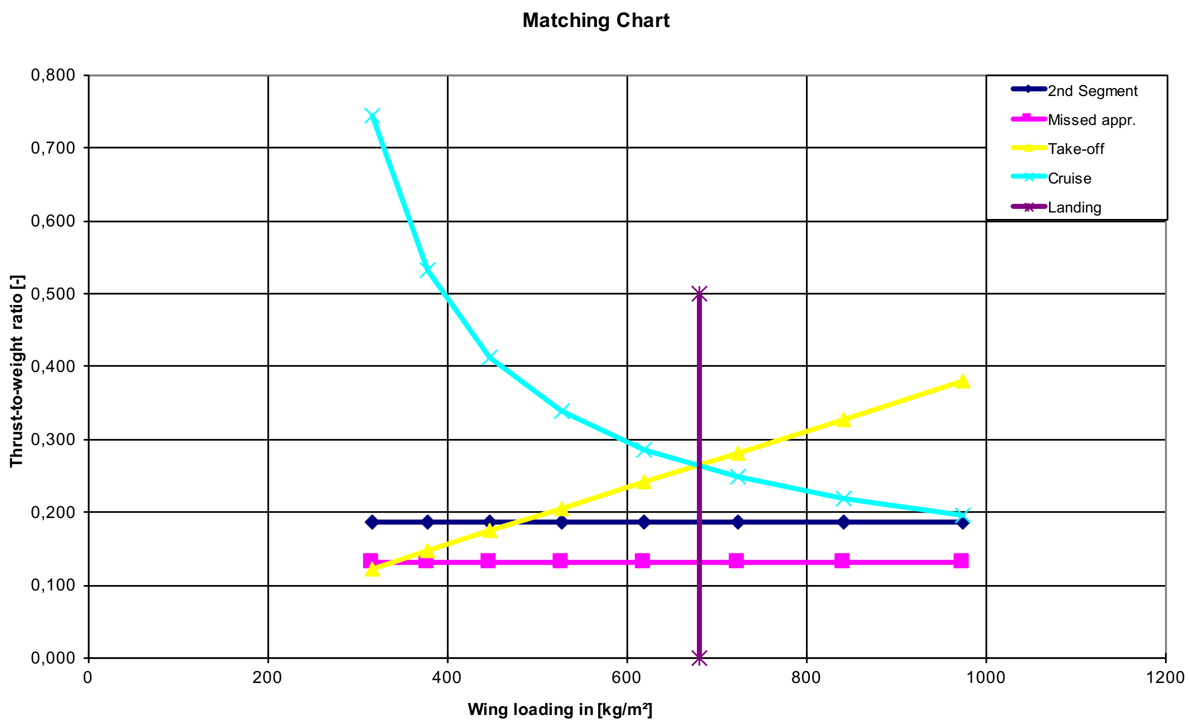
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,08	
Span	b_W	79,75	m
Winglet height	h	**4,57**	m
Aspect ratio	A	7,52	
Effective aspect ratio	A_{eff}	8,14	
Efficiency factor, short range	k_E	17,25	
Relative wetted area	S_{wet}/S_W	**6,30**	
Verification value maximum aerodynamic efficiency	E_{max}	**19,6**	
RE value maximum aerodynamic efficiency		18,94	

4%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,850	
Cruise altitude	h_{CR}	10668	m
By Pass Ratio	μ	8,70	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	374,00	kN
Overall Pressure ratio	OAPR	**45,60**	
Turbine entry temperature	TET	**1498,61**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,93	
Ventilator efficiency	$\eta_{ventilator}$	0,90	
Compressor efficiency	$\eta_{compresor}$	0,88	
Turbine efficiency	$\eta_{turbine}$	0,91	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,81	K
Dimensionless turbine entry temperature	ϕ	6,85	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,14	
Temperature function	χ	2,26	
Gas generator efficiency	η_{gasgen}	0,97	
Gas generator function	G	2,08	
Verification value specific fuel consumption	SFC	0,54	kg/daN/h
Verification value specific fuel consumption	SFC	**1,50E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,48E-05	kg/N/s
1%			


Matching Chart
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
200
400
600
800
1000
1200
Thrust-to-weight ratio [-]
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix Z Bombardier CRJ700

Data Collection			CRJ700		1	2		3	4		5	6	7	8	9
				Source:	Aircraft characteristics for airport planning	Jane's		Jenkinson	Engine		Scholz	Paul Müller	Elodie Rou	Data collectior	Webs
Parameter	Symbol	Units	Chosen value			Standard	LR								
PAX			78		70	70							78-66		
Landing field length	s_{LFL}	m	1550		1550	1551							1478	1509	1536
Approach speed	V_{APP}	m/s	69,45		69,45										
Temperature above ISA (288,15K)	ΔT_L	K	0		0										
Relative density	s														
Take-off field length	s_{TOFL}	m	1564		1575	1564	1676						1564	1565	1605
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0										
Relative density	s														
Range (max payload)	R	km	1556		1740	3053	3604						1556		3121
Cruise Mach number	M_{CR}		0,77			0,78							0,77	0,77	0,78
Wing area	S_W	m²	68,63			68,63							68,63		70,61
Wing span	b_W	m	23,24		23,25	23,24							23,24	23,24	23,24
Aspect ratio	A		7,87			7,4							7,87		
Maximum take-off mass	m_{MTO}	kg	34019		32999	32999	34019						32999	34000	34019
Payload mass	m_{PL}	kg	8528			8528							8990		8527
Mass ratio, payload - take-off	m_{PL}/m_{MTO}												0,272		
Maximum landing mass	m_{ML}	kg	30390		30390	30390							30390		
Mass ratio, landing - take-off	m_{ML}/m_{MTO}														
Operating empty mass	m_{OE}	kg	19269		19731	19731							19269		20069
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}												0,584		
Wing loading	m_{MTO}/S_W	kg/m²	480,8			480,8	495,7						481		
Maximum zero fuel mass	m_{MZF}	kg	28259		28259	28259							28259		28801
Number of engines	n_E		2		2								2	2	2
Engine type	GE CF34		CF34-8C1		GE CF34−8C5	CF34-8C1			CF34-8C1	CF34-8C5			CF34-8C1	GE CF34 - 8C1	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	61,341			56,4 - 61,3			61,341	64,4992			61,341	61,3	56,4
Total take-off thrust	T_{TO}	kN													
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,38			0,34826	0,33788						0,38		
Bypass ratio	μ		4,9						4,9	4,9			4,9		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	1,05E-05						1,05E-05	1,10E-05			1,05E-05		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s													
Available fuel volume	$V_{fuel,available}$	m³	10,989		10,989	10,989							11,5		
Cruise speed	V_{CR}	m/s	228			228,4								227,38444	225
Cruise altitude	h_{CR}	m													
Sweep angle	ϕ_{25}	°	26,6										26,6		
Mean aerodynamic chord	c_{MAC}	m													
Position of maximum camber	$x_{(y\_c),max}$	%c													
Camber	$(y_c)_{max}/c$	%c													
Position of maximum thickness	$x_{t,max}$	%c													
Relative thickness	t/c	%													
Taper	λ														
Overall pressure ratio	OAPR		27						27						
Turbine entry temperature	TET	K													

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1550**	m		
Approach speed	**Known**	V_{APP}	**69,45**	m/s	69,4	69,4
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**1564**	m	1564	1564
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**840**	NM		
Cruise Mach number		M_{CR}	**0,77**			
Wing area		S_W	**69**	m²		
Wing span	**Known**	b_W	**23,24**	m²	23,24	23,24
Aspect ratio		A	7,87			
Maximum take-off mass		m_{MTO}	**34019**	kg		
Maximum payload mass		m_{PL}	**8528**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,251			
Maximum landing mass		m_{ML}	**30390**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,893			
Operating empty mass		m_{OE}	**19269**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,566			
Wing loading		m_{MTO}/S_W	495,7	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**61,341**	kN		
Total take-off thrust		T_{TO}	122,682	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,368			
Bypass ratio		μ	**4,9**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed		V_{CR}	228	m/s		
Cruise altitude		h_{CR}	11278	m		
Speed ratio		V/V_{md}	1,205	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	26,6	°		
Mean aerodynamic chord		c_{MAC}	4,2	m		
Position of maximum camber		$x_{(y\_c),max}$	30	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	4	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	30	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	11,7	%		
Taper		λ	0,24			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1550	1550	m	0,00%
Approach speed	V_{APP}	69,45	69,4	m/s	0,00%
Take-off field length	s_{TOFL}	1564	1564	m	0,00%
Span	b_W	23,24	23,24	m	0,00%
Aspect ratio	A	7,87	7,87		0,00%
Cruise speed	V_{CR}	228,0	227	m/s	-0,33%
Cruise altitude	h_{CR}	11278	11278	m	0,00%
Squared Sum					**1,11E-05**
Absolute maximum deviation					*0,3%*

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	2,67	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	2,02	
Maximum aerodynamic efficiency	E_{max}	13,54	
Specific fuel consumption	SFC	1,48E-05	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1550	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	69,45	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,89	
Wing loading at maximum take-off mass	m_{MTO}/S_W	495,7	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,67**	

Take-off

Take-off field length	s_{TOFL}	1564	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,368	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,02**	

2nd Segment

Aspect ratio	A	7,870
Lift coefficient, take-off	$C_{L,TO}$	1,40
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,015
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,035
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	9,44
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,260

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,58
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,024
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,059
Glide ratio in landing configuration	E_L	7,77
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,267

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,77	
Aspect ratio	A	7,87	
Bypass ratio	μ	4,90	
Wing loading	m_{MTO}/S_W	496	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,368	

Variables		
	V/V_{md}	**1,2**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,029
Lift coefficient at E_{max}	$C_{L,md}$	0,78
Ratio, lift coefficient	$C_L/C_{L,md}$	0,689
Lift coefficient, cruise	C_L	0,535
Actual aerodynamic efficiency, cruise	E	12,65
Max. glide ratio, cruise	E_{max}	**13,54**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,38	-0,02	0,00
f'(x)	-0,16	-0,15	-0,15
E_{max}	16	13,65	13,54

3) Specific Fuel Consumption

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications

Range	R	840	NM
Mach number, cruise	M_{CR}	0,77	
Bypass ratio	μ	4,90	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,368	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	34019	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,251	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,566	

Calculated values

Actual aerodynamic efficiency, cruise	E	12,65	
Cruise altitude	h_{CR}	11278	m
Cruise speed	V_{CR}	227	m/s

Mission fuel fraction

Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations

Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,183	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,817	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,561	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,448	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,48E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 4 digit**	
Wing span	b_W	23,24	m
Structural wing span	$b_{W,struct}$	25,99	m
Wing area	S_W	68,6	m²
Aspect ratio	A	7,87	
Sweep	φ_{25}	26,6	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,7	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	69,45	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,77	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	3,0	%c
Leading edge sweep	φ_{LE}	31,1	°
Reynoldsnumber	Re	2,1E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,58	
Correction term, camber	$\Delta_1 c_{L,max}$	0,17	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,086	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,835	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,79	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,44	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_φ	0,86	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,41	
Use flapped span	b_W,fA	**15,1**	m
Percentage of flaps allong the wing		58%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,70	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,73	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,70	
Calculations increase of lift coefficient due to slats			**1 slat type**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**30**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,89	
Use slatted span	b_W,sA	**20**	m
Percentage of slats allong the wing		77%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,59	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,89	
Use slatted span	b_W,sB	**0**	m
Percentage of slats allong the wing		0%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,00	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,59	

Wing

Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,70**	
RE value maximum lift coefficient, landing		2,67	
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,04**	
RE value maximum lift coefficient, take-off		2,02	

1%

Aerodynamic efficiency

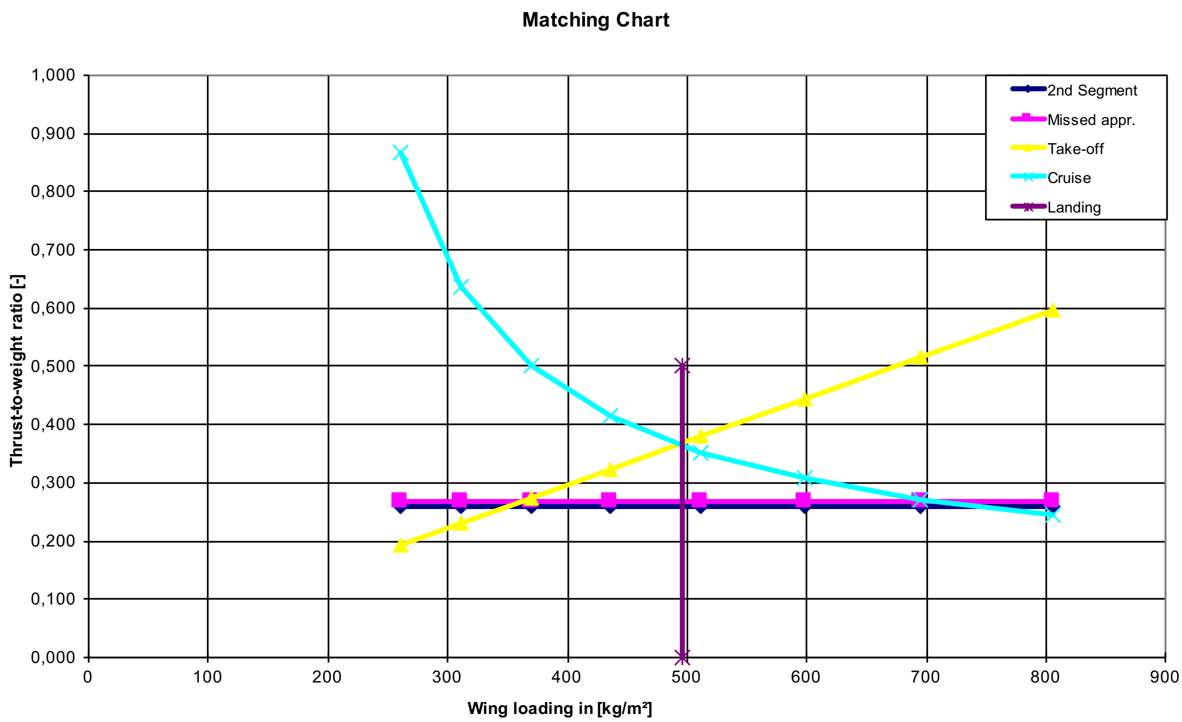
Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,08	
Span	b_W	23,24	m
Winglet height	h	**1,3**	m
Aspect ratio	A	7,87	
Effective aspect ratio	A_{eff}	8,50	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**17,5**	
RE value maximum aerodynamic efficiency		13,54	

30%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,770	
Cruise altitude	h_{CR}	11278	m
By Pass Ratio	μ	4,90	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	61,34	kN
Overall Pressure ratio	OAPR	**28,50**	
Turbine entry temperature	TET	**1389,58**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,83	
Compressor efficiency	$\eta_{compresor}$	0,84	
Turbine efficiency	$\eta_{turbine}$	0,88	
Nozzle efficiency	η_{nozzle}	0,97	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,41	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,79	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	1,88	
Verification value specific fuel consumption	SFC	0,65	kg/daN/h
Verification value specific fuel consumption	SFC	**1,80E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,48E-05	kg/N/s

21%


Matching Chart
2nd Segment
Missed appr.
Take-off
Cruise
Landing
Thrust-to-weight ratio [-]
1,000
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
100
200
300
400
500
600
700
800
900
Wing loading in [kg/m²]

Appendix AA Comac C919

Data Collection			C919		1	2	3	4	5	6	7	8	9	
				Source:	Aircraft characteristics for airport planning	Jane's	Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collection	Webs	
Parameter	Symbol	Units	Chosen value										STD	ER
PAX			168										158-168	
Landing field length	s_{LFL}	m	1600										1600	
Approach speed	V_{APP}	m/s	69,45						69,45				69,45	
Temperature above ISA (288,15K)	ΔT_L	K	0											
Relative density	s													
Take-off field length	s_{TOFL}	m	2200						2200				2000	2200
Temperature above ISA (288,15K)	ΔT_{TO}	K	0											
Relative density	s													
Range (max payload)	R	km	4075										4075	5555
Cruise Mach number	M_{CR}		0,73						0,785				0,785	0,73
Wing area	S_W	m²	129,15						129					
Wing span	b_W	m	35,8						35				35,8	
Aspect ratio	A								9,5					
Maximum take-off mass	m_{MTO}	kg	77393						77393				72500	77300
Payload mass	m_{PL}	kg	20500						20500				20400	
Mass ratio, payload - take-off	m_{PL}/m_{MTO}													
Maximum landing mass	m_{ML}	kg	66682						66682					
Mass ratio, landing - take-off	m_{ML}/m_{MTO}								0,8616					
Operating empty mass	m_{OE}	kg	42100						42179				42100	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}								0,545					
Wing loading	m_{MTO}/S_W	kg/m²							600					
Maximum zero fuel mass	m_{MZF}	kg							62679					
Number of engines	n_E		2						2					
Engine type	CFM LEAP-1C		CFM LEAP-1C						CFM International LEAP-X				LEAP-1C	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	137,14						104,384				137,14	
Total take-off thrust	T_{TO}	kN												
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$								0,275					
Bypass ratio	μ		11						11				11	
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s												
Specific Fuel Comsumption (cruise)	SFC (cruise)	kg/N s												
Available fuel volume	$V_{fuel,available}$	m³	24,45						22,9				24,45	
Cruise speed	V_{CR}	m/s	231,5										231,5	
Cruise altitude	h_{CR}	m	11278						7965				11278	
Sweep angle	ϕ_{25}	°												
Mean aerodynamic chord	c_{MAC}	m												
Position of maximum camber	$x_{(y\_c),max}$	%c												
Camber	$(y_c)_{max}/c$	%c												
Position of maximum thickness	$x_{t,max}$	%c												
Relative thickness	t/c	%												
Taper	λ													
Overall pressure ratio	OAPR		40										40	
Turbine entry temperature	TET	K												

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1600**	m		
Approach speed	**Known**	V_{APP}	**69,45**	m/s	69,5	69,5
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2200**	m	2200	2200
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**2200**	NM		
Cruise Mach number		M_{CR}	**0,73**			
Wing area		S_W	**129**	m²		
Wing span	**Known**	b_W	**35,8**	m²	35,8	35,8
Aspect ratio		A	9,92			
Maximum take-off mass		m_{MTO}	**77393**	kg		
Maximum payload mass		m_{PL}	**20500**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,265			
Maximum landing mass		m_{ML}	**66682**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,862			
Operating empty mass		m_{OE}	**42100**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,544			
Wing loading		m_{MTO}/S_W	599,2	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**137,9**	kN		
Total take-off thrust		T_{TO}	275,8	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,363			
Bypass ratio		μ	**11**			
Available fuel volume		$V_{fuel,available}$	**24,45**	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed		V_{CR}	**232**	m/s		
Cruise altitude		h_{CR}	**11278**	m		
Speed ratio		V/V_{md}	**1,014**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**25**	°		
Mean aerodynamic chord		c_{MAC}	**4,2**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**12,2**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1600	1600	m	0,00%
Approach speed	V_{APP}	69,45	69,5	m/s	0,00%
Take-off field length	s_{TOFL}	2200	2200	m	0,00%
Span	b_W	35,8	35,8	m	0,00%
Aspect ratio	A	9,92	9,92		0,00%
Cruise speed	V_{CR}	231,5	215	m/s	-6,94%
Cruise altitude	h_{CR}	11278	11278	m	0,00%
Squared Sum					**4,82E-03**
Absolute maximum deviation					*6,9%*

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,02**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,75**	
Maximum aerodynamic efficiency	E_{max}	**17,97**	
Specific fuel consumption	SFC	**1,09E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1600	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	69,45	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,86	
Wing loading at maximum take-off mass	m_{MTO}/S_W	599,2	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,02**	

Take-off

Take-off field length	s_{TOFL}	2200	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,363	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,75**	

2nd Segment

Aspect ratio	A	9,924
Lift coefficient, take-off	$C_{L,TO}$	1,22
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,006
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,026
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	12,97
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,202

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,78
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,034
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,069
Glide ratio in landing configuration	E_L	8,29
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,244

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,73	
Aspect ratio	A	9,92	
Bypass ratio	μ	11,00	
Wing loading	m_{MTO}/S_W	599	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,363	

Variables		
	V/V_{md}	**1,0**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,021
Lift coefficient at E_{max}	$C_{L,md}$	0,74
Ratio, lift coefficient	$C_L/C_{L,md}$	0,972
Lift coefficient, cruise	C_L	0,716
Actual aerodynamic efficiency, cruise	E	17,96
Max. glide ratio, cruise	E_{max}	**17,97**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,22	-0,01	0,00
f'(x)	-0,11	-0,11	-0,11
E_{max}	16	18,05	17,97

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	2200	NM
Mach number, cruise	M_{CR}	0,73	
Bypass ratio	μ	11,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,363	
Available fuel volume	$V_{fuel,available}$	24,45	m³
Maximum take-off mass	m_{MTO}	77393	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,265	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,544	

Calculated values			
Actual aerodynamic efficiency, cruise	E	17,96	
Cruise altitude	h_{CR}	11278	m
Cruise speed	V_{CR}	215	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,191	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,809	
Available fuel mass	$m_{F,available}$	19560	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,253	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,762	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,09E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 4 digit**	
Wing span	b_W	35,8	m
Structural wing span	$b_{W,struct}$	39,50	m
Wing area	S_W	129,2	m²
Aspect ratio	A	9,92	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	12,2	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	69,45	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,73	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	3,2	%c
Leading edge sweep	φ_{LE}	28,5	°
Reynoldsnumber	Re	2,1E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,59	
Correction term, camber	$\Delta_1 c_{L,max}$	0,14	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,103	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,836	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,80	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,46	

Calculations increase of lift coefficient due to flaps		**2 flap types**	
Correction factor, sweep	K_φ	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,43	
Use flapped span	b_W,fA	**8,95**	m
Percentage of flaps allong the wing		23%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,28	
• Flap group B			
Double-slotted flap	$\Delta c_{L,max,fB}$	1,43	
Use flapped span	b_W,fB	**15,8**	m
Percentage of flaps allong the wing		40%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,50	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,78	

Calculations increase of lift coefficient due to slats		**2 slat types**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**28**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,90	
Use slatted span	b_W,sA	**6,8**	m
Percentage of slats allong the wing		17%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,14	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**22,2**	m
Percentage of slats allong the wing		56%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,45	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,59	

Wing			
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,78**	
RE value maximum lift coefficient, landing		3,02	
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,62**	
RE value maximum lift coefficient, take-off		1,75	
-8%			

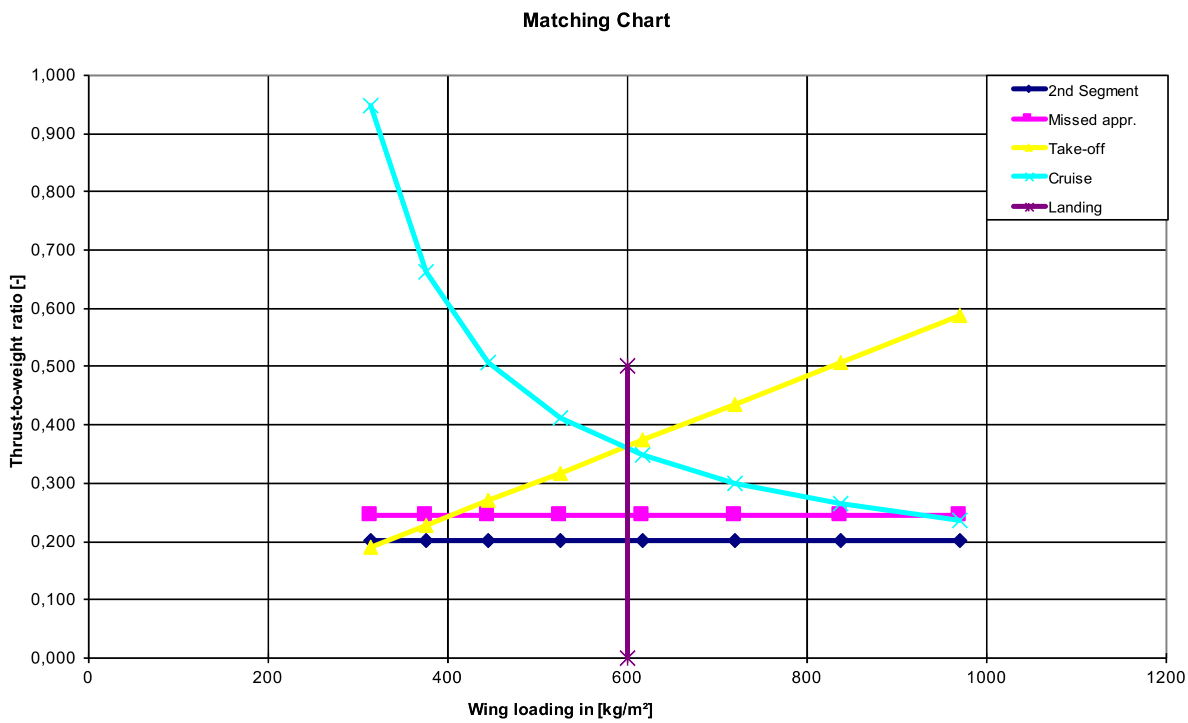
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,08	
Span	b_W	35,8	m
Winglet height	h	**1,9**	m
Aspect ratio	A	9,92	
Effective aspect ratio	A_{eff}	10,68	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**19,6**	
RE value maximum aerodynamic efficiency		17,97	
9%			

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,730	
Cruise altitude	h_{CR}	11278	m
By Pass Ratio	μ	11,00	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	137,90	kN
Overall Pressure ratio	OAPR	**40,00**	
Turbine entry temperature	TET	**1461,99**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,92	
Ventilator efficiency	$\eta_{ventilator}$	0,89	
Compressor efficiency	$\eta_{compresor}$	0,88	
Turbine efficiency	$\eta_{turbine}$	0,91	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,75	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,11	
Temperature function	χ	2,07	
Gas generator efficiency	η_{gasgen}	0,97	
Gas generator function	G	2,10	
Verification value specific fuel consumption	SFC	0,48	kg/daN/h
Verification value specific fuel consumption	SFC	**1,35E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,09E-05	kg/N/s

24%


Matching Chart
1,000
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix AB Mitsubishi MRJ90

Data Collection			MRJ90		1			2			3	4	5	6	7	8	9		
				Source:	Aircraft characteristics for airport planning			Jane's			Jenkinson	Engine	Scholz	Paul Müller	Elodie Rou	Data collectior	Webs		
Parameter	Symbol	Units	Chosen value		STD	ER	LR	STD	ER	LR							STD	ER	LR
PAX			88			88			86-96									86-96	
Landing field length	s_{LFL}	m	1480			1480			1510									1450	
Approach speed	V_{APP}	m/s	70			69,96													
Temperature above ISA (288,15K)	ΔT_L	K	0																
Relative density	s																		
Take-off field length	s_{TOFL}	m	1500		1490	1600	1740	1520	1660	1770							1460	1590	1690
Temperature above ISA (288,15K)	ΔT_{TO}	K	0																
Relative density	s																		
Range (max payload)	R	km	1610		2120	2870	3770	1610	2590	3320							1610	2590	3280
Cruise Mach number	M_{CR}		0,78			0,78			0,78									0,78	
Wing area	S_W	m²																	
Wing span	b_W	m	30,9						30,9									29,7	
Aspect ratio	A																		
Maximum take-off mass	m_{MTO}	kg	39600		39600	40995	42800	39400	41300	42700							39600	41450	42800
Payload mass	m_{PL}	kg	8976															8976	
Mass ratio, payload - take-off	m_{PL}/m_{MTO}																		
Maximum landing mass	m_{ML}	kg	38400			38000			38400									38500	
Mass ratio, landing - take-off	m_{ML}/m_{MTO}																		
Operating empty mass	m_{OE}	kg	24900			25100			24900									22600	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}																		
Wing loading	m_{MTO}/S_W	kg/m²																	
Maximum zero fuel mass	m_{MZF}	kg	36150			36150													
Number of engines	n_E		2			2												2	
Engine type	PW1217G (GTF)		PW1217G			PW1217G												PW1000G	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	78,2			78,2			76,1									75,6	
Total take-off thrust	T_{TO}	kN																	
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,4					0,39398	0,37653	0,36443									
Bypass ratio	μ		8,4															8,4	
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s																	
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s																	
Available fuel volume	$V_{fuel,available}$	m³																	
Cruise speed	V_{CR}	m/s	230															230	
Cruise altitude	h_{CR}	m	11900			11900													
Sweep angle	φ_{25}	°																	
Mean aerodynamic chord	c_{MAC}	m																	
Position of maximum camber	$x_{(y\_c),max}$	%c																	
Camber	$(y_c)_{max}/c$	%c																	
Position of maximum thickness	$x_{t,max}$	%c																	
Relative thickness	t/c	%																	
Taper	λ																		
Overall pressure ratio	OAPR																		
Turbine entry temperature	TET	K																	

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1480**	m		
Approach speed	**Known**	V_{APP}	**70,00**	m/s	70,0	70,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**1500**	m	1500	1500
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**869**	NM		
Cruise Mach number		M_{CR}	**0,78**			
Wing area		S_W	**86**	m²		
Wing span	**Known**	b_W	**30,9**	m²	30,9	30,9
Aspect ratio		A	11,10			
Maximum take-off mass		m_{MTO}	**40995**	kg		
Maximum payload mass		m_{PL}	**8976**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,219			
Maximum landing mass		m_{ML}	**38400**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,937			
Operating empty mass		m_{OE}	**24900**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,607			
Wing loading		m_{MTO}/S_W	476,7	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**78,2**	kN		
Total take-off thrust		T_{TO}	156,4	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,389			
Bypass ratio		μ	**8,4**			
Available fuel volume		$V_{fuel,available}$	**23,86**	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed	V_{CR}	**230**	m/s			
Cruise altitude	h_{CR}	**11900**	m			
Speed ratio	V/V_{md}	**1,241**	-		1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**25**	°		
Mean aerodynamic chord		c_{MAC}	**4,2**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,6**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1480	1480	m	0,00%
Approach speed	V_{APP}	70,00	70,0	m/s	0,00%
Take-off field length	s_{TOFL}	1500	1500	m	0,00%
Span	b_W	30,9	30,9	m	0,00%
Aspect ratio	A	11,10	11,10		0,00%
Cruise speed	V_{CR}	230,0	230	m/s	0,08%
Cruise altitude	h_{CR}	11900	11900	m	0,00%
Squared Sum					**6,90E-07**
Absolute maximum deviation					0,1%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,82**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,91**	
Maximum aerodynamic efficiency	E_{max}	**17,41**	
Specific fuel consumption	SFC	**1,68E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing			
Landing field length	s_{LFL}	1480	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	70,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,94	
Wing loading at maximum take-off mass	m_{MTO}/S_W	476,7	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,82**	

Take-off			
Take-off field length	s_{TOFL}	1500	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,389	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,91**	

2nd Segment		
Aspect ratio	A	11,102
Lift coefficient, take-off	$C_{L,TO}$	1,33
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,011
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,031
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	12,82
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,204

Missed approach		
Lift coefficient, landing	$C_{L,L}$	1,67
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,028
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,063
Glide ratio in landing configuration	E_L	9,40
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,239

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,78	
Aspect ratio	A	11,10	
Bypass ratio	μ	8,40	
Wing loading	m_{MTO}/S_W	477	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,389	

Variables		
	V/V_{md}	**1,2**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,024
Lift coefficient at E_{max}	$C_{L,md}$	0,85
Ratio, lift coefficient	$C_L/C_{L,md}$	0,649
Lift coefficient, cruise	C_L	0,553
Actual aerodynamic efficiency, cruise	E	15,90
Max. glide ratio, cruise	E_{max}	**17,41**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,17	0,00	0,00
f'(x)	-0,11	-0,12	-0,12
E_{max}	16	17,45	17,41

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	869	NM
Mach number, cruise	M_{CR}	0,78	
Bypass ratio	μ	8,40	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,389	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	40995	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,219	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,607	

Calculated values			
Actual aerodynamic efficiency, cruise	E	15,90	
Cruise altitude	h_{CR}	11900	m
Cruise speed	V_{CR}	230	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,174	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,826	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,466	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,545	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,68E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 64 series**	
Wing span	b_W	30,9	m
Structural wing span	$b_{W,struct}$	34,09	m
Wing area	S_W	86,0	m²
Aspect ratio	A	11,10	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,6	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	70,00	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,78	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,5	%c
Leading edge sweep	φ_{LE}	28,2	°
Reynoldsnumber	Re	2,1E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,42	
Correction term, camber	$\Delta_1 c_{L,max}$	0,35	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,007	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,771	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,81	
Correction term, Mach number	$\Delta C_{L,max}$	-0,03	
Lift coefficient, wing	$C_{L,max}$	1,40	

Calculations increase of lift coefficient due to flaps			**2 flap types**
Correction factor, sweep	K_{φ}	0,87	
• Flap group A			
0,3c Single-slotted fowler flap	$\Delta c_{L,max,fA}$	1,66	
Use flapped span	b_W,fA	**8,3**	m
Percentage of flaps allong the wing		24%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,35	
• Flap group B			
0,3c Single-slotted fowler flap	$\Delta c_{L,max,fB}$	1,66	
Use flapped span	b_W,fB	**12,7**	m
Percentage of flaps allong the wing		37%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,54	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,89	
Calculations increase of lift coefficient due to slats			**2 slat types**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**26**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,87	
Use slatted span	b_W,sA	**5,9**	m
Percentage of slats allong the wing		17%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,14	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,87	
Use slatted span	b_W,sB	**20,1**	m
Percentage of slats allong the wing		59%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,46	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,60	

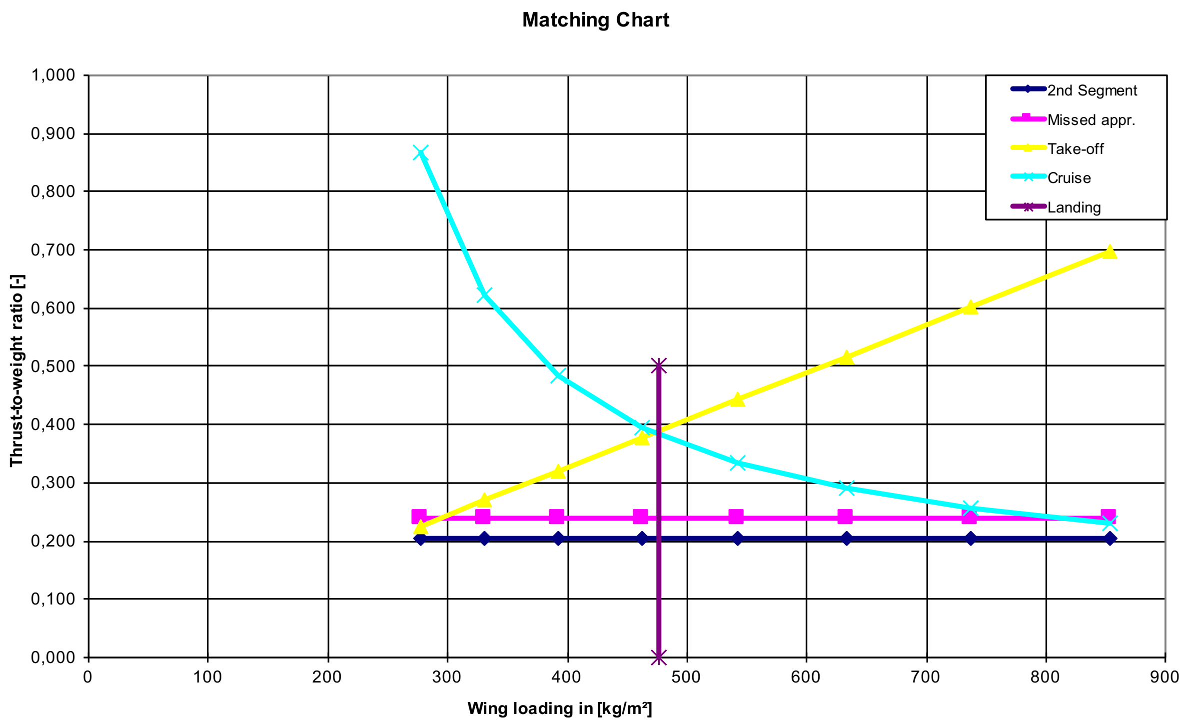
Wing			
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,84**	
RE value maximum lift coefficient, landing		2,82	
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,93**	
RE value maximum lift coefficient, take-off		1,91	
1%			

Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,07	
Span	b_W	30,9	m
Winglet height	h	**1,6**	m
Aspect ratio	A	11,10	
Effective aspect ratio	A_{eff}	11,93	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**20,8**	
RE value maximum aerodynamic efficiency		17,41	
19%			

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,780	
Cruise altitude	h_{CR}	11900	m
By Pass Ratio	μ	8,40	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	78,20	kN
Overall Pressure ratio	OAPR	**29,59**	
Turbine entry temperature	TET	**1417,70**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,93	
Ventilator efficiency	$\eta_{ventilator}$	0,85	
Compressor efficiency	$\eta_{compresor}$	0,86	
Turbine efficiency	$\eta_{turbine}$	0,89	
Nozzle efficiency	η_{nozzle}	0,97	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,54	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,83	
Gas generator efficiency	η_{gasgen}	0,97	
Gas generator function	G	2,01	
Verification value specific fuel consumption	SFC	0,60	kg/daN/h
Verification value specific fuel consumption	SFC	**1,66E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,68E-05	kg/N/s
-1%			



Matching Chart
1,000
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
100
200
300
400
500
600
700
800
900
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix AC Boeing 737-300

Data Collection			737-300	Source:	1		2		3	4	5	6	7	8	9
					Aircraft characteristics for airport planning		Jane's		Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collectior	Webs
Parameter	Symbol	Units	Chosen value		A	B	Basic	LR							
PAX			149		128-134-149		128-149		149-128			149	149-128		
Landing field length	s_{LFL}	m	1433		1460		1433		1396			1433	1396	1400	
Approach speed	V_{APP}	m/s	69,45				69,45		68,42			69,44		66,877778	
Temperature above ISA (288,15K)	ΔT_L	K	0		0		0		0			0			
Relative density	s														
Take-off field length	s_{TOFL}	m	1940		2980	2225	2286		1939				1939	1600	2300
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0	0	15		0						
Relative density	s														
Range (max payload)	R	km	1464		3550		4204		2922			4204	1464		4204
Cruise Mach number	M_{CR}		0,745				0,745			0,8			0,74	0,745	0,745
Wing area	S_W	m²	105,4				105,4		91,04			105,4	91,04		
Wing span	b_W	m	28,88		28,88-31,22		28,88		28,9			28,88	28,88	28,9	28,88
Aspect ratio	A		7,9				7,9		9,1740993			7,9	9,16		9,11
Maximum take-off mass	m_{MTO}	kg	58967		56472-58967	63276	56470	62820	56470			56470	56473	56470	62820
Payload mass	m_{PL}	kg	16148		16148	15404			16030				16148		
Mass ratio, payload - take-off	m_{PL}/m_{MTO}					0,24344143			0,2838675				0,286		
Maximum landing mass	m_{ML}	kg	51710		51710	52889	51720	52890	51710			51720	51710		51700
Mass ratio, landing - take-off	m_{ML}/m_{MTO}					0,83584613			0,9157075						
Operating empty mass	m_{OE}	kg	31869		31479	32904	32704	33266	31869				31480		32700
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}					0,52000759			0,5643528				0,557		
Wing loading	m_{MTO}/S_W	kg/m²	535,6				535,6	595,8	620,2768				620		
Maximum zero fuel mass	m_{MZF}	kg	47627		47627	49714	47625	49715	47630				47628		48410
Number of engines	n_E		2						2				2	2	2
Engine type	CFM56-3		CFM56-3B1		CFM56-3B1	CFM56-3B2	CFM56-3C-1		CFM56-3-B1	CFM56-3B1			CFM56-3B1	CFM56-3B1	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	88,964			97,7942	89-97,9		89	88,96444			88,964	90	90
Total take-off thrust	T_{TO}	kN													
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,32						0,3213166				0,32		
Bypass ratio	μ		6							6			6		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	1,08E-05							1,0754E-05			1,08E-05		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s	1,89E-05							1,8876E-05			1,89E-05		
Available fuel volume	$V_{fuel,available}$	m³	20,102		20,102	23,827	20,104-23,83		20,105-23,170				20,102		23,17
Cruise speed	V_{CR}	m/s	220,7						220,7-252,6					220,69667	
Cruise altitude	h_{CR}	m	10668				10195		10668-7924,8	10668			10668		
Sweep angle	ϕ_{25}	°	25						25				25		25
Mean aerodynamic chord	c_{MAC}	m	3,73						3,73				3,73		
Position of maximum camber	$x_{(y\_c),max}$	%c	10												10
Camber	$(y_c)_{max}/c$	%c	0,8												0,8
Position of maximum thickness	$x_{t,max}$	%c	29,7												29,7
Relative thickness	t/c	%	12,9						12,89				12,9		12,5
Taper	λ		0,24						3,73				0,24		
Overall pressure ratio	OAPR		22,6							22,6					
Turbine entry temperature	TET	K													

Aeroplane Specifications

Data to apply reverse engineering

					LL	*UL*
Landing field length	**Known**	s_{LFL}	**1433**	m		
Approach speed	**Known**	V_{APP}	**69,45**	m/s	69,5	69,5
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**1940**	m	1940	1940
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**790**	NM		
Cruise Mach number		M_{CR}	**0,745**			
Wing area		S_W	**105**	m²		
Wing span	**Known**	b_W	**28,88**	m²	28,88	28,88
Aspect ratio		A	7,91			
Maximum take-off mass		m_{MTO}	**58967**	kg		
Maximum payload mass		m_{PL}	**16148**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,274			
Maximum landing mass		m_{ML}	**51710**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,877			
Operating empty mass		m_{OE}	**31869**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,540			
Wing loading		m_{MTO}/S_W	559,5	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**88,964**	kN		
Total take-off thrust		T_{TO}	177,928	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,308			
Bypass ratio		μ	**6**			
Available fuel volume		$V_{fuel,available}$	**20,1**	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	**221**	m/s		
Cruise altitude	h_{CR}	**10668**	m		
Speed ratio	V/V_{md}	**1,103**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**25**	°		
Mean aerodynamic chord		c_{MAC}	**3,73**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**12,0**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1433	1433	m	0,00%
Approach speed	V_{APP}	69,45	69,5	m/s	0,00%
Take-off field length	s_{TOFL}	1940	1940	m	0,00%
Span	b_W	28,88	28,88	m	0,00%
Aspect ratio	A	7,91	7,91		0,00%
Cruise speed	V_{CR}	220,7	221	m/s	0,11%
Cruise altitude	h_{CR}	10668	10670	m	0,02%
Squared Sum					**1,29E-06**
Absolute maximum deviation					0,1%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,20**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,19**	
Maximum aerodynamic efficiency	E_{max}	**14,84**	
Specific fuel consumption	SFC	**1,78E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1433	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	69,45	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,88	
Wing loading at maximum take-off mass	m_{MTO}/S_W	559,5	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,20**	

Take-off

Take-off field length	s_{TOFL}	1940	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,308	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,19**	

2nd Segment

Aspect ratio	A	7,913
Lift coefficient, take-off	$C_{L,TO}$	1,52
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,021
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,041
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	8,73
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,277

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,89
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,040
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,075
Glide ratio in landing configuration	E_L	6,75
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,297

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,745	
Aspect ratio	A	7,91	
Bypass ratio	μ	6,00	
Wing loading	m_{MTO}/S_W	559	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,308	

Variables		
	V/V_{md}	**1,1**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,024
Lift coefficient at E_{max}	$C_{L,md}$	0,71
Ratio, lift coefficient	$C_L/C_{L,md}$	0,822
Lift coefficient, cruise	C_L	0,586
Actual aerodynamic efficiency, cruise	E	14,56
Max. glide ratio, cruise	E_{max}	**14,84**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,15	0,00	0,00
f'(x)	-0,13	-0,13	-0,13
E_{max}	16	14,86	14,84

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	790	NM
Mach number, cruise	M_{CR}	0,745	
Bypass ratio	μ	6,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,308	
Available fuel volume	$V_{fuel,available}$	20,1	m³
Maximum take-off mass	m_{MTO}	58967	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,274	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,540	

Calculated values			
Actual aerodynamic efficiency, cruise	E	14,56	
Cruise altitude	h_{CR}	10670	m
Cruise speed	V_{CR}	221	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,186	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,814	
Available fuel mass	$m_{F,available}$	16080	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,273	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,742	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,78E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	28,88	m
Structural wing span	$b_{W,struct}$	31,87	m
Wing area	S_W	105,4	m²
Aspect ratio	A	7,91	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	3,73	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	12,0	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	69,45	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,745	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,2	%c
Leading edge sweep	φ_{LE}	29,4	°
Reynoldsnumber	Re	1,8E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,30	
Correction term, camber	$\Delta_1 c_{L,max}$	0,40	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,023	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,720	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,85	
Correction term, Mach number	$\Delta C_{L,max}$	-0,02	
Lift coefficient, wing	$C_{L,max}$	1,44	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_φ	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,41	
Use flapped span	b_W,fA	**20,8**	m
Percentage of flaps allong the wing		65%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,80	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,74	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,80	

Calculations increase of lift coefficient due to slats			**1 slat type**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**28**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,89	
Use slatted span	b_W,sA	**18,5**	m
Percentage of slats allong the wing		58%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,46	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,89	
Use slatted span	b_W,sB	**0**	m
Percentage of slats allong the wing		0%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,00	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,46	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,66**
RE value maximum lift coefficient, landing		3,20
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,83**
RE value maximum lift coefficient, take-off		2,19

-17%

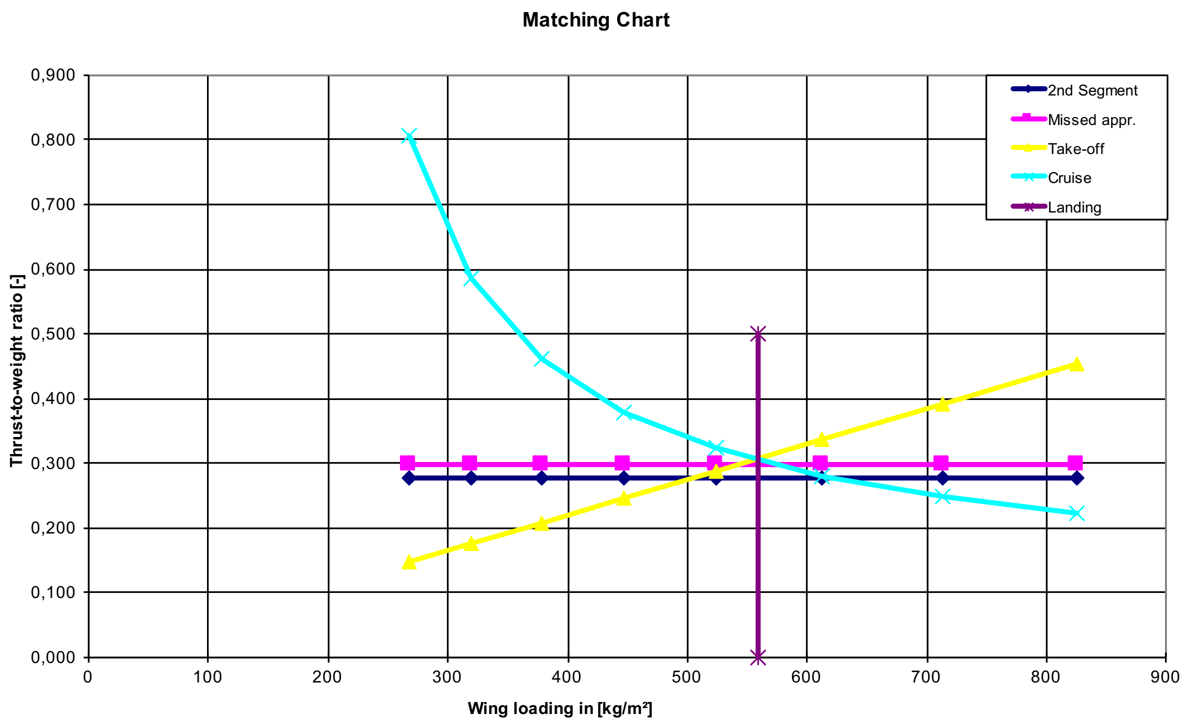
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
No winglets	$k_{e,WL}$	1,00	
Span	b_W	28,88	m
Winglet height	h	**2,1**	m
Aspect ratio	A	7,91	
Effective aspect ratio	A_{eff}	7,91	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**5,96**	
Verification value maximum aerodynamic efficiency	E_{max}	**17,5**	
RE value maximum aerodynamic efficiency		14,84	

18%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,745	
Cruise altitude	h_{CR}	10668	m
By Pass Ratio	μ	6,00	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	88,96	kN
Overall Pressure ratio	OAPR	**21,15**	
Turbine entry temperature	TET	**1430,08**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,94	
Ventilator efficiency	$\eta_{ventilator}$	0,86	
Compressor efficiency	$\eta_{compresor}$	0,86	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,98	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,81	K
Dimensionless turbine entry temperature	ϕ	6,54	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,11	
Temperature function	χ	1,55	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,12	
Verification value specific fuel consumption	SFC	0,60	kg/daN/h
Verification value specific fuel consumption	SFC	**1,67E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,78E-05	kg/N/s
6%			


Matching Chart
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
100
200
300
400
500
600
700
800
900
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix AD Airbus A350-1000

Data Collection			A350-1000		1		2	3	4	5	6	7	8	9
				Source:	Aircraft characteristics for airport planning		Jane's	Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collection	Webs
Parameter	Symbol	Units	Chosen value		WV009	WV002								
PAX			369		369							350		
Landing field length	s_{LFL}	m	2110		2110									
Approach speed	V_{APP}	m/s	75		75,6									
Temperature above ISA (288,15K)	ΔT_L	K	0		0									
Relative density	s													
Take-off field length	s_{TOFL}	m	2950		2950									
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0									
Relative density	s													
Range (max payload)	R	km	10400		10400		14815							16100
Cruise Mach number	M_{CR}		0,85				0,85					0,85		0,85
Wing area	S_W	m²	443				443					443		460
Wing span	b_W	m	64,75		64,75		64					64	64,75	64,75
Aspect ratio	A		9,25									9,25		
Maximum take-off mass	m_{MTO}	kg	316000		290000	316000	295000					295000	308000	319000
Payload mass	m_{PL}	kg	67250			67250								
Mass ratio, payload - take-off	m_{PL}/m_{MTO}													
Maximum landing mass	m_{ML}	kg	236000		233000	236000	225500					225500		236000
Mass ratio, landing - take-off	m_{ML}/m_{MTO}													
Operating empty mass	m_{OE}	kg	115700											115700
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}													
Wing loading	m_{MTO}/S_W	kg/m²	666				665,9					666		
Maximum zero fuel mass	m_{MZF}	kg	210000		220000	223000	211000					210000		223000
Number of engines	n_E		2				2					2	2	2
Engine type	RR Trent XWB		Trent XWB-97				RR Trent XWB-74/-83/-92					GEnx 1A72	Trent XWB-97	Trent XWB-97
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	431				329/369/409					320	431	431
Total take-off thrust	T_{TO}	kN												
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,22									0,22		
Bypass ratio	μ		9,6				9,6					8,9		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s												
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s												
Available fuel volume	$V_{fuel,available}$	m³	156		156		156					150		159
Cruise speed	V_{CR}	m/s	250,5										250,534444	250,83
Cruise altitude	h_{CR}	m	12190									13100		12190
Sweep angle	ϕ_{25}	°	35				35					28		31,9
Mean aerodynamic chord	c_{MAC}	m	8,35									8,35		
Position of maximum camber	$x_{(y\_c),max}$	%c												
Camber	$(y_c)_{max}/c$	%c												
Position of maximum thickness	$x_{t,max}$	%c												
Relative thickness	t/c	%												
Taper	λ		0,113									0,113		
Overall pressure ratio	OAPR		50				50							
Turbine entry temperature	TET	K												

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**2110**	m		
Approach speed	**Known**	V_{APP}	**75,00**	m/s	75,0	75,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2950**	m	2950	2950
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**7999**	NM		
Cruise Mach number		M_{CR}	**0,85**			
Wing area		S_W	**443**	m²		
Wing span	**Known**	b_W	**64,75**	m²	64,75	64,75
Aspect ratio		A	9,46			
Maximum take-off mass		m_{MTO}	**316000**	kg		
Maximum payload mass		m_{PL}	**67250**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,213			
Maximum landing mass		m_{ML}	**236000**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,747			
Operating empty mass		m_{OE}	**115700**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,366			
Wing loading		m_{MTO}/S_W	713,3	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**431**	kN		
Total take-off thrust		T_{TO}	862	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,278			
Bypass ratio		μ	**9,6**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	**251**	m/s		
Cruise altitude	h_{CR}	**12190**	m		
Speed ratio	V/V_{md}	**1,000**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**35**	°		
Mean aerodynamic chord		c_{MAC}	**8,35**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**10,6**	%		
Taper		λ	**0,113**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	2110	2110	m	0,00%
Approach speed	V_{APP}	75,00	75,0	m/s	0,00%
Take-off field length	s_{TOFL}	2950	2950	m	0,00%
Span	b_W	64,75	64,75	m	0,00%
Aspect ratio	A	9,46	9,46		0,00%
Cruise speed	V_{CR}	250,5	251	m/s	0,14%
Cruise altitude	h_{CR}	12190	11064	m	-9,24%
Squared Sum					**8,53E-03**
Absolute maximum deviation					*9,2%*

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,36**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,03**	
Maximum aerodynamic efficiency	E_{max}	**20,76**	
Specific fuel consumption	SFC	**1,53E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	2110	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	75,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,75	
Wing loading at maximum take-off mass	m_{MTO}/S_W	713,3	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,36**	

Take-off

Take-off field length	s_{TOFL}	2950	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,278	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,03**	

2nd Segment

Aspect ratio	A	9,464
Lift coefficient, take-off	$C_{L,TO}$	1,41
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,016
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,036
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	10,74
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,234

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,40
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,015
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,050
Glide ratio in landing configuration	E_L	9,73
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,185

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	
Specifications			
Mach number, cruise	M_{CR}	0,85	
Aspect ratio	A	9,46	
Bypass ratio	μ	9,60	
Wing loading	m_{MTO}/S_W	713	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,278	
Variables			
	V/V_{md}	**1,0**	
Calculations			
Zero-lift drag coefficient	$C_{D,0}$	0,015	
Lift coefficient at E_{max}	$C_{L,md}$	0,61	
Ratio, lift coefficient	$C_L/C_{L,md}$	1,000	
Lift coefficient, cruise	C_L	0,609	
Actual aerodynamic efficiency, cruise	E	20,76	
Max. glide ratio, cruise	E_{max}	**20,76**	

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,42	-0,04	0,00
f'(x)	-0,08	-0,10	-0,10
E_{max}	16	21,19	20,76

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	7999	NM
Mach number, cruise	M_{CR}	0,85	
Bypass ratio	μ	9,60	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,278	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	316000	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,213	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,366	

Calculated values			
Actual aerodynamic efficiency, cruise	E	20,76	
Cruise altitude	h_{CR}	11064	m
Cruise speed	V_{CR}	251	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,421	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,579	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,060	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,959	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**no**	
	international	**yes**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	1111107	m
Loiter time	t_{loiter}	1800	s
Specific fuel consumption	SFC	**1,53E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	64,75	m
Structural wing span	$b_{W,struct}$	79,05	m
Wing area	S_W	443,0	m²
Aspect ratio	A	9,46	
Sweep	φ_{25}	35	°
Mean aerodynamic chord	c_{MAC}	8,35	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	10,6	%
Taper	λ	0,113	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	75,00	m/s
Mach number, landing	M_{APP}	0,23	
Mach number, cruise	M_{CR}	0,85	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	1,9	%c
Leading edge sweep	φ_{LE}	39,8	°
Reynoldsnumber	Re	4,5E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,17	
Correction term, camber	$\Delta_1 c_{L,max}$	0,39	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,079	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,639	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,91	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,48	

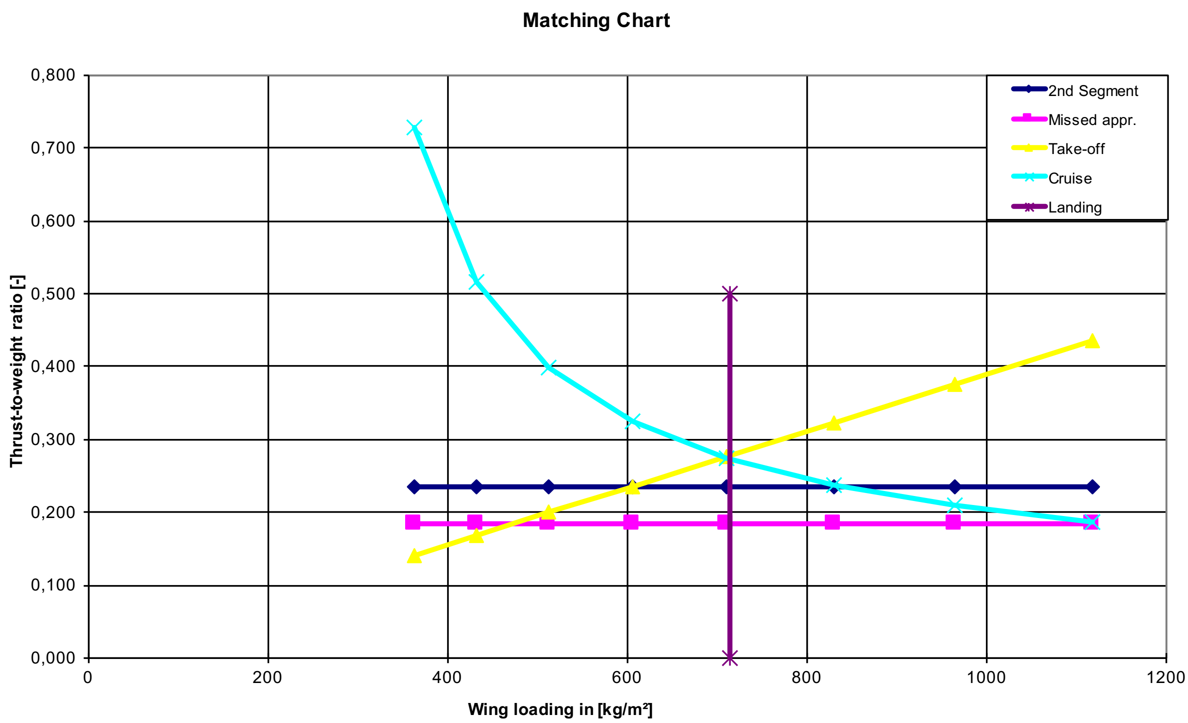
Calculations increase of lift coefficient due to flaps		**2 flap types**	
Correction factor, sweep	K_φ	0,81	
• Flap group A			
Single-slotted flap	$\Delta c_{L,max,fA}$	0,79	
Use flapped span	b_W,fA	**15,2**	m
Percentage of flaps allong the wing		19%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,12	
• Flap group B			
Single-slotted flap	$\Delta c_{L,max,fB}$	0,79	
Use flapped span	b_W,fB	**22,8**	m
Percentage of flaps allong the wing		29%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,19	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,31	
Calculations increase of lift coefficient due to slats		**2 slat types**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**36**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,92	
Use slatted span	b_W,sA	**14,2**	m
Percentage of slats allong the wing		18%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,13	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,92	
Use slatted span	b_W,sB	**39,5**	m
Percentage of slats allong the wing		50%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,37	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,50	
Wing			
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,28**	
RE value maximum lift coefficient, landing		2,36	
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,96**	
RE value maximum lift coefficient, take-off		2,03	
-4%			

Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,05	
Span	b_W	64,75	m
Winglet height	h	**2,43**	m
Aspect ratio	A	9,46	
Effective aspect ratio	A_{eff}	9,97	
Efficiency factor, short range	k_E	17,25	
Relative wetted area	S_{wet}/S_W	**5,80**	
Verification value maximum aerodynamic efficiency	E_{max}	**22,6**	
RE value maximum aerodynamic efficiency		20,76	
9%			

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,850	
Cruise altitude	h_{CR}	12190	m
By Pass Ratio	μ	9,60	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	431,00	kN
Overall Pressure ratio	OAPR	**50,00**	
Turbine entry temperature	TET	**1501,44**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,93	
Ventilator efficiency	$\eta_{ventilator}$	0,90	
Compressor efficiency	$\eta_{compresor}$	0,88	
Turbine efficiency	$\eta_{turbine}$	0,91	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,93	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,14	
Temperature function	χ	2,36	
Gas generator efficiency	η_{gasgen}	0,97	
Gas generator function	G	2,09	
Verification value specific fuel consumption	SFC	0,53	kg/daN/h
Verification value specific fuel consumption	SFC	**1,47E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,53E-05	kg/N/s
-4%			



Matching Chart
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix AE Bombardier CS300 / Airbus A220

Data Collection

Parameter	Symbol	Units	A220 Chosen value	Source: 1 Aircraft characteristics for airport planning	2 Jane's	3 Jenkinson	4 Engine	5 Scholz	6 Paul Müller	7 Elodie Rou	8 Data collectior	9 Webs 100	9 Webs 300
PAX			160	120				160				108-133	130-160
Landing field length	s_{LFL}	m	1509	1390				1509				1387	1509
Approach speed	V_{APP}	m/s	66,1	66,4				66,1					
Temperature above ISA (288,15K)	ΔT_L	K	0	0				0					
Relative density	s												
Take-off field length	s_{TOFL}	m	1890	2370				1890				1463	1890
Temperature above ISA (288,15K)	ΔT_{TO}	K	0	0				0					
Relative density	s												
Range (max payload)	R	km	3610	3610				6204				5741	6112
Cruise Mach number	M_{CR}		0,78					0,78				0,78	
Wing area	S_W	m²	112,3					113				112,3	
Wing span	b_W	m	35,1	35,1				35,3				35,1	
Aspect ratio	A		10,97					10,97					
Maximum take-off mass	m_{MTO}	kg	67585	60781				69776				54885-60781	59874-67585
Payload mass	m_{PL}	kg	18711					18711				13767-15127	16670-18711
Mass ratio, payload - take-off	m_{PL}/m_{MTO}												
Maximum landing mass	m_{ML}	kg	51029	52390				59310				51029-52390	56472-58740
Mass ratio, landing - take-off	m_{ML}/m_{MTO}							0,85					
Operating empty mass	m_{OE}	kg	37051					37051				35221	37081
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}							0,531					
Wing loading	m_{MTO}/S_W	kg/m²	615					615					
Maximum zero fuel mass	m_{MZF}	kg	55792	50349				55762				50349	55792
Number of engines	n_E		2	2				2				2	
Engine type	PW1000G (GTF)		PW1525G	PW1519G				PW1500G				PW1521G/24G/25G	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	108,54	87,96				102				97,73/103,6/108,54	
Total take-off thrust	T_{TO}	kN	217,08					204,546					
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,299					0,299					
Bypass ratio	μ		12					12					
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	0,0000112					1,12E-05					
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s											
Available fuel volume	$V_{fuel,available}$	m³	21,805	21,805				18,9					21,805
Cruise speed	V_{CR}	m/s	230					230				230,27	
Cruise altitude	h_{CR}	m	11126					11126					
Sweep angle	ϕ_{25}	°											
Mean aerodynamic chord	c_{MAC}	m											
Position of maximum camber	$x_{(y\_c),max}$	%c											
Camber	$(y_c)_{max}/c$	%c											
Position of maximum thickness	$x_{t,max}$	%c											
Relative thickness	t/c	%											
Taper	λ												
Overall pressure ratio	OAPR												
Turbine entry temperature	TET	K											

Aeroplane Specifications

Data to apply reverse engineering					LL	UL
Landing field length	Known	s_{LFL}	1509	m		
Approach speed	Known	V_{APP}	66,10	m/s	66,1	66,1
Temperature above ISA (288,15K)		ΔT_L	0	K		
Relative density		σ	1			
Take-off field length	Known	s_{TOFL}	1890	m	1890	1890
Temperature above ISA (288,15K)		ΔT_{TO}	0	K		
Relative density		σ	1,000			
Range (maximum payload)		R	1949	NM		
Cruise Mach number		M_{CR}	0,78			
Wing area		S_W	112	m²		
Wing span	Known	b_W	35,1	m²	35,1	35,1
Aspect ratio		A	10,97			
Maximum take-off mass		m_{MTO}	67585	kg		
Maximum payload mass		m_{PL}	18711	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,277			
Maximum landing mass		m_{ML}	51029	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,755			
Operating empty mass		m_{OE}	37051	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,548			
Wing loading		m_{MTO}/S_W	601,8	kg/m²		
Number of engines		n_E	2			
Take-off thrust for one engine		$T_{TO,one\ engine}$	108,54	kN		
Total take-off thrust		T_{TO}	217,08	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,327			
Bypass ratio		μ	12			
Available fuel volume		$V_{fuel,available}$	21,805	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	**230**	m/s		
Cruise altitude	h_{CR}	**11126**	m		
Speed ratio	V/V_{md}	**1,066**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**25**	°		
Mean aerodynamic chord		c_{MAC}	**4,2**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,6**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1509	1509	m	0,00%
Approach speed	V_{APP}	66,10	66,1	m/s	0,00%
Take-off field length	s_{TOFL}	1890	1890	m	0,00%
Span	b_W	35,1	35,1	m	0,00%
Aspect ratio	A	10,97	10,97		0,00%
Cruise speed	V_{CR}	230,0	230	m/s	0,08%
Cruise altitude	h_{CR}	11126	11126	m	0,00%
Squared Sum					**6,90E-07**
Absolute maximum deviation					0,1%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,81**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,28**	
Maximum aerodynamic efficiency	E_{max}	**20,98**	
Specific fuel consumption	SFC	**1,26E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1509	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	66,10	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,76	
Wing loading at maximum take-off mass	m_{MTO}/S_W	601,8	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,81**	

Take-off

Take-off field length	s_{TOFL}	1890	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,327	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,28**	

2nd Segment

Aspect ratio	A	10,971
Lift coefficient, take-off	$C_{L,TO}$	1,58
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,024
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,044
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	10,71
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,235

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,67
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,028
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,063
Glide ratio in landing configuration	E_L	9,34
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,193

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,78	
Aspect ratio	A	10,97	
Bypass ratio	μ	12,00	
Wing loading	m_{MTO}/S_W	602	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,327	

Variables		
	V/V_{md}	**1,1**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,017
Lift coefficient at E_{max}	$C_{L,md}$	0,70
Ratio, lift coefficient	$C_L/C_{L,md}$	0,880
Lift coefficient, cruise	C_L	0,615
Actual aerodynamic efficiency, cruise	E	20,81
Max. glide ratio, cruise	E_{max}	**20,98**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,45	-0,05	0,00
f'(x)	-0,08	-0,10	-0,10
E_{max}	16	21,47	20,98

3) Specific Fuel Consumption

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications

Range	R	1949	NM
Mach number, cruise	M_{CR}	0,78	
Bypass ratio	μ	12,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,327	
Available fuel volume	$V_{fuel,available}$	21,805	m³
Maximum take-off mass	m_{MTO}	67585	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,277	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,548	

Calculated values

Actual aerodynamic efficiency, cruise	E	20,81	
Cruise altitude	h_{CR}	11126	m
Cruise speed	V_{CR}	230	m/s

Mission fuel fraction

Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations

Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,175	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,825	
Available fuel mass	$m_{F,available}$	17444	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,258	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,757	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,26E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	35,1	m
Structural wing span	$b_{W,struct}$	38,73	m
Wing area	S_W	112,3	m²
Aspect ratio	A	10,97	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,6	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	66,10	m/s
Mach number, landing	M_{APP}	0,20	
Mach number, cruise	M_{CR}	0,78	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,1	%c
Leading edge sweep	φ_{LE}	28,2	°
Reynoldsnumber	Re	2,0E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,26	
Correction term, camber	$\Delta_1 c_{L,max}$	0,40	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,034	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,697	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,87	
Correction term, Mach number	$\Delta C_{L,max}$	0,00	
Lift coefficient, wing	$C_{L,max}$	1,47	

Calculations increase of lift coefficient due to flaps		**2 flap types**	
Correction factor, sweep	K_φ	0,87	
• Flap group A			
Single-slotted flap	$\Delta c_{L,max,fA}$	0,79	
Use flapped span	b_W,fA	**10,53**	m
Percentage of flaps allong the wing		27%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,19	
• Flap group B			
Single-slotted flap	$\Delta c_{L,max,fB}$	0,79	
Use flapped span	b_W,fB	**15,4**	m
Percentage of flaps allong the wing		40%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,27	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,46	
Calculations increase of lift coefficient due to slats		**2 slat types**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**29**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,91	
Use slatted span	b_W,sA	**7**	m
Percentage of slats allong the wing		18%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,14	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,91	
Use slatted span	b_W,sB	**23,9**	m
Percentage of slats allong the wing		62%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,49	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,64	
Wing			
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,55**	
RE value maximum lift coefficient, landing		2,81	
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,06**	
RE value maximum lift coefficient, take-off		2,28	
-9%			

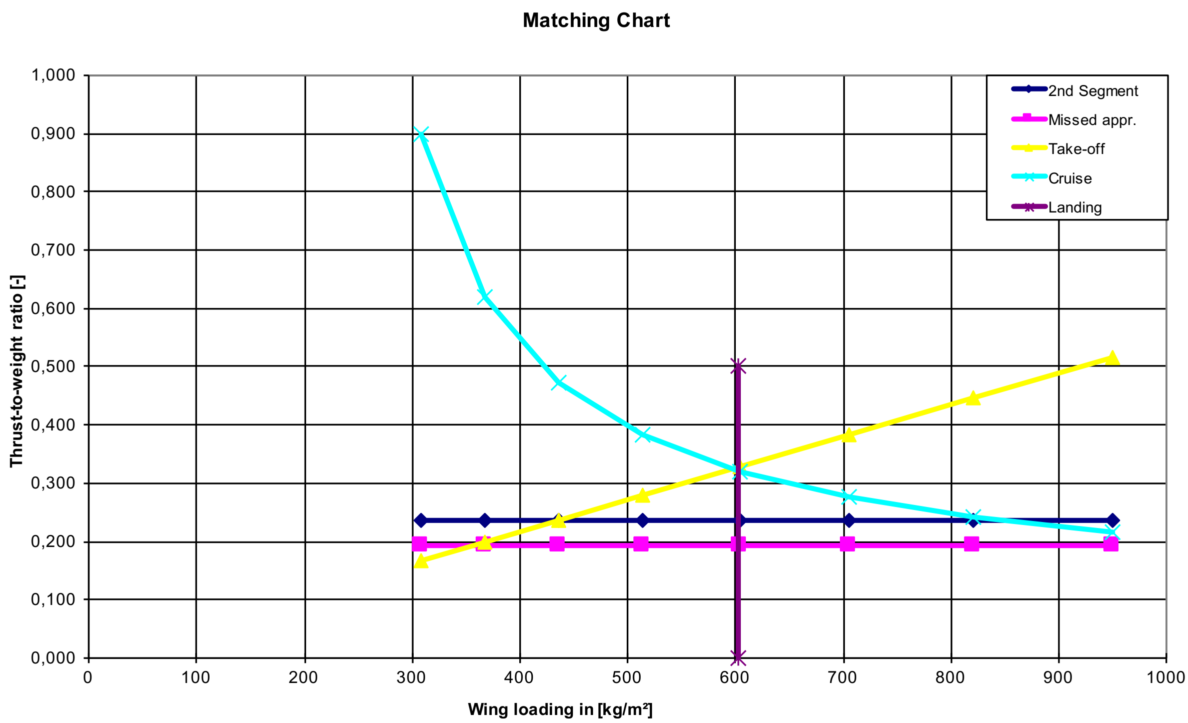
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,06	
Span	b_W	35,1	m
Winglet height	h	**1,5**	m
Aspect ratio	A	10,97	
Effective aspect ratio	A_{eff}	11,64	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**20,5**	
RE value maximum aerodynamic efficiency		20,98	
-2%			

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,780	
Cruise altitude	h_{CR}	11126	m
By Pass Ratio	μ	12,00	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	108,54	kN
Overall Pressure ratio	OAPR	**42,25**	
Turbine entry temperature	TET	**1446,29**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,91	
Ventilator efficiency	$\eta_{ventilator}$	0,88	
Compressor efficiency	$\eta_{compresor}$	0,87	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,98	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,68	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	2,15	
Gas generator efficiency	η_{gasgen}	0,97	
Gas generator function	G	1,98	
Verification value specific fuel consumption	SFC	0,54	kg/daN/h
Verification value specific fuel consumption	SFC	**1,51E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,26E-05	kg/N/s

20%


Matching Chart
1,000
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
100
200
300
400
500
600
700
800
900
1000
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix AF Boeing 767-300F

Data Collection			767-300F	Source:	1			2			4		7		8	9
					Aircraft characteristics for airport planning			Jane's			Engine		Elodie Roux		Data collectior	Webs
Parameter	Symbol	Units	Chosen value					3GB	3PB	3RB						
PAX																
Landing field length	s_{LFL}	m	1740		1700								1740			
Approach speed	V_{APP}	m/s														
Temperature above ISA (288,15K)	ΔT_L	K	0		0											
Relative density	s															
Take-off field length	s_{TOFL}	m	2926		2700-2740								2926			2410
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0											
Relative density	s															
Range (max payload)	R	km	6098		6065			5556					6098			10300
Cruise Mach number	M_{CR}		0,8		0,8			0,8			0,8		0,8			0,8
Wing area	S_W	m²	283,3					283,3					283,3			283,3
Wing span	b_W	m	47,57		47,57			47,57					47,57			47,6
Aspect ratio	A		7,99					8					7,99			
Maximum take-off mass	m_{MTO}	kg	186880		185066-186880			185065-186880					185066			158760
Payload mass	m_{PL}	kg	50800		54885	54839	53978	50800					54885			
Mass ratio, payload - take-off	m_{PL}/m_{MTO}												0,297			
Maximum landing mass	m_{ML}	kg	147871		147871			147871					147871			
Mass ratio, landing - take-off	m_{ML}/m_{MTO}															
Operating empty mass	m_{OE}	kg	85275		85275	85321	86183						85275			86070
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}												0,461			
Wing loading	m_{MTO}/S_W	kg/m²	653					659,5					653			
Maximum zero fuel mass	m_{MZF}	kg	140160		140160			140160					140160			
Number of engines	n_E		2		2								2			2
Engine type	GE CF6		CF6-80C2B7F		CF6-80C2-B8F/B7F1	PW4060/4062	RB211-524H	CF6-80C2B6F/B7F	PW4060/4062	RB211-524H	CF6-80C2B2	CF6-80C2B4	CF6-80C2B7F	PW4062		
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	276,233		269,3794367	269,38/266,71	269,37944	267			229,483773	254,349334	276,233	281,571		220
Total take-off thrust	T_{TO}	kN														
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,3					0,29154519					0,3	0,31		
Bypass ratio	μ										5,31	5,15		4,9		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	9,15E-06								8,9994E-06	9,2258E-06	9,15E-06			
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s									1,6301E-05					
Available fuel volume	$V_{fuel,available}$	m³	91,38		91,38								91,38			
Cruise speed	V_{CR}	m/s	238,33													238,33
Cruise altitude	h_{CR}	m	11887		10668-11887						10668		11887			
Sweep angle	ϕ_{25}	°	31,5										31,5			
Mean aerodynamic chord	c_{MAC}	m	6,98										6,98			
Position of maximum camber	$x_{(y\_c),max}$	%c														20
Camber	$(y_c)_{max}/c$	%c														1,5
Position of maximum thickness	$x_{t,max}$	%c														20
Relative thickness	t/c	%	11,5										11,5			12
Taper	λ		0,207										0,207			
Overall pressure ratio	OAPR		31,8								30,4	29,9	27,1–31,8			
Turbine entry temperature	TET	K														

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1740**	m		
Approach speed	**Unknown**	V_{APP}	66,10	m/s	71,0	71,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2926**	m	2926	2926
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**3000**	NM		
Cruise Mach number		M_{CR}	**0,8**			
Wing area		S_W	**283**	m²		
Wing span	**Known**	b_W	**47,57**	m²	47,57	47,57
Aspect ratio		A	7,99			
Maximum take-off mass		m_{MTO}	**186880**	kg		
Maximum payload mass		m_{PL}	**50800**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,272			
Maximum landing mass		m_{ML}	**147871**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,791			
Operating empty mass		m_{OE}	**85275**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,456			
Wing loading		m_{MTO}/S_W	659,7	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**276,233**	kN		
Total take-off thrust		T_{TO}	552,466	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,301			
Bypass ratio		μ	**5,3**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed	V_{CR}	238	m/s			
Cruise altitude	h_{CR}	11887	m			
Speed ratio	V/V_{md}	1,000	-		1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	31,5	°		
Mean aerodynamic chord		c_{MAC}	4,2	m		
Position of maximum camber		$x_{(y\_c),max}$	30	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	4	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	30	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	11,3	%		
Taper		λ	0,207			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1740	1740	m	0,00%
Approach speed	V_{APP}	Unknown	71,0	m/s	0,00%
Take-off field length	s_{TOFL}	2926	2926	m	0,00%
Span	b_W	47,57	47,57	m	0,00%
Aspect ratio	A	7,99	7,99		0,00%
Cruise speed	V_{CR}	238,3	236	m/s	-0,94%
Cruise altitude	h_{CR}	11887	11368	m	-4,36%

Squared Sum	**1,99E-03**
Absolute maximum deviation	*4,4%*

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	2,80	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	1,75	
Maximum aerodynamic efficiency	E_{max}	15,95	
Specific fuel consumption	SFC	1,43E-05	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1740	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	(m/s²) $^{0.5}$
Approach speed	V_{APP}	70,99	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,79	
Wing loading at maximum take-off mass	m_{MTO}/S_W	659,7	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,80**	

Take-off

Take-off field length	s_{TOFL}	2926	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,301	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,75**	

2nd Segment

Aspect ratio	A	7,988
Lift coefficient, take-off	$C_{L,TO}$	1,22
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,006
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,026
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	11,06
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,229

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,66
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,028
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,063
Glide ratio in landing configuration	E_L	7,55
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,243

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,8	
Aspect ratio	A	7,99	
Bypass ratio	μ	5,30	
Wing loading	m_{MTO}/S_W	660	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,301	

Variables		
	V/V_{md}	**1,0**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,021
Lift coefficient at E_{max}	$C_{L,md}$	0,67
Ratio, lift coefficient	$C_L/C_{L,md}$	1,000
Lift coefficient, cruise	C_L	0,669
Actual aerodynamic efficiency, cruise	E	15,95
Max. glide ratio, cruise	E_{max}	**15,95**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,01	0,00	0,00
f'(x)	-0,13	-0,12	-0,12
E_{max}	16	15,95	15,95

3) Specific Fuel Consumption

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications

Range	R	3000	NM
Mach number, cruise	M_{CR}	0,8	
Bypass ratio	μ	5,30	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}{*}g)$	0,301	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	186880	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,272	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,456	

Calculated values

Actual aerodynamic efficiency, cruise	E	15,95	
Cruise altitude	h_{CR}	11368	m
Cruise speed	V_{CR}	236	m/s

Mission fuel fraction

Type of aeroplane (according to Roskam)	**Transport jet**	
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980
Fuel-Fraction, descent	$M_{ff,DES}$	0,990
Fuel-Fraction, landing	$M_{ff,L}$	0,992

Calculations

Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,272	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,728	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,102	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,916	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,43E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	47,57	m
Structural wing span	$b_{W,struct}$	55,79	m
Wing area	S_W	283,3	m²
Aspect ratio	A	7,99	
Sweep	φ_{25}	31,5	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,3	%
Taper	λ	0,207	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	70,99	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,8	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,1	%c
Leading edge sweep	φ_{LE}	36,2	°
Reynoldsnumber	Re	2,1E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,24	
Correction term, camber	$\Delta_1 c_{L,max}$	0,40	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,044	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,683	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,87	
Correction term, Mach number	$\Delta C_{L,max}$	-0,02	
Lift coefficient, wing	$C_{L,max}$	1,44	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_{φ}	0,84	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,41	
Use flapped span	b_W,fA	**35,7**	m
Percentage of flaps allong the wing		64%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,76	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,74	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,76	

Calculations increase of lift coefficient due to slats			**2 slat types**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**34**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,89	
Use slatted span	b_W,sA	**9,7**	m
Percentage of slats allong the wing		17%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,13	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,89	
Use slatted span	b_W,sB	**36,4**	m
Percentage of slats allong the wing		65%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,48	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,61	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,77**
RE value maximum lift coefficient, landing		2,80
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,73**
RE value maximum lift coefficient, take-off		1,75
-1%		

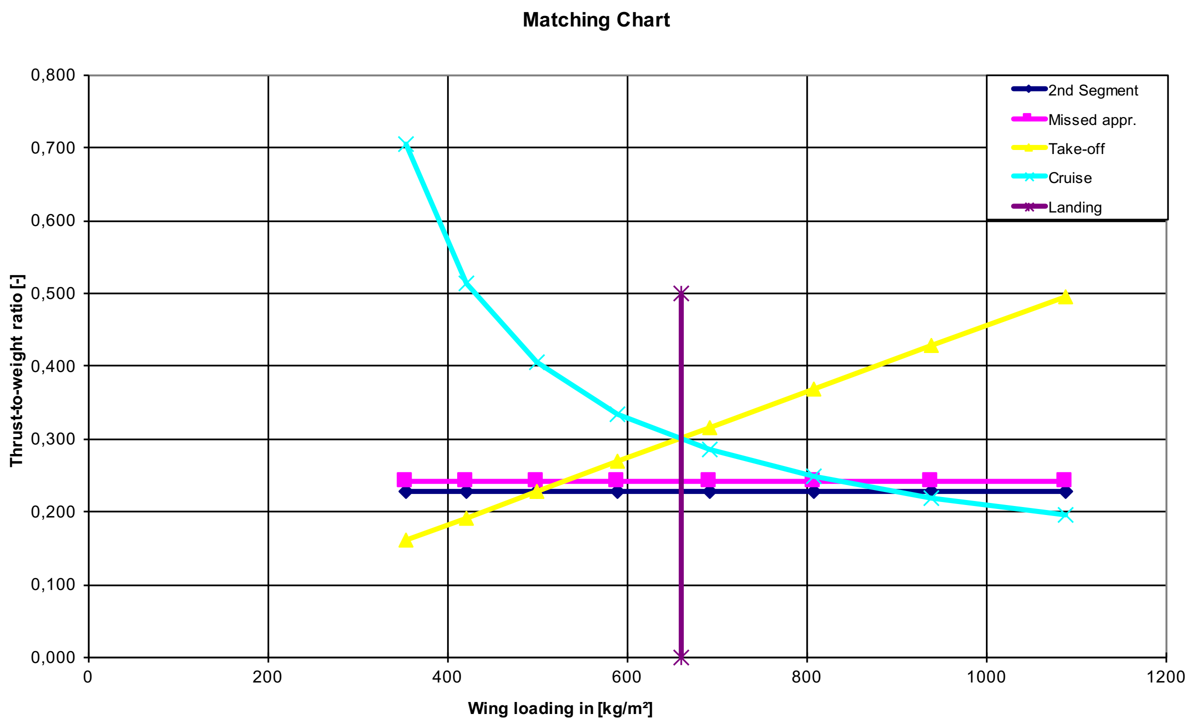
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
No winglets	$k_{e,WL}$	1,00	
Span	b_W	47,57	m
Winglet height	h	**3,4**	m
Aspect ratio	A	7,99	
Effective aspect ratio	A_{eff}	7,99	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**5,44**	
Verification value maximum aerodynamic efficiency	E_{max}	**18,4**	
RE value maximum aerodynamic efficiency		15,95	
15%			

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,800	
Cruise altitude	h_{CR}	11887	m
By Pass Ratio	μ	5,30	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	276,23	kN
Overall Pressure ratio	OAPR	**31,80**	
Turbine entry temperature	TET	**1491,04**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,89	
Compressor efficiency	$\eta_{compresor}$	0,87	
Turbine efficiency	$\eta_{turbine}$	0,91	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	216,65	K
Dimensionless turbine entry temperature	ϕ	6,88	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,13	
Temperature function	χ	1,90	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,28	
Verification value specific fuel consumption	SFC	0,56	kg/daN/h
Verification value specific fuel consumption	SFC	**1,55E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,43E-05	kg/N/s

9%


Matching Chart
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600
800
1000
1200
Thrust-to-weight ratio [-]
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix AG Comac ARJ21-700

Data Collection			ARJ21-700	Source:	1		2		3	4	5	6	7	8	9	
					Aircraft characteristics for airport planning		Jane's		Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collectior	Webs	
Parameter	Symbol	Units	Chosen value		STD	LR	STD	ER							STD	ER
PAX			90		78-90		90						90-78		78-90	
Landing field length	s_{LFL}	m	1550		1600	1700	1550	1650					1550			
Approach speed	V_{APP}	m/s														
Temperature above ISA (288,15K)	ΔT_L	K	0													
Relative density	s															
Take-off field length	s_{TOFL}	m	1700		1700	1900	1700	1900					1700		1700	1900
Temperature above ISA (288,15K)	ΔT_{TO}	K	0													
Relative density	s															
Range (max payload)	R	km	2225		1200	2000	2222	3704					2225		2200	3700
Cruise Mach number	M_{CR}		0,78		0,78								0,78		0,78	
Wing area	S_W	m²	79,86		79,86		79,86						79,86		79,86	
Wing span	b_W	m	27,29		27,288		27,29						27,29		27,28	
Aspect ratio	A		9,32				9,3						9,32			
Maximum take-off mass	m_{MTO}	kg	43500		40500	43500	40500	43500					40500		40500	43500
Payload mass	m_{PL}	kg	8935		8935		8935						8935			
Mass ratio, payload - take-off	m_{PL}/m_{MTO}												0,221			
Maximum landing mass	m_{ML}	kg	37665		37665	40455	37665	40455					37665			
Mass ratio, landing - take-off	m_{ML}/m_{MTO}															
Operating empty mass	m_{OE}	kg	24955		24955		24955						24955		24955	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}												0,616			
Wing loading	m_{MTO}/S_W	kg/m²	507,1				507,1	544,7					507			
Maximum zero fuel mass	m_{MZF}	kg	33890		33890		33890						33890			
Number of engines	n_E		2				2						2			
Engine type	GE CF34-10A		CF34-10A		CF34-10A		CF34-10A						CF34-10A		CF34-10A	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	68,2				68,2						80,068		75,87	
Total take-off thrust	T_{TO}	kN														
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,4				0,34357	0,31988					0,4			
Bypass ratio	μ		5										5			
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s														
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s														
Available fuel volume	$V_{fuel,available}$	m³	12,719		13,231		12,719						12,719			
Cruise speed	V_{CR}	m/s	230												230	
Cruise altitude	h_{CR}	m	10668		10668								10668		11900	
Sweep angle	φ_{25}	°	25		25								25		25	
Mean aerodynamic chord	c_{MAC}	m														
Position of maximum camber	$x_{(y\_c),max}$	%c														
Camber	$(y_c)_{max}/c$	%c														
Position of maximum thickness	$x_{t,max}$	%c														
Relative thickness	t/c	%														
Taper	λ															
Overall pressure ratio	OAPR															
Turbine entry temperature	TET	K														

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1550**	m		
Approach speed	**Unknown**	V_{APP}	66,10	m/s	67,0	67,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**1700**	m	1700	1700
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**1201**	NM		
Cruise Mach number		M_{CR}	**0,78**			
Wing area		S_W	**80**	m²		
Wing span	**Known**	b_W	**27,29**	m²	27,29	27,29
Aspect ratio		A	9,33			
Maximum take-off mass		m_{MTO}	**43500**	kg		
Maximum payload mass		m_{PL}	**8935**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,205			
Maximum landing mass		m_{ML}	**37665**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,866			
Operating empty mass		m_{OE}	**24955**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,574			
Wing loading		m_{MTO}/S_W	544,7	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**68,2**	kN		
Total take-off thrust		T_{TO}	136,4	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,320			
Bypass ratio		μ	**5**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	**230**	m/s		
Cruise altitude	h_{CR}	**10668**	m		
Speed ratio	V/V_{md}	**1,267**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**25**	°		
Mean aerodynamic chord		c_{MAC}	**4,2**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,6**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1550	1550	m	0,00%
Approach speed	V_{APP}	Unknown	**67,0**	m/s	0,00%
Take-off field length	s_{TOFL}	1700	1700	m	0,00%
Span	b_W	27,29	27,29	m	0,00%
Aspect ratio	A	9,33	9,33		0,00%
Cruise speed	V_{CR}	230,0	231	m/s	0,57%
Cruise altitude	h_{CR}	10668	10678	m	0,09%
Squared Sum					**3,28E-05**
Absolute maximum deviation					0,6%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,84**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,35**	
Maximum aerodynamic efficiency	E_{max}	**14,89**	
Specific fuel consumption	SFC	**1,72E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1550	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	67,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,87	
Wing loading at maximum take-off mass	m_{MTO}/S_W	544,7	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,84**	

Take-off

Take-off field length	s_{TOFL}	1700	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,320	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,35**	

2nd Segment

Aspect ratio	A	9,326
Lift coefficient, take-off	$C_{L,TO}$	1,63
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,026
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,046
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	9,26
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,264

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,68
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,029
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,064
Glide ratio in landing configuration	E_L	8,32
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,244

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,78	
Aspect ratio	A	9,33	
Bypass ratio	μ	5,00	
Wing loading	m_{MTO}/S_W	545	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,320	

Variables		
	V/V_{md}	**1,3**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,028
Lift coefficient at E_{max}	$C_{L,md}$	0,84
Ratio, lift coefficient	$C_L/C_{L,md}$	0,623
Lift coefficient, cruise	C_L	0,521
Actual aerodynamic efficiency, cruise	E	13,37
Max. glide ratio, cruise	E_{max}	**14,89**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,15	0,00	0,00
f'(x)	-0,13	-0,13	-0,13
E_{max}	16	14,91	14,89

3) Specific Fuel Consumption

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications

Range	R	1201	NM
Mach number, cruise	M_{CR}	0,78	
Bypass ratio	μ	5,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,320	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	43500	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,205	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,574	

Calculated values

Actual aerodynamic efficiency, cruise	E	13,37	
Cruise altitude	h_{CR}	10678	m
Cruise speed	V_{CR}	231	m/s

Mission fuel fraction

Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations

Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,221	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,779	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,439	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,573	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,72E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 64 series**	
Wing span	b_W	27,29	m
Structural wing span	$b_{W,struct}$	30,11	m
Wing area	S_W	79,9	m²
Aspect ratio	A	9,33	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,6	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	67,00	m/s
Mach number, landing	M_{APP}	0,20	
Mach number, cruise	M_{CR}	0,78	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,5	%c
Leading edge sweep	φ_{LE}	28,8	°
Reynoldsnumber	Re	2,0E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,42	
Correction term, camber	$\Delta_1 c_{L,max}$	0,35	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,007	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,770	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,80	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,42	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_φ	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,39	
Use flapped span	b_W,fA	**21**	m
Percentage of flaps allong the wing		70%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,84	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,73	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,84	
Calculations increase of lift coefficient due to slats			**1 slat type**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**27**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,88	
Use slatted span	b_W,sA	**24,6**	m
Percentage of slats allong the wing		82%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,64	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,88	
Use slatted span	b_W,sB	**0**	m
Percentage of slats allong the wing		0%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,00	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,64	
Wing			
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,86**	
RE value maximum lift coefficient, landing		2,84	
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,36**	
RE value maximum lift coefficient, take-off		2,35	
0%			

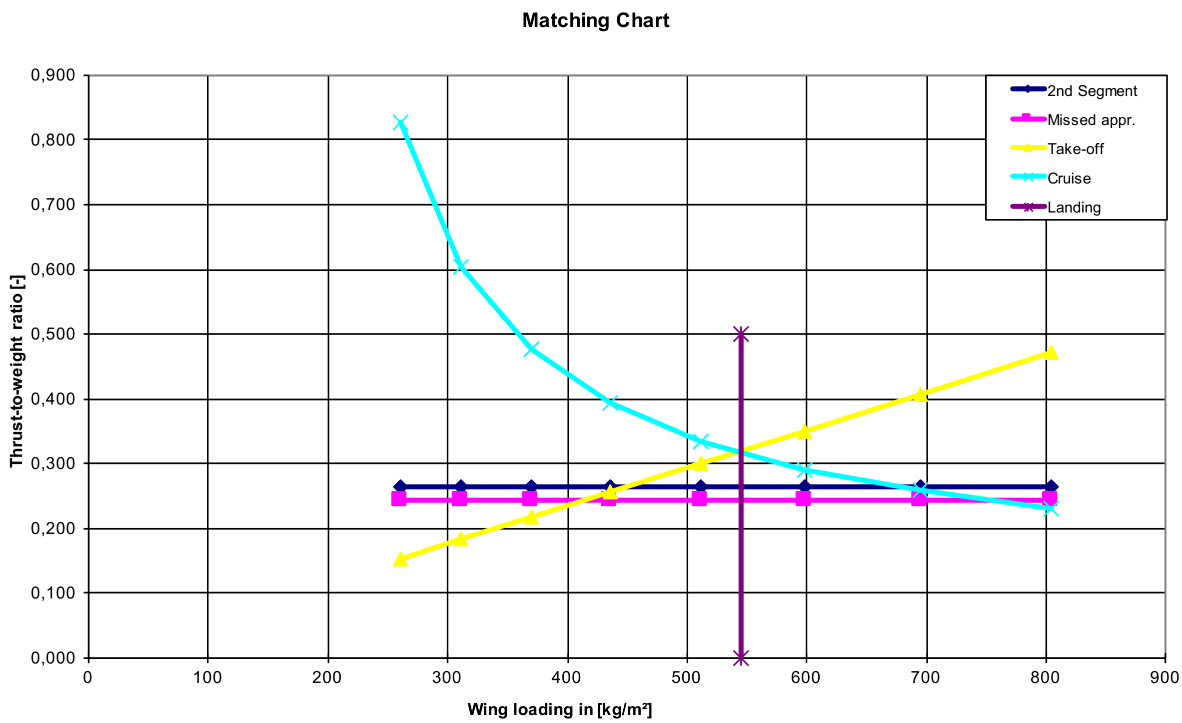
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,06	
Span	b_W	27,29	m
Winglet height	h	**1,2**	m
Aspect ratio	A	9,33	
Effective aspect ratio	A_{eff}	9,91	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**18,9**	
RE value maximum aerodynamic efficiency		14,89	

27%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,780	
Cruise altitude	h_{CR}	10668	m
By Pass Ratio	μ	5,00	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	68,20	kN
Overall Pressure ratio	OAPR	**29,00**	
Turbine entry temperature	TET	**1402,70**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,83	
Compressor efficiency	$\eta_{compresor}$	0,85	
Turbine efficiency	$\eta_{turbine}$	0,88	
Nozzle efficiency	η_{nozzle}	0,97	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,81	K
Dimensionless turbine entry temperature	ϕ	6,41	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,81	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	1,89	
Verification value specific fuel consumption	SFC	0,64	kg/daN/h
Verification value specific fuel consumption	SFC	**1,78E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,72E-05	kg/N/s
3%			



Matching Chart
Thrust-to-weight ratio [-]
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
100
200
300
400
500
600
700
800
900
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix AH Comac ARJ21-900

Data Collection			ARJ21-900		1	2		3	4	5	6	7	8	9	
				Source:	Aircraft characteristics for airport planning	Jane's		Jenkinson	Engine	Scholz	Paul Müller	Elodie Rou	Data collectior	Webs	
Parameter	Symbol	Units	Chosen value			STD	ER							STD	ER
PAX			105			105						105-98		98-105	
Landing field length	s_{LFL}	m	1600			1600	1700					1600			
Approach speed	V_{APP}	m/s													
Temperature above ISA (288,15K)	ΔT_L	K	0												
Relative density	s														
Take-off field length	s_{TOFL}	m	1750			1750	1950					1750		1750	1950
Temperature above ISA (288,15K)	ΔT_{TO}	K	0												
Relative density	s														
Range (max payload)	R	km	2222			2222	3333					3334		2200	3300
Cruise Mach number	M_{CR}		0,78									0,78		0,78	
Wing area	S_W	m²	79,86			79,86						79,86		79,86	
Wing span	b_W	m	27,29			27,29						27,29		27,28	
Aspect ratio	A		9,32			9,3						9,32			
Maximum take-off mass	m_{MTO}	kg	47182			43616	47182					43616		43616	47182
Payload mass	m_{PL}	kg	11246			11246						11246		11246	
Mass ratio, payload - take-off	m_{PL}/m_{MTO}											0,258			
Maximum landing mass	m_{ML}	kg	40563			40563	43879					40563		38513	
Mass ratio, landing - take-off	m_{ML}/m_{MTO}														
Operating empty mass	m_{OE}	kg	26270			26270	26770					26270		26270	26770
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}											0,602			
Wing loading	m_{MTO}/S_W	kg/m²	546,2			546,2	590,8					546			
Maximum zero fuel mass	m_{MZF}	kg	37516			37516	38016					37516			
Number of engines	n_E		2			2						2			
Engine type	GE CF34-10A		CF34-10A			CF34-10A						CF34-10A		CF34-10A	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	75,9			75,9						80,068		82	
Total take-off thrust	T_{TO}	kN													
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,37			0,35554	0,32811					0,37			
Bypass ratio	μ		5									5			
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s													
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s													
Available fuel volume	$V_{fuel,available}$	m³	12,719			12,719	13,355					12,719			
Cruise speed	V_{CR}	m/s	230											230	
Cruise altitude	h_{CR}	m	10668									10668		11900	
Sweep angle	ϕ_{25}	°	25									25		25	
Mean aerodynamic chord	c_{MAC}	m													
Position of maximum camber	$x_{(y\_c),max}$	%c													
Camber	$(y_c)_{max}/c$	%c													
Position of maximum thickness	$x_{t,max}$	%c													
Relative thickness	t/c	%													
Taper	λ														
Overall pressure ratio	OAPR														
Turbine entry temperature	TET	K													

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1600**	m		
Approach speed	**Unknown**	V_{APP}	66,10	m/s	68,1	68,1
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**1750**	m	1750	1750
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**1200**	NM		
Cruise Mach number		M_{CR}	**0,78**			
Wing area		S_W	**80**	m²		
Wing span	**Known**	b_W	**27,29**	m²	27,29	27,29
Aspect ratio		A	9,33			
Maximum take-off mass		m_{MTO}	**47182**	kg		
Maximum payload mass		m_{PL}	**11246**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,238			
Maximum landing mass		m_{ML}	**40563**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,860			
Operating empty mass		m_{OE}	**26270**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,557			
Wing loading		m_{MTO}/S_W	590,8	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**75,9**	kN		
Total take-off thrust		T_{TO}	151,8	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,328			
Bypass ratio		μ	**5**			
Available fuel volume		$V_{fuel,available}$	12,72	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed		V_{CR}	230	m/s		
Cruise altitude		h_{CR}	10668	m		
Speed ratio		V/V_{md}	1,242	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	25	°		
Mean aerodynamic chord		c_{MAC}	4,2	m		
Position of maximum camber		$x_{(y\_c),max}$	30	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	4	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	30	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	11,6	%		
Taper		λ	0,24			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1600	1600	m	0,00%
Approach speed	V_{APP}	Unknown	68,1	m/s	0,00%
Take-off field length	s_{TOFL}	1750	1750	m	0,00%
Span	b_W	27,29	27,29	m	0,00%
Aspect ratio	A	9,33	9,33		0,00%
Cruise speed	V_{CR}	230,0	231	m/s	0,57%
Cruise altitude	h_{CR}	10668	10678	m	0,09%
Squared Sum					**3,28E-05**
Absolute maximum deviation					0,6%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	2,97	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	2,41	
Maximum aerodynamic efficiency	E_{max}	14,28	
Specific fuel consumption	SFC	1,49E-05	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1600	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	68,07	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,86	
Wing loading at maximum take-off mass	m_{MTO}/S_W	590,8	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,97**	

Take-off

Take-off field length	s_{TOFL}	1750	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,328	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,41**	

2nd Segment

Aspect ratio	A	9,326
Lift coefficient, take-off	$C_{L,TO}$	1,67
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,029
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,049
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	9,04
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,269

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,76
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,033
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,068
Glide ratio in landing configuration	E_L	8,05
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,250

2) Maximum Aerodynamic Efficiency

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications

Mach number, cruise	M_{CR}	0,78	
Aspect ratio	A	9,33	
Bypass ratio	μ	5,00	
Wing loading	m_{MTO}/S_W	591	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,328	

Variables

	V/V_{md}	**1,2**

Calculations

Zero-lift drag coefficient	$C_{D,0}$	0,031
Lift coefficient at E_{max}	$C_{L,md}$	0,87
Ratio, lift coefficient	$C_L/C_{L,md}$	0,648
Lift coefficient, cruise	C_L	0,565
Actual aerodynamic efficiency, cruise	E	13,03
Max. glide ratio, cruise	E_{max}	**14,28**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,24	-0,01	0,00
f'(x)	-0,14	-0,13	-0,13
E_{max}	16	14,33	14,28

3) Specific Fuel Consumption

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications

Range	R	1200	NM
Mach number, cruise	M_{CR}	0,78	
Bypass ratio	μ	5,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,328	
Available fuel volume	$V_{fuel,available}$	12,72	m³
Maximum take-off mass	m_{MTO}	47182	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,238	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,557	

Calculated values

Actual aerodynamic efficiency, cruise	E	13,03	
Cruise altitude	h_{CR}	10678	m
Cruise speed	V_{CR}	231	m/s

Mission fuel fraction

Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations

Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,205	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,795	
Available fuel mass	$m_{F,available}$	10176	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,216	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,800	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,49E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	NACA 4 digit	
Wing span	b_W	27,29	m
Structural wing span	$b_{W,struct}$	30,11	m
Wing area	S_W	79,9	m²
Aspect ratio	A	9,33	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,6	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	68,07	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,78	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	3,0	%c
Leading edge sweep	φ_{LE}	28,8	°
Reynoldsnumber	Re	2,0E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,58	
Correction term, camber	$\Delta_1 c_{L,max}$	0,18	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,079	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,831	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,80	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,46	

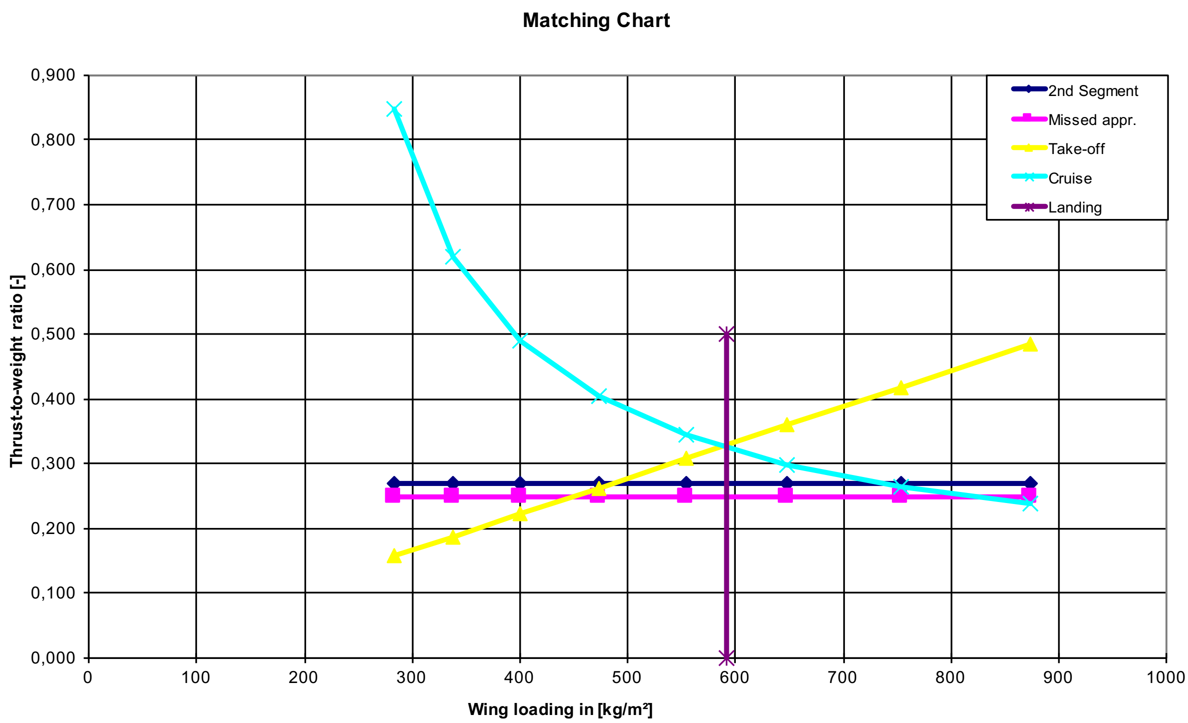
Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_φ	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,43	
Use flapped span	b_W,fA	**21**	m
Percentage of flaps allong the wing		70%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,86	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,74	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,86	
Calculations increase of lift coefficient due to slats			**1 slat type**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**27**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,90	
Use slatted span	b_W,sA	**24,6**	m
Percentage of slats allong the wing		82%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,66	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**0**	m
Percentage of slats allong the wing		0%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,00	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,66	
Wing			
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,93**	
RE value maximum lift coefficient, landing		2,97	
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,38**	
RE value maximum lift coefficient, take-off		2,41	
-1%			

Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,06	
Span	b_W	27,29	m
Winglet height	h	**1,2**	m
Aspect ratio	A	9,33	
Effective aspect ratio	A_{eff}	9,91	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**18,9**	
RE value maximum aerodynamic efficiency		14,28	
33%			

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,780	
Cruise altitude	h_{CR}	10668	m
By Pass Ratio	μ	5,00	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	75,90	kN
Overall Pressure ratio	OAPR	**29,00**	
Turbine entry temperature	TET	**1414,60**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,84	
Compressor efficiency	$\eta_{compresor}$	0,85	
Turbine efficiency	$\eta_{turbine}$	0,88	
Nozzle efficiency	η_{nozzle}	0,97	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,81	K
Dimensionless turbine entry temperature	ϕ	6,47	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,81	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	1,94	
Verification value specific fuel consumption	SFC	0,63	kg/daN/h
Verification value specific fuel consumption	SFC	**1,75E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,49E-05	kg/N/s
17%			


Matching Chart
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
100
200
300
400
500
600
700
800
900
1000
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix AI Boeing 787-10

Data Collection			787-10	Source:	1	2	3	4		5	6	7	8	9
Parameter	Symbol	Units	Chosen value		Aircraft characteristics for airport planning (GE / RR)	Jane's	Jenkinson	Engine		Scholz	Paul Müller	Elodie Roux	Data collection	Webs
PAX			440		330-440									327-396-44
Landing field length	s_{LFL}	m	1855		1855									
Approach speed	V_{APP}	m/s												
Temperature above ISA (288,15K)	ΔT_L	K	0		0									
Relative density	s													
Take-off field length	s_{TOFL}	m	2995		2995									
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0									
Relative density	s													
Range (max payload)	R	km	7710		7710									12900
Cruise Mach number	M_{CR}		0,85		0,85									0,85
Wing area	S_W	m²	325											325
Wing span	b_W	m	60,12		60,12									60
Aspect ratio	A		11,1											
Maximum take-off mass	m_{MTO}	kg	254011		254011									250836
Payload mass	m_{PL}	kg	57276		57276									
Mass ratio, payload - take-off	m_{PL}/m_{MTO}													
Maximum landing mass	m_{ML}	kg	201848		201848									201849
Mass ratio, landing - take-off	m_{ML}/m_{MTO}													
Operating empty mass	m_{OE}	kg	135500											135500
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}													
Wing loading	m_{MTO}/S_W	kg/m²												
Maximum zero fuel mass	m_{MZF}	kg	192776		192776									201849
Number of engines	n_E		2					2						2
Engine type	GE GEnx 1B (62%), RR		Genx 72A1					GEnx 72A1	Trent 1000					Genx
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	340					235,756	235,756					340
Total take-off thrust	T_{TO}	kN												
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$													
Bypass ratio	μ								11					
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s												
Specific Fuel Comsumption (cruise)	SFC (cruise)	kg/N s												
Available fuel volume	$V_{fuel,available}$	m³	138,7		126,429									138,7
Cruise speed	V_{CR}	m/s	253,61											253,61
Cruise altitude	h_{CR}	m	10700											10700
Sweep angle	ϕ_{25}	°	32,2											32,2
Mean aerodynamic chord	c_{MAC}	m												
Position of maximum camber	$x_{(y\_c),max}$	%c												
Camber	$(y_c)_{max}/c$	%c												
Position of maximum thickness	$x_{t,max}$	%c												
Relative thickness	t/c	%												
Taper	λ													
Overall pressure ratio	OAPR													
Turbine entry temperature	TET	K												

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1855**	m		
Approach speed	**Unknown**	V_{APP}	66,10	m/s	73,3	73,3
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2995**	m	2995	2995
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**4163**	NM		
Cruise Mach number		M_{CR}	**0,85**			
Wing area		S_W	**325**	m²		
Wing span	**Known**	b_W	**60,12**	m²	60,12	60,12
Aspect ratio		A	11,12			
Maximum take-off mass		m_{MTO}	**254011**	kg		
Maximum payload mass		m_{PL}	**57276**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,225			
Maximum landing mass		m_{ML}	**201848**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,795			
Operating empty mass		m_{OE}	**135500**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,533			
Wing loading		m_{MTO}/S_W	781,6	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**340**	kN		
Total take-off thrust		T_{TO}	680	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,273			
Bypass ratio		μ	**9**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	**254**	m/s		
Cruise altitude	h_{CR}	**10700**	m		
Speed ratio	V/V_{md}	**1,097**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**32,2**	°		
Mean aerodynamic chord		c_{MAC}	**4,2**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**10,6**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1855	1855	m	0,00%
Approach speed	V_{APP}	Unknown	**73,3**	m/s	0,00%
Take-off field length	s_{TOFL}	2995	2995	m	0,00%
Span	b_W	60,12	60,12	m	0,00%
Aspect ratio	A	11,12	11,12		0,00%
Cruise speed	V_{CR}	253,6	252	m/s	-0,63%
Cruise altitude	h_{CR}	10700	10689	m	-0,10%
Squared Sum					**4,05E-05**
Absolute maximum deviation					0,6%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,13**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,24**	
Maximum aerodynamic efficiency	E_{max}	**19,62**	
Specific fuel consumption	SFC	**1,14E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1855	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	73,30	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,79	
Wing loading at maximum take-off mass	m_{MTO}/S_W	781,6	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,13**	

Take-off

Take-off field length	s_{TOFL}	2995	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,273	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,24**	

2nd Segment

Aspect ratio	A	11,121
Lift coefficient, take-off	$C_{L,TO}$	1,55
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,023
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,043
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	10,99
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,230

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,85
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,038
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,073
Glide ratio in landing configuration	E_L	8,70
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,216

2) Maximum Aerodynamic Efficiency

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications

Mach number, cruise	M_{CR}	0,85	
Aspect ratio	A	11,12	
Bypass ratio	μ	9,00	
Wing loading	m_{MTO}/S_W	782	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,273	

Variables

	V/V_{md}	**1,1**

Calculations

Zero-lift drag coefficient	$C_{D,0}$	0,019
Lift coefficient at E_{max}	$C_{L,md}$	0,76
Ratio, lift coefficient	$C_L/C_{L,md}$	0,831
Lift coefficient, cruise	C_L	0,629
Actual aerodynamic efficiency, cruise	E	19,29
Max. glide ratio, cruise	E_{max}	**19,62**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,34	-0,02	0,00
f'(x)	-0,09	-0,10	-0,10
E_{max}	16	19,86	19,62

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	4163	NM
Mach number, cruise	M_{CR}	0,85	
Bypass ratio	μ	9,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,273	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	254011	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,225	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,533	

Calculated values			
Actual aerodynamic efficiency, cruise	E	19,29	
Cruise altitude	h_{CR}	10689	m
Cruise speed	V_{CR}	252	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,241	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,759	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,075	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,944	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,14E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	60,12	m
Structural wing span	$b_{W,struct}$	71,05	m
Wing area	S_W	325,0	m²
Aspect ratio	A	11,12	
Sweep	φ_{25}	32,2	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	10,6	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	73,30	m/s
Mach number, landing	M_{APP}	0,22	
Mach number, cruise	M_{CR}	0,85	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	1,9	%c
Leading edge sweep	φ_{LE}	35,4	°
Reynoldsnumber	Re	2,2E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,17	
Correction term, camber	$\Delta_1 c_{L,max}$	0,39	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,064	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,624	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,91	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,46	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_φ	0,83	
• Flap group A			
0,4c Single-slotted fowler flap	$\Delta c_{L,max,fA}$	2,04	
Use flapped span	b_W,fA	**40,7**	m
Percentage of flaps allong the wing		57%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,97	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,75	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,97	

Calculations increase of lift coefficient due to slats			**2 slat types**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**34,5**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,91	
Use slatted span	b_W,sA	**13,4**	m
Percentage of slats allong the wing		19%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,14	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,91	
Use slatted span	b_W,sB	**40,1**	m
Percentage of slats allong the wing		56%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,42	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,56	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,95**
RE value maximum lift coefficient, landing		3,13
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,11**
RE value maximum lift coefficient, take-off		2,24
-6%		

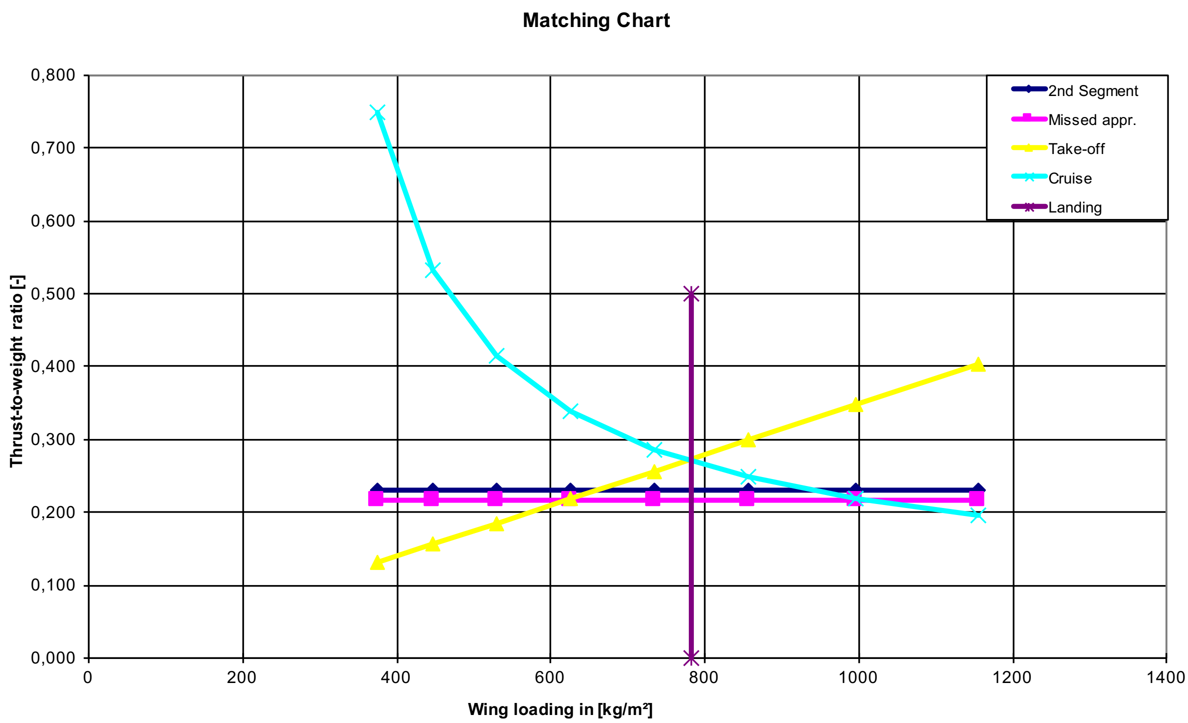
Aerodynamic efficiency

Real aircraft average	k_{WL}	**2,83**	
No winglets	$k_{e,WL}$	1,00	
Span	b_W	60,12	m
Winglet height	h	**1,6**	m
Aspect ratio	A	11,12	
Effective aspect ratio	A_{eff}	11,12	
Efficiency factor, short range	k_E	16,19	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**21,4**	
RE value maximum aerodynamic efficiency		19,62	
9%			

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,850	
Cruise altitude	h_{CR}	10700	m
By Pass Ratio	μ	9,00	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	340,00	kN
Overall Pressure ratio	OAPR	**53,30**	
Turbine entry temperature	TET	**1496,47**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,93	
Ventilator efficiency	$\eta_{ventilator}$	0,90	
Compressor efficiency	$\eta_{compresor}$	0,88	
Turbine efficiency	$\eta_{turbine}$	0,91	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,60	K
Dimensionless turbine entry temperature	ϕ	6,85	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,14	
Temperature function	χ	2,42	
Gas generator efficiency	η_{gasgen}	0,97	
Gas generator function	G	1,98	
Verification value specific fuel consumption	SFC	0,54	kg/daN/h
Verification value specific fuel consumption	SFC	**1,49E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,14E-05	kg/N/s

31%


Matching Chart
2nd Segment
Missed appr.
Take-off
Cruise
Landing
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
1400
Wing loading in [kg/m²]

Appendix AJ Boeing 747-400

Data Collection			747-400		1			2			3	4			6	7			8	9
				Source:	Aircraft characteristics for airport planning			Jane's			Jenkinson	Engine			Paul Müller	Elodie Roux			Data collection	Webs
Parameter	Symbol	Units	Chosen value		GE	PW	RR	GB	PB	RB										
PAX			620			400			416-		660-496-412				496		620-420			
Landing field length	s_{LFL}	m	2100			2070			1905		2130				2072		2130		2130	
Approach speed	V_{APP}	m/s	75,1						75,1		78,71				75				82,31111111	
Temperature above ISA (288,15K)	ΔT_L	K	0			0					0									
Relative density	s																			
Take-off field length	s_{TOFL}	m	3200		3215		3050	2820		2850	3310						3310		3300	3018
Temperature above ISA (288,15K)	ΔT_{TO}	K	0			0			15		0									
Relative density	s																			
Range (max payload)	R	km	10695		10560	10695	10465	11454	11473	11186	12699,1				9800		8480			13450
Cruise Mach number	M_{CR}		0,85			0,85			0,85			0,8		0,85			0,85		0,85	0,85
Wing area	S_W	m²	541,16						541,16		525				524,9		541,16			
Wing span	b_W	m	64,44			64,44-64,92			64,44-64,92		62,3				64,44		64,44		64,4	64,9
Aspect ratio	A		7,67						7,7		7,3929333				7,9		7,67			
Maximum take-off mass	m_{MTO}	kg	396830			362874-396894			362875		396830				385555		362874		396890	396890
Payload mass	m_{PL}	kg	63657		63917-67319	63657-67059	62921-67457				61186						63657			
Mass ratio, payload - take-off	m_{PL}/m_{MTO}										0,1541869						0,175			
Maximum landing mass	m_{ML}	kg	260362			260362-285764			260360		285760				260360		260362			
Mass ratio, landing - take-off	m_{ML}/m_{MTO}										0,7201068									
Operating empty mass	m_{OE}	kg	179015		178756	179015	179752	180485	180845	181435	181484						179015			178800
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}										0,4573344						0,493			
Wing loading	m_{MTO}/S_W	kg/m²	670,5						670,5		755,86667						671			
Maximum zero fuel mass	m_{MZF}	kg	242672		242672-246074		242672-24720		242670		242670						242672			
Number of engines	n_E		4			4					4						4		4	4
Engine type	GE CF6-80 (37%), PW4(		PW4056		CF6-80C2B1F	PW4056	RB211-524G2	CF6-80C2B1F	PW4056	RB211-524G	P&W4056	CF6-80C2B1F	PW4056	RB.211-524G		CF6-80C2B1F	PW4056	RB.211-524G	RB211-524 G/H	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	252		257,377383	252,2654	257,8184	258	252	258	252,4	254,26037	252,436599	257,996876		254,259	252,435	257,996	258	282
Total take-off thrust	T_{TO}	kN																		
Thrust to weight ratio	$T_{TO}/(m_{MTO}{}^*g)$		0,28					0,28988868	0,2842	0,2898887	0,2593438					0,29	0,28	0,29		
Bypass ratio	μ		4,9									5,15	4,85	4,3		5,2	4,9	4,3		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	9,06E-06									8,9428E-06	9,056E-06			8,95E-06	9,06E-06			
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s										1,5961E-05		1,6131E-05		1,60E-05		1,62E-05		
Available fuel volume	$V_{fuel,available}$	m³	204,333		203,501-215,9(	204,333-216,824		203,523	204,355		204,35-216,85						204,35			216,84
Cruise speed	V_{CR}	m/s	253								252,08-260,82								262,3666667	253,33
Cruise altitude	h_{CR}	m	10668						10575		10668	10668	10668	10668			10668			
Sweep angle	ϕ_{25}	°	37,5								37,5						37,5			
Mean aerodynamic chord	c_{MAC}	m	9,68								9,68						9,68			
Position of maximum camber	$x_{(y\_c),max}$	%c	15																	15
Camber	$(y_c)_{max}/c$	%c	1,4																	1,4
Position of maximum thickness	$x_{t,max}$	%c	35																	35
Relative thickness	t/c	%	9,4								9,4						13,4-7,8-8			11,3
Taper	λ		0,278						0,277511962		0,275						0,278			
Overall pressure ratio	OAPR		30,2									30,4	30,2	32,9						
Turbine entry temperature	TET	K																		

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**2100**	m		
Approach speed	**Known**	V_{APP}	**75,10**	m/s	75,1	75,1
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**3200**	m	3200	3200
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**5775**	NM		
Cruise Mach number		M_{CR}	**0,85**			
Wing area		S_W	**541**	m²		
Wing span	**Known**	b_W	**64,44**	m²	64,44	64,44
Aspect ratio		A	7,67			
Maximum take-off mass		m_{MTO}	**396830**	kg		
Maximum payload mass		m_{PL}	**63657**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,160			
Maximum landing mass		m_{ML}	**260362**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,656			
Operating empty mass		m_{OE}	**179015**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,451			
Wing loading		m_{MTO}/S_W	733,3	kg/m²		
Number of engines		n_E	**4**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**252**	kN		
Total take-off thrust		T_{TO}	1008	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,259			
Bypass ratio		μ	**4,9**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed		V_{CR}	**253**	m/s		
Cruise altitude		h_{CR}	**10668**	m		
Speed ratio		V/V_{md}	**1,029**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**37,5**	°		
Mean aerodynamic chord		c_{MAC}	**9,68**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**10,6**	%		
Taper		λ	**0,278**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	2100	2100	m	0,00%
Approach speed	V_{APP}	75,10	75,1	m/s	0,00%
Take-off field length	s_{TOFL}	3200	3200	m	0,00%
Span	b_W	64,44	64,44	m	0,00%
Aspect ratio	A	7,67	7,67		0,00%
Cruise speed	V_{CR}	253,0	252	m/s	-0,35%
Cruise altitude	h_{CR}	10668	10662	m	-0,06%
Squared Sum					**1,25E-05**
Absolute maximum deviation					0,3%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,14**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,07**	
Maximum aerodynamic efficiency	E_{max}	**16,42**	
Specific fuel consumption	SFC	**1,46E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	2100	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	75,10	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,66	
Wing loading at maximum take-off mass	m_{MTO}/S_W	733,3	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,14**	

Take-off

Take-off field length	s_{TOFL}	3200	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,259	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,07**	

2nd Segment

Aspect ratio	A	7,673
Lift coefficient, take-off	$C_{L,TO}$	1,44
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,017
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,037
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	9,02
Number of engines	n_E	4
Climb gradient	$\sin(\gamma)$	0,030
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,188

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,27
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,008
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,043
Glide ratio in landing configuration	E_L	9,15
Climb gradient	$\sin(\gamma)$	0,027
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,119

2) Maximum Aerodynamic Efficiency

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications

Mach number, cruise	M_{CR}	0,85	
Aspect ratio	A	7,67	
Bypass ratio	μ	4,90	
Wing loading	m_{MTO}/S_W	733	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,259	

Variables

	V/V_{md}	**1,0**

Calculations

Zero-lift drag coefficient	$C_{D,0}$	0,019
Lift coefficient at E_{max}	$C_{L,md}$	0,62
Ratio, lift coefficient	$C_L/C_{L,md}$	0,944
Lift coefficient, cruise	C_L	0,589
Actual aerodynamic efficiency, cruise	E	16,39
Max. glide ratio, cruise	E_{max}	**16,42**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,05	0,00	0,00
f'(x)	-0,11	-0,12	-0,12
E_{max}	16	16,42	16,42

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	5775	NM
Mach number, cruise	M_{CR}	0,85	
Bypass ratio	μ	4,90	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,259	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	396830	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,160	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,451	

Calculated values			
Actual aerodynamic efficiency, cruise	E	16,39	
Cruise altitude	h_{CR}	10662	m
Cruise speed	V_{CR}	252	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,388	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,612	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,048	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,971	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**no**	
	international	**yes**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	905165	m
Loiter time	t_{loiter}	1800	s
Specific fuel consumption	SFC	**1,46E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 63 series**	
Wing span	b_W	64,44	m
Structural wing span	$b_{W,struct}$	81,22	m
Wing area	S_W	541,2	m²
Aspect ratio	A	7,67	
Sweep	φ_{25}	37,5	°
Mean aerodynamic chord	c_{MAC}	9,68	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	10,6	%
Taper	λ	0,278	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	75,10	m/s
Mach number, landing	M_{APP}	0,23	
Mach number, cruise	M_{CR}	0,85	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,3	%c
Leading edge sweep	φ_{LE}	41,7	°
Reynoldsnumber	Re	5,2E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,36	
Correction term, camber	$\Delta_1 c_{L,max}$	0,38	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,018	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,760	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,77	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,34	

Calculations increase of lift coefficient due to flaps		**1 flap type**	
Correction factor, sweep	K_{φ}	0,80	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,31	
Use flapped span	b_W,fA	**41,2**	m
Percentage of flaps allong the wing		51%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,53	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,68	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,53	

Calculations increase of lift coefficient due to slats		**2 slat types**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**42**	°
• Slat group A			
0,1c Kruger flap	$\Delta c_{L,max,sA}$	0,61	
Use slatted span	b_W,sA	**8,7**	m
Percentage of slats allong the wing		11%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,05	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,83	
Use slatted span	b_W,sB	**32,8**	m
Percentage of slats allong the wing		40%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,25	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,30	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,14**
RE value maximum lift coefficient, landing		2,14
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,07**
RE value maximum lift coefficient, take-off		2,07

0%

Aerodynamic efficiency

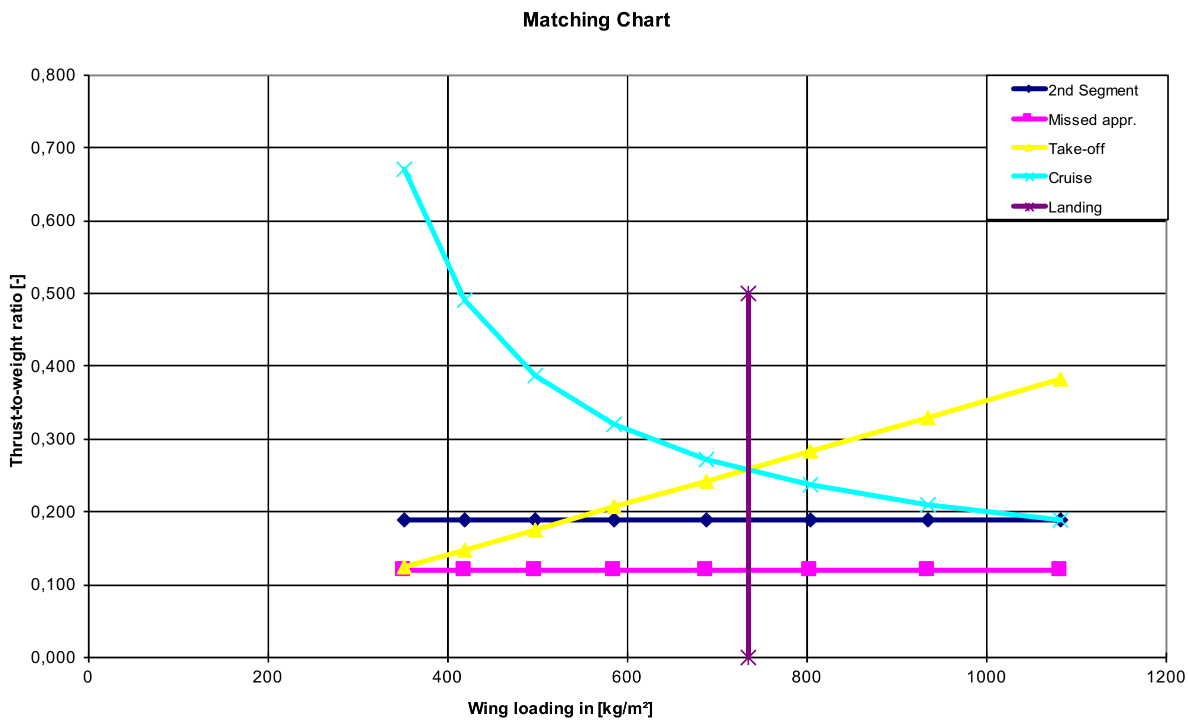
Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,04	
Span	b_W	64,44	m
Winglet height	h	**1,6**	m
Aspect ratio	A	7,67	
Effective aspect ratio	A_{eff}	7,95	
Efficiency factor, short range	k_E	17,25	
Relative wetted area	S_{wet}/S_W	**6,30**	
Verification value maximum aerodynamic efficiency	E_{max}	**19,4**	
RE value maximum aerodynamic efficiency		16,42	

18%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,850	
Cruise altitude	h_{CR}	10668	m
By Pass Ratio	μ	4,90	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	252,00	kN
Overall Pressure ratio	OAPR	**30,20**	
Turbine entry temperature	TET	**1488,25**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,88	
Compressor efficiency	$\eta_{compresor}$	0,86	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,81	K
Dimensionless turbine entry temperature	ϕ	6,80	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,14	
Temperature function	χ	1,89	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,21	
Verification value specific fuel consumption	SFC	0,60	kg/daN/h
Verification value specific fuel consumption	SFC	**1,68E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,46E-05	kg/N/s

15%


Matching Chart
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
200
400
600
800
1000
1200
Thrust-to-weight ratio [-]
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix AK Boeing 737-500

Data Collection			737-500		1	2		3	4	5	6	7	8	9
				Source:	Aircraft characteristics	Jane's		Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collectior	Webs
Parameter	Symbol	Units	Chosen value		for airport planning	Basic	LR							
PAX			149		108-122-149	108-138		108-130			132	149-108		123-132
Landing field length	s_{LFL}	m	1362		1400	1356		1362			1356	1362	1400	
Approach speed	V_{APP}	m/s	66			65,85		66,8777778			65,8333		65,848889	
Temperature above ISA (288,15K)	ΔT_L	K	0		0			0						
Relative density	s													
Take-off field length	s_{TOFL}	m	1832		2500	2633		1832				1832	1500	2470
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0	15		0						
Relative density	s													
Range (max payload)	R	km	2518,72		3333,6	4481		2518,72			4481	960		4445
Cruise Mach number	M_{CR}		0,745			0,745		0,82	0,8			0,74	0,745	0,74
Wing area	S_W	m²	91,04			105,4		91,04			105,4	91,04		
Wing span	b_W	m	28,88		28,88	28,88		28,9			28,88	28,88	28,8	28,9
Aspect ratio	A		9,16			7,9		9,1740993			7,9	9,16		
Maximum take-off mass	m_{MTO}	kg	60555		60555-61689	52390	60555	52390			52390	52390	52390	60550
Payload mass	m_{PL}	kg	15182		15182			15530				15182		
Mass ratio, payload - take-off	m_{PL}/m_{MTO}							0,29643062				0,29		
Maximum landing mass	m_{ML}	kg	49895		49895	49895		49900			49895	49896		50000
Mass ratio, landing - take-off	m_{ML}/m_{MTO}							0,95247185						
Operating empty mass	m_{OE}	kg	31312		31311	31660	32223	30960				31312		31300
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}							0,59095247				0,598		
Wing loading	m_{MTO}/S_W	kg/m²	575			496,8	574,3	575,461336				575		
Maximum zero fuel mass	m_{MZF}	kg	46490		46493-46720	46495	46720	46490				46490		
Number of engines	n_E		2					2				2	2	2
Engine type	CFM56-3		CFM56-3B1		CFM56-3B1	CFM56-3C-1		CFM56-3-B1R	CFM56-3B1			CFM56-3B1	CFM56-3B1	CFM 56-3B-1
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	88,964		88,90410452	82,29-88,97		82,3	88,96444			88,964	89	89
Total take-off thrust	T_{TO}	kN												
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,35					0,32026717				0,35		
Bypass ratio	μ		6						6			6		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	1,08E-05						1,0754E-05			1,08E-05		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s	1,89E-05						1,8876E-05			1,89E-05		
Available fuel volume	$V_{fuel,available}$	m³	20,102		23,168-23,827	20,104-23,83		20,105-23,17				20,102		23,8
Cruise speed	V_{CR}	m/s	221					220,7-253,11					221,21111	216,666667
Cruise altitude	h_{CR}	m	10668			10440		10668-7924,8	10668			10668		
Sweep angle	ϕ_{25}	°	25					25				25		25
Mean aerodynamic chord	c_{MAC}	m	3,73					3,73				3,73		
Position of maximum camber	$x_{(y\_c),max}$	%c												
Camber	$(y_c)_{max}/c$	%c												
Position of maximum thickness	$x_{t,max}$	%c												
Relative thickness	t/c	%	12,9					12,89				12,9		
Taper	λ		0,24					0,24				0,24		
Overall pressure ratio	OAPR		22,6						22,6					
Turbine entry temperature	TET	K												

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1362**	m		
Approach speed	**Known**	V_{APP}	**66,00**	m/s	66,0	66,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**1832**	m	1832	1832
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**1360**	NM		
Cruise Mach number		M_{CR}	**0,745**			
Wing area		S_W	**91**	m²		
Wing span	**Known**	b_W	**28,88**	m²	28,88	28,88
Aspect ratio		A	9,16			
Maximum take-off mass		m_{MTO}	**60555**	kg		
Maximum payload mass		m_{PL}	**15182**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,251			
Maximum landing mass		m_{ML}	**49895**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,824			
Operating empty mass		m_{OE}	**31312**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,517			
Wing loading		m_{MTO}/S_W	665,1	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**88,964**	kN		
Total take-off thrust		T_{TO}	177,928	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,300			
Bypass ratio		μ	**6**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	**221**	m/s		
Cruise altitude	h_{CR}	**10668**	m		
Speed ratio	V/V_{md}	**1,078**	-	1	1,316

Data to execute the verification

					Range
Sweep angle		φ_{25}	**25**	°	
Mean aerodynamic chord		c_{MAC}	**3,73**	m	
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50 %c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6 %c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45 %c
Relative thickness	**Unknown**	t/c	**12,0**	%	
Taper		λ	**0,24**		

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1362	1362	m	0,00%
Approach speed	V_{APP}	66,00	66,0	m/s	0,00%
Take-off field length	s_{TOFL}	1832	1832	m	0,00%
Span	b_W	28,88	28,88	m	0,00%
Aspect ratio	A	9,16	9,16		0,00%
Cruise speed	V_{CR}	221,0	221	m/s	-0,02%
Cruise altitude	h_{CR}	10668	10668	m	0,00%
Squared Sum					**4,19E-08**
Absolute maximum deviation					0,0%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,76**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,84**	
Maximum aerodynamic efficiency	E_{max}	**15,11**	
Specific fuel consumption	SFC	**1,84E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1362	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	66,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,82	
Wing loading at maximum take-off mass	m_{MTO}/S_W	665,1	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,76**	

Take-off

Take-off field length	s_{TOFL}	1832	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,300	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,84**	

2nd Segment

Aspect ratio	A	9,161
Lift coefficient, take-off	$C_{L,TO}$	1,97
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,043
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,063
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	7,69
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,308

Missed approach

Lift coefficient, landing	$C_{L,L}$	2,23
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,056
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,091
Glide ratio in landing configuration	E_L	6,60
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,284

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,745	
Aspect ratio	A	9,16	
Bypass ratio	μ	6,00	
Wing loading	m_{MTO}/S_W	665	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,300	

Variables		
	V/V_{md}	**1,1**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,027
Lift coefficient at E_{max}	$C_{L,md}$	0,81
Ratio, lift coefficient	$C_L/C_{L,md}$	0,860
Lift coefficient, cruise	C_L	0,696
Actual aerodynamic efficiency, cruise	E	14,94
Max. glide ratio, cruise	E_{max}	**15,11**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,11	0,00	0,00
f'(x)	-0,13	-0,13	-0,13
E_{max}	16	15,13	15,11

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	1360	NM
Mach number, cruise	M_{CR}	0,745	
Bypass ratio	μ	6,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,300	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	60555	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,251	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,517	

Calculated values			
Actual aerodynamic efficiency, cruise	E	14,94	
Cruise altitude	h_{CR}	10668	m
Cruise speed	V_{CR}	221	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,232	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,768	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,315	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,699	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,84E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	28,88	m
Structural wing span	$b_{W,struct}$	31,87	m
Wing area	S_W	91,0	m²
Aspect ratio	A	9,16	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	3,73	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	12,0	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	66,00	m/s
Mach number, landing	M_{APP}	0,20	
Mach number, cruise	M_{CR}	0,745	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,2	%c
Leading edge sweep	φ_{LE}	28,8	°
Reynoldsnumber	Re	1,8E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,30	
Correction term, camber	$\Delta_1 c_{L,max}$	0,40	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,020	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,718	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,85	
Correction term, Mach number	$\Delta C_{L,max}$	0,00	
Lift coefficient, wing	$C_{L,max}$	1,46	

Calculations increase of lift coefficient due to flaps		**1 flap type**	
Correction factor, sweep	K_φ	0,87	
• Flap group A			
0,4c Single-slotted fowler flap	$\Delta c_{L,max,fA}$	2,04	
Use flapped span	b_W,fA	**20,8**	m
Percentage of flaps allong the wing		65%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	1,16	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,75	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	1,16	

Calculations increase of lift coefficient due to slats		**1 slat type**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**28**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,91	
Use slatted span	b_W,sA	**19,1**	m
Percentage of slats allong the wing		60%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,48	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,91	
Use slatted span	b_W,sB	**0**	m
Percentage of slats allong the wing		0%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,00	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,48	

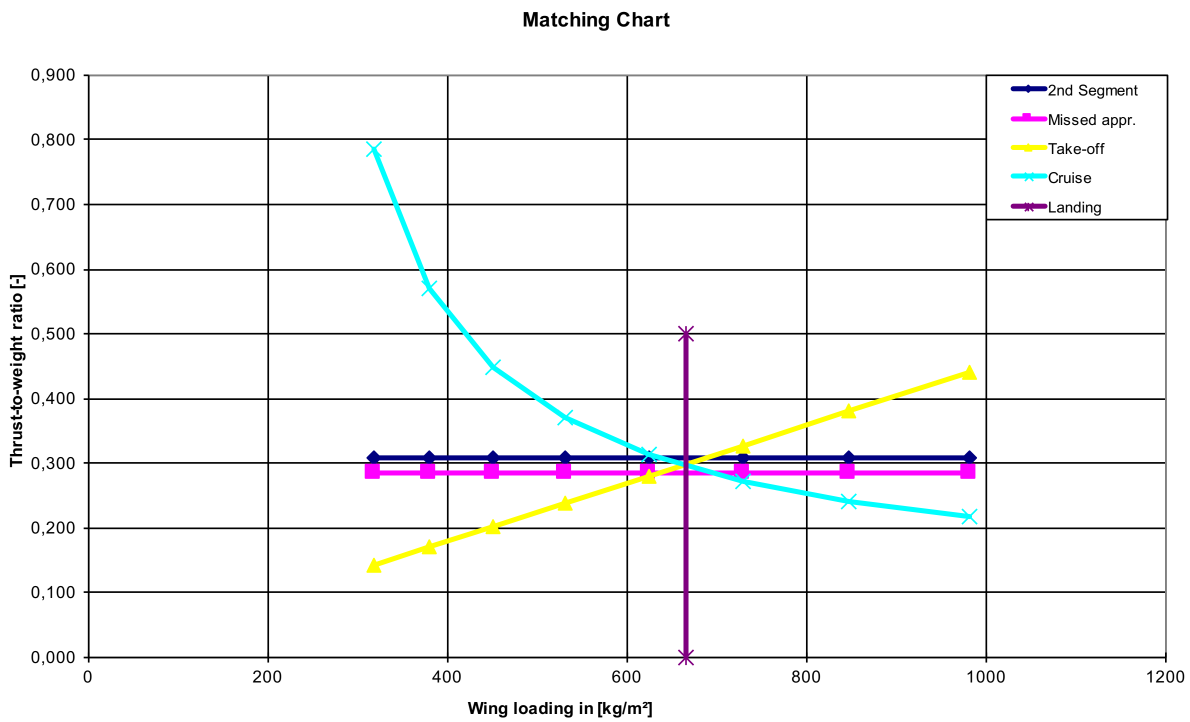
Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**3,04**
RE value maximum lift coefficient, landing		3,76
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,30**
RE value maximum lift coefficient, take-off		2,84
	19%	

Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
No winglets	$k_{e,WL}$	1,00	
Span	b_W	28,88	m
Winglet height	h	**2,7**	m
Aspect ratio	A	9,16	
Effective aspect ratio	A_{eff}	9,16	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**18,2**	
RE value maximum aerodynamic efficiency		15,11	
	20%		

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,745	
Cruise altitude	h_{CR}	10668	m
By Pass Ratio	μ	6,00	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	88,96	kN
Overall Pressure ratio	OAPR	**22,60**	
Turbine entry temperature	TET	**1430,08**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,94	
Ventilator efficiency	$\eta_{ventilator}$	0,86	
Compressor efficiency	$\eta_{compresor}$	0,86	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,98	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,81	K
Dimensionless turbine entry temperature	ϕ	6,54	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,11	
Temperature function	χ	1,60	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,11	
Verification value specific fuel consumption	SFC	0,60	kg/daN/h
Verification value specific fuel consumption	SFC	**1,65E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,84E-05	kg/N/s
10%			


Matching Chart
Thrust-to-weight ratio [-]
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
200
400
600
800
1000
1200
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix AL Boeing 777F

Data Collection			777F		1	2	3	4	5	6	7	8	9
Parameter	Symbol	Units	Chosen value	Source:	Aircraft characteristics for airport planning	Jane's	Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collection	Webs
PAX					-								
Landing field length	s_{LFL}	m	1750		1750							1700	
Approach speed	V_{APP}	m/s	72									72,0222222	
Temperature above ISA (288,15K)	ΔT_L	K	0		0								
Relative density	s												
Take-off field length	s_{TOFL}	m	3000		3130							2970	2990
Temperature above ISA (288,15K)	ΔT_{TO}	K	0										
Relative density	s												
Range (max payload)	R	km	9050		9050	9195							9070
Cruise Mach number	M_{CR}		0,84		0,84						0,84	0,84	0,84
Wing area	S_W	m²											
Wing span	b_W	m	64,8		64,8						64,8	60,9	64,8
Aspect ratio	A												
Maximum take-off mass	m_{MTO}	kg	347815		347815	347450					347815	347450	347800
Payload mass	m_{PL}	kg	103737		103737	103875							
Mass ratio, payload - take-off	m_{PL}/m_{MTO}												
Maximum landing mass	m_{ML}	kg	260816		260816						260816		260816
Mass ratio, landing - take-off	m_{ML}/m_{MTO}												
Operating empty mass	m_{OE}	kg	144379		144379								144400
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}												
Wing loading	m_{MTO}/S_W	kg/m²											
Maximum zero fuel mass	m_{MZF}	kg	248115		248115						248115		
Number of engines	n_E		2								2	2	2
Engine type	GE90		GE90-110B1L		GE90-110B1L	GE90-110B1L		GE90-110B1			GE90-110B1	GE 90-110B1	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	489		488,971			489,30442			489,302	489	514
Total take-off thrust	T_{TO}	kN											
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,29								0,29		
Bypass ratio	μ		9								7,2		9
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s											
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s											
Available fuel volume	$V_{fuel,available}$	m³	181,283		181,283						181,283		181,283
Cruise speed	V_{CR}	m/s	252									252,077778	251,39
Cruise altitude	h_{CR}	m	10668								10668		
Sweep angle	ϕ_{25}	°	31,64										31,64
Mean aerodynamic chord	c_{MAC}	m											
Position of maximum camber	$x_{(y\_c),max}$	%c	30										30
Camber	$(y_c)_{max}/c$	%c	5,9										5,9
Position of maximum thickness	$x_{t,max}$	%c	30										30
Relative thickness	t/c	%	22										22
Taper	λ												
Overall pressure ratio	OAPR		42										42
Turbine entry temperature	TET	K											

Aeroplane Specifications

Data to apply reverse engineering

					LL	*UL*
Landing field length	**Known**	s_{LFL}	**1750**	m		
Approach speed	**Known**	V_{APP}	**72,00**	m/s	72,0	72,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**3000**	m	3000	3000
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**4887**	NM		
Cruise Mach number		M_{CR}	**0,84**			
Wing area		S_W	**428**	m²		
Wing span	**Known**	b_W	**64,8**	m²	64,8	64,8
Aspect ratio		A	9,82			
Maximum take-off mass		m_{MTO}	**347815**	kg		
Maximum payload mass		m_{PL}	**103737**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,298			
Maximum landing mass		m_{ML}	**260816**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,750			
Operating empty mass		m_{OE}	**144379**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,415			
Wing loading		m_{MTO}/S_W	813,0	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**489**	kN		
Total take-off thrust		T_{TO}	978	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,287			
Bypass ratio		μ	**9**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	**252**	m/s		
Cruise altitude	h_{CR}	**10668**	m		
Speed ratio	V/V_{md}	**1,037**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**31,64**	°		
Mean aerodynamic chord		c_{MAC}	**4,2**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**10,8**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1750	1750	m	0,00%
Approach speed	V_{APP}	72,00	72,0	m/s	0,00%
Take-off field length	s_{TOFL}	3000	3000	m	0,00%
Span	b_W	64,8	64,8	m	0,00%
Aspect ratio	A	9,82	9,82		0,00%
Cruise speed	V_{CR}	252,0	249	m/s	-1,11%
Cruise altitude	h_{CR}	10668	10649	m	-0,17%
Squared Sum					**1,27E-04**
Absolute maximum deviation					1,1%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,26**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,21**	
Maximum aerodynamic efficiency	E_{max}	**18,30**	
Specific fuel consumption	SFC	**1,19E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1750	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	72,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,75	
Wing loading at maximum take-off mass	m_{MTO}/S_W	813,0	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,26**	

Take-off

Take-off field length	s_{TOFL}	3000	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,287	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,21**	

2nd Segment

Aspect ratio	A	9,815
Lift coefficient, take-off	$C_{L,TO}$	1,54
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,022
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,042
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	10,16
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,245

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,93
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,041
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,076
Glide ratio in landing configuration	E_L	7,76
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,225

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,84	
Aspect ratio	A	9,82	
Bypass ratio	µ	9,00	
Wing loading	m_{MTO}/S_W	813	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,287	

Variables		
	V/V_{md}	**1,0**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,020
Lift coefficient at E_{max}	$C_{L,md}$	0,72
Ratio, lift coefficient	$C_L/C_{L,md}$	0,930
Lift coefficient, cruise	C_L	0,666
Actual aerodynamic efficiency, cruise	E	18,25
Max. glide ratio, cruise	E_{max}	**18,30**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,24	-0,01	0,00
f'(x)	-0,10	-0,11	-0,11
E_{max}	16	18,40	18,30

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	4887	NM
Mach number, cruise	M_{CR}	0,84	
Bypass ratio	μ	9,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,287	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	347815	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,298	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,415	

Calculated values			
Actual aerodynamic efficiency, cruise	E	18,25	
Cruise altitude	h_{CR}	10649	m
Cruise speed	V_{CR}	249	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,287	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,713	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,055	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,964	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**no**	
	international	**yes**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	822936	m
Loiter time	t_{loiter}	1800	s
Specific fuel consumption	SFC	**1,19E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	64,8	m
Structural wing span	$b_{W,struct}$	76,11	m
Wing area	S_W	427,8	m²
Aspect ratio	A	9,82	
Sweep	φ_{25}	31,64	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	10,8	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	72,00	m/s
Mach number, landing	M_{APP}	0,22	
Mach number, cruise	M_{CR}	0,84	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,0	%c
Leading edge sweep	φ_{LE}	35,2	°
Reynoldsnumber	Re	2,2E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,19	
Correction term, camber	$\Delta_1 c_{L,max}$	0,39	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,059	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,636	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,90	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,46	

Calculations increase of lift coefficient due to flaps			**2 flap types**
Correction factor, sweep	K_φ	0,83	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,43	
Use flapped span	b_W,fA	**11,4**	m
Percentage of flaps allong the wing		15%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,18	
• Flap group B			
Double-slotted flap	$\Delta c_{L,max,fB}$	1,43	
Use flapped span	b_W,fB	**26,7**	m
Percentage of flaps allong the wing		35%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,42	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,60	

Calculations increase of lift coefficient due to slats			**2 slat types**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**34**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,91	
Use slatted span	b_W,sA	**12,5**	m
Percentage of slats allong the wing		16%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,12	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,91	
Use slatted span	b_W,sB	**43,6**	m
Percentage of slats allong the wing		57%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,43	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,55	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,58**
RE value maximum lift coefficient, landing		3,26
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,75**
RE value maximum lift coefficient, take-off		2,21

-21%

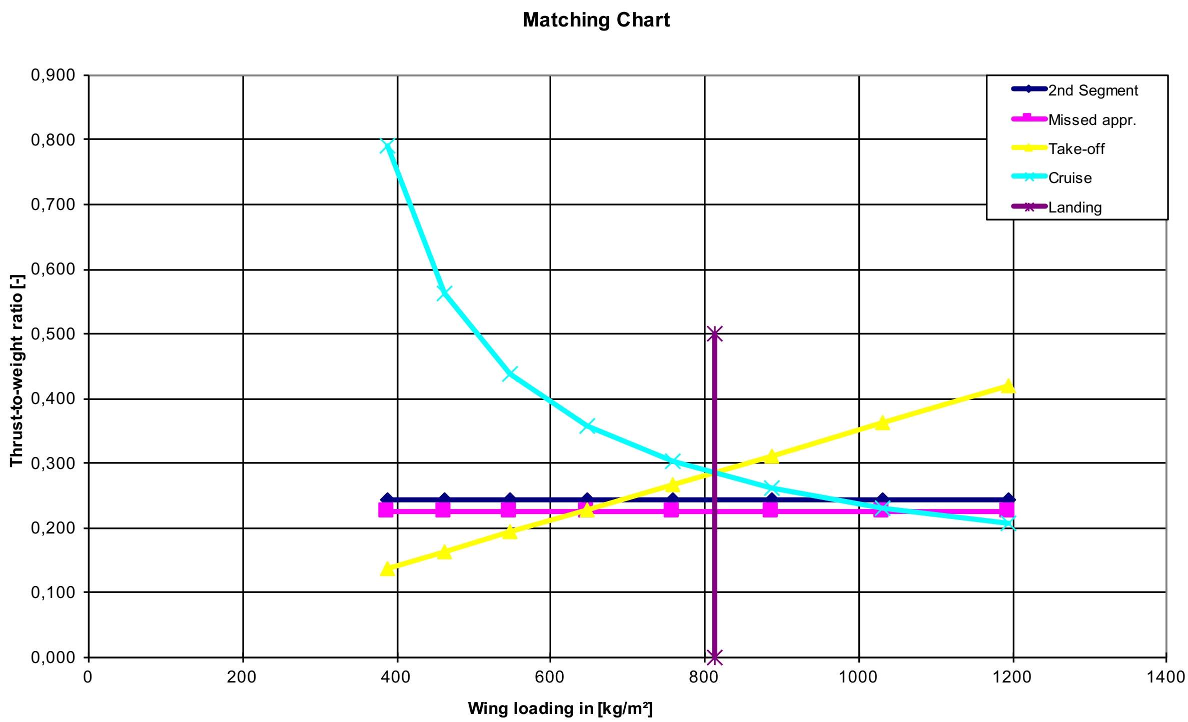
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
No winglets	$k_{e,WL}$	1,00	
Span	b_W	64,8	m
Winglet height	h	**2,7**	m
Aspect ratio	A	9,82	
Effective aspect ratio	A_{eff}	9,82	
Efficiency factor, short range	k_E	16,19	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**20,1**	
RE value maximum aerodynamic efficiency		18,30	

10%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,840	
Cruise altitude	h_{CR}	10668	m
By Pass Ratio	μ	9,00	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	489,00	kN
Overall Pressure ratio	OAPR	**42,00**	
Turbine entry temperature	TET	**1503,64**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,93	
Ventilator efficiency	$\eta_{ventilator}$	0,90	
Compressor efficiency	$\eta_{compresor}$	0,88	
Turbine efficiency	$\eta_{turbine}$	0,91	
Nozzle efficiency	η_{nozzle}	1,00	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,81	K
Dimensionless turbine entry temperature	ϕ	6,87	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,14	
Temperature function	χ	2,18	
Gas generator efficiency	η_{gasgen}	0,97	
Gas generator function	G	2,16	
Verification value specific fuel consumption	SFC	0,53	kg/daN/h
Verification value specific fuel consumption	SFC	**1,47E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,19E-05	kg/N/s
	24%		


Matching Chart
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
1400
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix AM Embraer 195

Data Collection			Embraer 195	Source:	1	2			3	4	5	6	7	8	9
Parameter	Symbol	Units	Chosen value		Aircraft characteristics for airport planning	Jane's Standard	Jane's Long-Range	Jane's IGW	Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collectior	Webs
PAX			118		118		108-118						110-106		
Landing field length	s_{LFL}	m	1435		1280		1435						1435	1412	
Approach speed	V_{APP}	m/s													
Temperature above ISA (288,15K)	ΔT_L	K	0		0										
Relative density	s														
Take-off field length	s_{TOFL}	m	2251		2130		2251						2251	1490	
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0										
Relative density	s														
Range (max payload)	R	km	1445		2778			3889					1445		2593
Cruise Mach number	M_{CR}		0,78		0,78		0,82						0,78	0,82	0,82
Wing area	S_W	m²	92,53		92,5		92,53						92,5		
Wing span	b_W	m	28,72		28,72		28,72						28,72	35,1	28,72
Aspect ratio	A		8,92		8,1								8,92		
Maximum take-off mass	m_{MTO}	kg	52290		52290	48790	50790	52290					48790	61500	50790
Payload mass	m_{PL}	kg	13530		13900		12720						13530		
Mass ratio, payload - take-off	m_{PL}/m_{MTO}												0,277		
Maximum landing mass	m_{ML}	kg	45000		45800	45000		45800					45000		
Mass ratio, landing - take-off	m_{ML}/m_{MTO}														
Operating empty mass	m_{OE}	kg	28970		28700	28970		29070					28970		28970
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}												0,594		
Wing loading	m_{MTO}/S_W	kg/m²	527,3			527,3	548,9	565,1					527		
Maximum zero fuel mass	m_{MZF}	kg	42500		42600	42500		42600					42500		
Number of engines	n_E		2										2	2	2
Engine type	GE CF34		CF34-10E5		GEAE CF34-10	CF34-10E, -10E6, -10E6A1, -10E5, -10E5A1							CF34-10E5	PW1900G	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	82,292		82,3		88,9						82,292	85-102	82,3
Total take-off thrust	T_{TO}	kN													
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,34			0,37241174	0,35803795	0,34707761					0,34		
Bypass ratio	μ		5										5		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	1,08E-05										1,08E-05		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s													
Available fuel volume	$V_{fuel,available}$	m³	16,029		16,029		16,153						16,029		
Cruise speed	V_{CR}	m/s	247												247,22
Cruise altitude	h_{CR}	m	10668		10668										
Sweep angle	ϕ_{25}	°													
Mean aerodynamic chord	c_{MAC}	m	3,68				3,68								
Position of maximum camber	$x_{(y\_c),max}$	%c	44,2												44,2
Camber	$(y_c)_{max}/c$	%c	2,7												2,7
Position of maximum thickness	$x_{t,max}$	%c	35												35
Relative thickness	t/c	%	11,8												11,8
Taper	λ														
Overall pressure ratio	OAPR														
Turbine entry temperature	TET	K													

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1435**	m		
Approach speed	**Unknown**	V_{APP}	72,00	m/s	64,5	64,5
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2251**	m	2251	2251
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**780**	NM		
Cruise Mach number		M_{CR}	**0,78**			
Wing area		S_W	**93**	m²		
Wing span	**Known**	b_W	**28,72**	m²	28,72	28,72
Aspect ratio		A	8,91			
Maximum take-off mass		m_{MTO}	**52290**	kg		
Maximum payload mass		m_{PL}	**13530**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,259			
Maximum landing mass		m_{ML}	**45000**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,861			
Operating empty mass		m_{OE}	**28970**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,554			
Wing loading		m_{MTO}/S_W	565,1	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**82,292**	kN		
Total take-off thrust		T_{TO}	164,584	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,321			
Bypass ratio		μ	**5**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	**247**	m/s		
Cruise altitude	h_{CR}	**10668**	m		
Speed ratio	V/V_{md}	**1,246**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**25**	°		
Mean aerodynamic chord		c_{MAC}	**3,68**	m		
Position of maximum camber		$x_{(y\_c),max}$	**44,2**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**2,7**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**35**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,6**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1435	1435	m	0,00%
Approach speed	V_{APP}	Unknown	**64,5**	m/s	0,00%
Take-off field length	s_{TOFL}	2251	2251	m	0,00%
Span	b_W	28,72	28,72	m	0,00%
Aspect ratio	A	8,91	8,91		0,00%
Cruise speed	V_{CR}	247,0	232	m/s	-6,21%
Cruise altitude	h_{CR}	10668	10570	m	-0,92%
Squared Sum					**3,94E-03**
Absolute maximum deviation					6,2%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,17**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,83**	
Maximum aerodynamic efficiency	E_{max}	**14,41**	
Specific fuel consumption	SFC	**1,70E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1435	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	64,47	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,86	
Wing loading at maximum take-off mass	m_{MTO}/S_W	565,1	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,17**	

Take-off

Take-off field length	s_{TOFL}	2251	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,321	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,83**	

2nd Segment

Aspect ratio	A	8,914
Lift coefficient, take-off	$C_{L,TO}$	1,27
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,009
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,029
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	11,45
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,223

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,87
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,039
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,074
Glide ratio in landing configuration	E_L	7,41
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,268

2) Maximum Aerodynamic Efficiency

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications

Mach number, cruise	M_{CR}	0,78	
Aspect ratio	A	8,91	
Bypass ratio	μ	5,00	
Wing loading	m_{MTO}/S_W	565	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,321	

Variables

	V/V_{md}	**1,2**

Calculations

Zero-lift drag coefficient	$C_{D,0}$	0,029
Lift coefficient at E_{max}	$C_{L,md}$	0,83
Ratio, lift coefficient	$C_L/C_{L,md}$	0,644
Lift coefficient, cruise	C_L	0,532
Actual aerodynamic efficiency, cruise	E	13,12
Max. glide ratio, cruise	E_{max}	**14,41**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,22	-0,01	0,00
f'(x)	-0,14	-0,13	-0,13
E_{max}	16	14,46	14,41

3) Specific Fuel Consumption

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications

Range	R	780	NM
Mach number, cruise	M_{CR}	0,78	
Bypass ratio	µ	5,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,321	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	52290	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,259	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,554	

Calculated values

Actual aerodynamic efficiency, cruise	E	13,12	
Cruise altitude	h_{CR}	10570	m
Cruise speed	V_{CR}	232	m/s

Mission fuel fraction

Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations

Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,187	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,813	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,365	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,648	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,70E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	28,72	m
Structural wing span	$b_{W,struct}$	31,69	m
Wing area	S_W	92,5	m²
Aspect ratio	A	8,91	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	3,68	m
Position of maximum camber	$x_{(y\_c),max}$	44,2	%c
Camber	$(y_c)_{max}/c$	2,7	%c
Position of maximum thickness	$x_{t,max}$	35	%c
Relative thickness	t/c	11,6	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	64,47	m/s
Mach number, landing	M_{APP}	0,19	
Mach number, cruise	M_{CR}	0,78	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,1	%c
Leading edge sweep	φ_{LE}	28,9	°
Reynoldsnumber	Re	1,7E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,26	
Correction term, camber	$\Delta_1 c_{L,max}$	0,23	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,16	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,025	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,679	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,87	
Correction term, Mach number	$\Delta C_{L,max}$	0,00	
Lift coefficient, wing	$C_{L,max}$	1,46	

Calculations increase of lift coefficient due to flaps		**2 flap types**	
Correction factor, sweep	K_{φ}	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,43	
Use flapped span	b_W,fA	**8,5**	m
Percentage of flaps allong the wing		27%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,33	
• Flap group B			
Double-slotted flap	$\Delta c_{L,max,fB}$	1,43	
Use flapped span	b_W,fB	**12,8**	m
Percentage of flaps allong the wing		40%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,50	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,83	

Calculations increase of lift coefficient due to slats		**2 slat types**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**26,5**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,90	
Use slatted span	b_W,sA	**4,8**	m
Percentage of slats allong the wing		15%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,12	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**20,1**	m
Percentage of slats allong the wing		63%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,51	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,63	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,88**
RE value maximum lift coefficient, landing		3,17
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,67**
RE value maximum lift coefficient, take-off		1,83

-9%

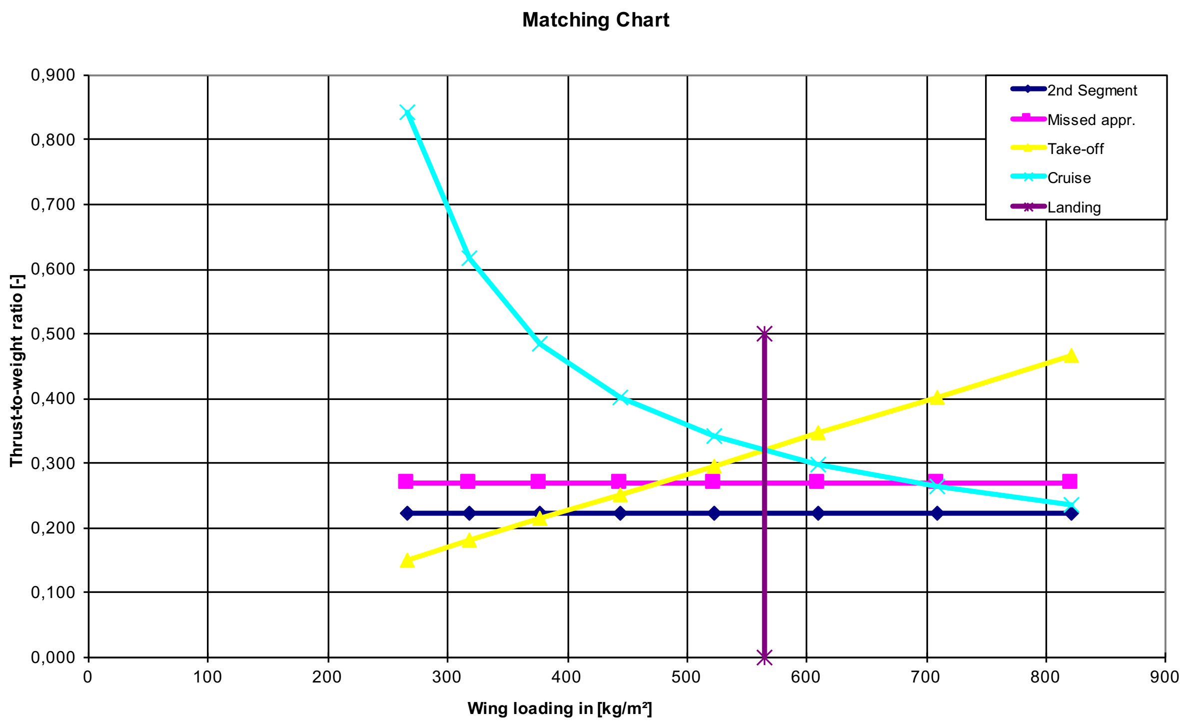
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,09	
Span	b_W	28,72	m
Winglet height	h	1,7	m
Aspect ratio	A	8,91	
Effective aspect ratio	A_{eff}	9,68	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**18,7**	
RE value maximum aerodynamic efficiency		14,41	

30%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,780
Cruise altitude	h_{CR}	10668 m
By Pass Ratio	μ	5,00
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	82,29 kN
Overall Pressure ratio	OAPR	**29,00**
Turbine entry temperature	TET	**1422,79**
Inlet pressure loss	ΔP/P	2%
Inlet efficiency	η_{inlet}	0,95
Ventilator efficiency	$\eta_{ventilator}$	0,85
Compressor efficiency	$\eta_{compresor}$	0,85
Turbine efficiency	$\eta_{turbine}$	0,89
Nozzle efficiency	η_{nozzle}	0,98
Temperature at SL	T_0	288,15 K
Temperature lapse rate in troposhpere	L	0,0065 K/m
Temperature (ISA) at tropopause	T_S	216,65 K
Temperature at cruise altitude	T(H)	218,81 K
Dimensionless turbine entry temperature	ϕ	6,50
Ratio of specific heats, air	γ	1,40
Ratio between stagnation point temperature and temperature	υ	1,12
Temperature function	χ	1,81
Gas generator efficiency	η_{gasgen}	0,98
Gas generator function	G	1,98
Verification value specific fuel consumption	SFC	0,62 kg/daN/h
Verification value specific fuel consumption	SFC	**1,72E-05** kg/N/s
RE value specific fuel consumption	SFC	1,70E-05 kg/N/s
2%		


Matching Chart
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
100
200
300
400
500
600
700
800
900
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix AN Boeing 717-200

Data Collection			717-200	Source: 1	2	3	4	5	6	7	8	9
Parameter	Symbol	Units	Chosen value	Aircraft characteristics for airport planning	Jane's	Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collection	Webs
PAX			106	106		106-110			106	106		106-117
Landing field length	s_{LFL}	m	1450	1524		1445			1469	1418	1600	
Approach speed	V_{APP}	m/s	69			66,87777778			69,4444		71,51	
Temperature above ISA (288,15K)	ΔT_L	K	0									
Relative density	s											
Take-off field length	s_{TOFL}	m	1677	1661,16						1677	2100	
Temperature above ISA (288,15K)	ΔT_{TO}	K	0	0								
Relative density	s											
Range (max payload)	R	km	1375	2160,666667		1375			3600	2000		
Cruise Mach number	M_{CR}		0,77			0,76				0,77	0,77	
Wing area	S_W	m²	92,97			92,97			92,97	92,97		93
Wing span	b_W	m	28,45	28,4		28,4			28,45	28,45	28,47	28,5
Aspect ratio	A		8,71			8,675486716			8,7	8,71		
Maximum take-off mass	m_{MTO}	kg	54900	54884		51710			54900	49895	54885	54900
Payload mass	m_{PL}	kg	14515	14515		12220				12020		
Mass ratio, payload - take-off	m_{PL}/m_{MTO}					0,236317927				0,241		
Maximum landing mass	m_{ML}	kg	49898	49898		46266			49900	45362		
Mass ratio, landing - take-off	m_{ML}/m_{MTO}					0,894720557						
Operating empty mass	m_{OE}	kg	31071	31071		31675				30618		31674
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}					0,612550764				0,614		
Wing loading	m_{MTO}/S_W	kg/m²	537			556,200925				537		
Maximum zero fuel mass	m_{MZF}	kg	45586	45586		43545				42638		
Number of engines	n_E		2			2				2	2	2
Engine type	BR700-715		BR715A1-30	BR715		BMW R-R715	BR715A1-30			BR715A1-30	BR715-A1-30	BR715-C1-30
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	82,292	93,34930975		97,9	82,292107			82,292		93,4
Total take-off thrust	T_{TO}	kN										
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,34			0,385983858				0,34		
Bypass ratio	μ		4,7				4,7			4,7		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	1,05E-05				1,0471E-05			1,05E-05		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s										
Available fuel volume	$V_{fuel,available}$	m³	13,905	16,665		13,892-16,065				13,905		
Cruise speed	V_{CR}	m/s	225,3			225,3266667					223,783333	225,277778
Cruise altitude	h_{CR}	m	10424			10668				10424		10393,68
Sweep angle	ϕ_{25}	°	24,5			24,5				24,5		
Mean aerodynamic chord	c_{MAC}	m	3,88			3,88				3,88		
Position of maximum camber	$x_{(y\_c),max}$	%c										
Camber	$(y_c)_{max}/c$	%c										
Position of maximum thickness	$x_{t,max}$	%c										
Relative thickness	t/c	%	11,6			11,6				11,6		
Taper	λ		0,206			0,196				0,206		
Overall pressure ratio	OAPR		32,1				32,1					
Turbine entry temperature	TET	K										

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1450**	m		
Approach speed	**Known**	V_{APP}	**69,00**	m/s	69,0	69,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**1677**	m	1677	1677
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**742**	NM		
Cruise Mach number		M_{CR}	**0,77**			
Wing area		S_W	**93**	m²		
Wing span	**Known**	b_W	**28,45**	m²	28,45	28,45
Aspect ratio		A	8,71			
Maximum take-off mass		m_{MTO}	**54900**	kg		
Maximum payload mass		m_{PL}	**14515**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,264			
Maximum landing mass		m_{ML}	**49898**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,909			
Operating empty mass		m_{OE}	**31071**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,566			
Wing loading		m_{MTO}/S_W	590,5	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**82,292**	kN		
Total take-off thrust		T_{TO}	164,584	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,306			
Bypass ratio		μ	**4,7**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed	V_{CR}	**225**	m/s			
Cruise altitude	h_{CR}	**10424**	m			
Speed ratio	V/V_{md}	**1,205**	-		1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**24,5**	°		
Mean aerodynamic chord		c_{MAC}	**3,88**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,7**	%		
Taper		λ	**0,206**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1450	1450	m	0,00%
Approach speed	V_{APP}	69,00	69,0	m/s	0,00%
Take-off field length	s_{TOFL}	1677	1677	m	0,00%
Span	b_W	28,45	28,45	m	0,00%
Aspect ratio	A	8,71	8,71		0,00%
Cruise speed	V_{CR}	225,3	229	m/s	1,69%
Cruise altitude	h_{CR}	10424	10450	m	0,24%
Squared Sum					**2,92E-04**
Absolute maximum deviation					1,7%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,46**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,70**	
Maximum aerodynamic efficiency	E_{max}	**14,30**	
Specific fuel consumption	SFC	**1,48E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing			
Landing field length	s_{LFL}	1450	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	69,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,91	
Wing loading at maximum take-off mass	m_{MTO}/S_W	590,5	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,46**	

Take-off			
Take-off field length	s_{TOFL}	1677	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,306	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,70**	

2nd Segment		
Aspect ratio	A	8,706
Lift coefficient, take-off	$C_{L,TO}$	1,87
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,039
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,059
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	7,75
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,306

Missed approach		
Lift coefficient, landing	$C_{L,L}$	2,05
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,047
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,082
Glide ratio in landing configuration	E_L	6,80
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,306

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,77	
Aspect ratio	A	8,71	
Bypass ratio	μ	4,70	
Wing loading	m_{MTO}/S_W	591	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,306	

Variables		
	V/V_{md}	**1,2**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,028
Lift coefficient at E_{max}	$C_{L,md}$	0,81
Ratio, lift coefficient	$C_L/C_{L,md}$	0,688
Lift coefficient, cruise	C_L	0,560
Actual aerodynamic efficiency, cruise	E	13,36
Max. glide ratio, cruise	E_{max}	**14,30**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,23	-0,01	0,00
f'(x)	-0,14	-0,13	-0,13
E_{max}	16	14,35	14,30

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	742	NM
Mach number, cruise	M_{CR}	0,77	
Bypass ratio	μ	4,70	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,306	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	54900	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,264	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,566	

Calculated values			
Actual aerodynamic efficiency, cruise	E	13,36	
Cruise altitude	h_{CR}	10450	m
Cruise speed	V_{CR}	229	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,170	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,830	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,348	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,666	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,48E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	28,45	m
Structural wing span	$b_{W,struct}$	31,27	m
Wing area	S_W	93,0	m²
Aspect ratio	A	8,71	
Sweep	φ_{25}	24,5	°
Mean aerodynamic chord	c_{MAC}	3,88	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,7	%
Taper	λ	0,206	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	69,00	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,77	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,1	%c
Leading edge sweep	φ_{LE}	28,8	°
Reynoldsnumber	Re	1,9E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,27	
Correction term, camber	$\Delta_1 c_{L,max}$	0,40	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,029	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,703	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,86	
Correction term, Mach number	$\Delta C_{L,max}$	-0,02	
Lift coefficient, wing	$C_{L,max}$	1,45	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_φ	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,42	
Use flapped span	b_W,fA	**18,5**	m
Percentage of flaps allong the wing		59%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,73	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,74	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,73	

Calculations increase of lift coefficient due to slats			**1 slat type**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**28**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,90	
Use slatted span	b_W,sA	**25,6**	m
Percentage of slats allong the wing		82%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,65	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**0**	m
Percentage of slats allong the wing		0%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,00	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,65	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,80**
RE value maximum lift coefficient, landing		3,46
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,18**
RE value maximum lift coefficient, take-off		2,70
	-19%	

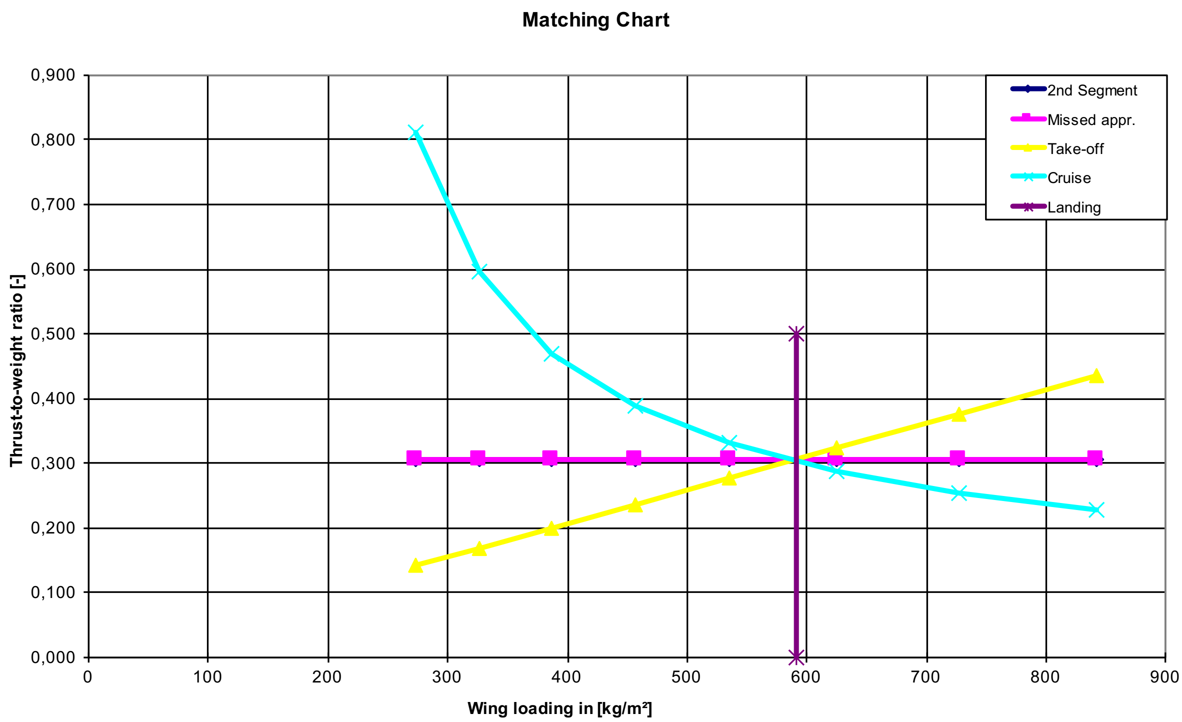
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
No winglets	$k_{e,WL}$	1,00	
Span	b_W	28,45	m
Winglet height	h	**2,7**	m
Aspect ratio	A	8,71	
Effective aspect ratio	A_{eff}	8,71	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**17,7**	
RE value maximum aerodynamic efficiency		14,30	
	24%		

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,770	
Cruise altitude	h_{CR}	10424	m
By Pass Ratio	μ	4,70	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	82,29	kN
Overall Pressure ratio	OAPR	**32,10**	
Turbine entry temperature	TET	**1422,79**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,85	
Compressor efficiency	$\eta_{compresor}$	0,85	
Turbine efficiency	$\eta_{turbine}$	0,89	
Nozzle efficiency	η_{nozzle}	0,98	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	220,39	K
Dimensionless turbine entry temperature	ϕ	6,46	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,90	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	1,90	
Verification value specific fuel consumption	SFC	0,61	kg/daN/h
Verification value specific fuel consumption	SFC	**1,70E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,48E-05	kg/N/s

15%


Matching Chart
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
100
200
300
400
500
600
700
800
900
Thrust-to-weight ratio [-]
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix AO Boeing 737-400

Data Collection			737-400		1		2		3	4	5	6	7	8	9
				Source:	Aircraft characteristics for airport planning		Jane's		Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collectior	Webs
Parameter	Symbol	Units	Chosen value		A	B	Basic	LR							
			189		146-159-189		146-168		170-146			149	189-146		
ield length	s_{LFL}	m	1582		1635		1539		1582			1539	1582	1500	
speed	V_{APP}	m/s	71				71,51		71			71,39		70,478889	
ture above ISA (288,15K)	ΔT_L	K	0			0	0		0			0			
density	s														
field length	s_{TOFL}	m	2222		2930	2550	2664		2222				2222	2000	2540
ture above ISA (288,15K)	ΔT_{TO}	K	0		0	0	15		0						
density	s														
nax payload)	R	km	3180		3180		3870		3611,4			3870	1801		4204
ach number	M_{CR}		0,745				0,745			0,8			0,75	0,745	0,74
a	S_W	m²	91,04				105,4		91,04			105,4	91,04		
n	b_W	m	28,88		28,88		28,88		28,9			28,88	28,88	28,9	28,9
tio	A		9,16				7,9		9,1740993			7,9	9,16		9,16
take-off mass	m_{MTO}	kg	68040		62823	68039	62820	68040	62820			62820	62823	62820	68050
mass	m_{PL}	kg	18066		18067	19427			17740				18066		
o, payload - take-off	m_{PL}/m_{MTO}								0,28239414				0,288		
landing mass	m_{ML}	kg	54885		54885	56245	54885	56245	54880			54885	54885		56200
o, landing - take-off	m_{ML}/m_{MTO}								0,87360713						
empty mass	m_{OE}	kg	33190		33189	33643	34382	35162	33370				33190		33200
o, operating empty - take-off	m_{OE}/m_{MTO}								0,53120025				0,528		
ding	m_{MTO}/S_W	kg/m²	690				595,8	645,3	690,026362				690		
zero fuel mass	m_{MZF}	kg	51256		51256	53070	51255	53070	51250				51256		53100
of engines	n_E		2						2				2	2	2
pe	CFM56-3		CFM56-3B2		CFM56-3B2	CFM56-3C	CFM56-3C-1		CFM56-3B-2	CFM56-3B2			CFM56-3B2	CFM56-3B2	
thrust for one engine	$T_{TO,one\ engine}$	kN	97,86			104,4582	97,9-104,5		97,9	97,860884			97,86	97,9	98
-off thrust	T_{TO}	kN													
weight ratio	$T_{TO}/(m_{MTO}*g)$		0,32						0,31772087				0,32		
atio	μ		5,9							5,9			5,9		
Fuel Comsumption (dry)	SFC (dry)	kg/N s	1,11E-05							1,1037E-05			1,11E-05		
Fuel Comsumption (cruise)	SFC (cruise	kg/N s	1,89E-05							1,8876E-05			1,89E-05		
fuel volume	$V_{fuel,available}$	m³	20,102		20,102	23,827	20,104-23,83		20,105-23,170						23,8
eed	V_{CR}	m/s	221,2						221,2-253,1					221,21111	216,67
itude	h_{CR}	m	10668				9662		10668-7924,8	10668			10668		
ngle	ϕ_{25}	°	25						25				25		25
rodynamic chord	c_{MAC}	m	3,73						3,73				3,73		
of maximum camber	$x_{(y\_c),max}$	%c	20,4												20,4
	$(y_c)_{max}/c$	%c	1,5												1,5
of maximum thickness	$x_{t,max}$	%c	39,9												39,9
thickness	t/c	%	12,9						12,89				12,9		10
	λ		0,24						0,24				0,24		
ressure ratio	OAPR		24,3							24,3					
entry temperature	TET	K													

Aeroplane Specifications

Data to apply reverse engineering					LL	UL
Landing field length	**Known**	s_{LFL}	**1582**	m		
Approach speed	**Known**	V_{APP}	**71,00**	m/s	71,0	71,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2222**	m	2222	2222
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**1717**	NM		
Cruise Mach number		M_{CR}	**0,745**			
Wing area		S_W	**91**	m²		
Wing span	**Known**	b_W	**28,88**	m²	28,88	28,88
Aspect ratio		A	9,16			
Maximum take-off mass		m_{MTO}	**68040**	kg		
Maximum payload mass		m_{PL}	**18066**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,266			
Maximum landing mass		m_{ML}	**54885**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,807			
Operating empty mass		m_{OE}	**33190**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,488			
Wing loading		m_{MTO}/S_W	747,4	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**97,86**	kN		
Total take-off thrust		T_{TO}	195,72	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,293			
Bypass ratio		μ	**5,9**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V$_{md}$

					LL	UL
Cruise speed		V_{CR}	**221**	m/s		
Cruise altitude		h_{CR}	**10668**	m		
Speed ratio		V/V_{md}	**1,015**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**25**	°		
Mean aerodynamic chord		c_{MAC}	**3,73**	m		
Position of maximum camber		$x_{(y\_c),max}$	**20,4**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**40**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**12,0**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1582	1582	m	0,00%
Approach speed	V_{APP}	71,00	71,0	m/s	0,00%
Take-off field length	s_{TOFL}	2222	2222	m	0,00%
Span	b_W	28,88	28,88	m	0,00%
Aspect ratio	A	9,16	9,16		0,00%
Cruise speed	V_{CR}	221,2	221	m/s	-0,11%
Cruise altitude	h_{CR}	10668	10666	m	-0,02%
Squared Sum					**1,20E-06**
Absolute maximum deviation					0,1%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,56**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,68**	
Maximum aerodynamic efficiency	E_{max}	**15,19**	
Specific fuel consumption	SFC	**1,73E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1582	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	71,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,81	
Wing loading at maximum take-off mass	m_{MTO}/S_W	747,4	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,56**	

Take-off

Take-off field length	s_{TOFL}	2222	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,293	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,68**	

2nd Segment

Aspect ratio	A	9,161
Lift coefficient, take-off	$C_{L,TO}$	1,86
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,038
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,058
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	8,08
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,295

Missed approach

Lift coefficient, landing	$C_{L,L}$	2,11
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,050
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,085
Glide ratio in landing configuration	E_L	6,89
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,268

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,745	
Aspect ratio	A	9,16	
Bypass ratio	μ	5,90	
Wing loading	m_{MTO}/S_W	747	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,293	

Variables		
	V/V_{md}	**1,0**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,026
Lift coefficient at E_{max}	$C_{L,md}$	0,81
Ratio, lift coefficient	$C_L/C_{L,md}$	0,971
Lift coefficient, cruise	C_L	0,782
Actual aerodynamic efficiency, cruise	E	15,19
Max. glide ratio, cruise	E_{max}	**15,19**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,10	0,00	0,00
f'(x)	-0,13	-0,13	-0,13
E_{max}	16	15,21	15,19

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	1717	NM
Mach number, cruise	M_{CR}	0,745	
Bypass ratio	μ	5,90	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,293	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	68040	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,266	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,488	

Calculated values			
Actual aerodynamic efficiency, cruise	E	15,19	
Cruise altitude	h_{CR}	10666	m
Cruise speed	V_{CR}	221	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,247	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,753	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,281	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,734	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,73E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	28,88	m
Structural wing span	$b_{W,struct}$	31,87	m
Wing area	S_W	91,0	m²
Aspect ratio	A	9,16	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	3,73	m
Position of maximum camber	$x_{(y\_c),max}$	20,4	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	39,9	%c
Relative thickness	t/c	12,0	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	71,00	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,745	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,2	%c
Leading edge sweep	φ_{LE}	28,8	°
Reynoldsnumber	Re	1,9E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,28	
Correction term, camber	$\Delta_1 c_{L,max}$	0,39	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,16	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,024	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,851	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,85	
Correction term, Mach number	$\Delta C_{L,max}$	-0,03	
Lift coefficient, wing	$C_{L,max}$	1,55	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_φ	0,87	
• Flap group A			
0,4c Single-slotted fowler flap	$\Delta c_{L,max,fA}$	2,16	
Use flapped span	b_W,fA	**20,8**	m
Percentage of flaps allong the wing		65%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	1,22	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,79	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	1,22	

Calculations increase of lift coefficient due to slats			**1 slat type**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**28**	°
• Slat group A			
0,3c Nose flap	$\Delta c_{L,max,sA}$	0,96	
Use slatted span	b_W,sA	**19**	m
Percentage of slats allong the wing		60%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,50	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,96	
Use slatted span	b_W,sB	**0**	m
Percentage of slats allong the wing		0%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,00	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,50	

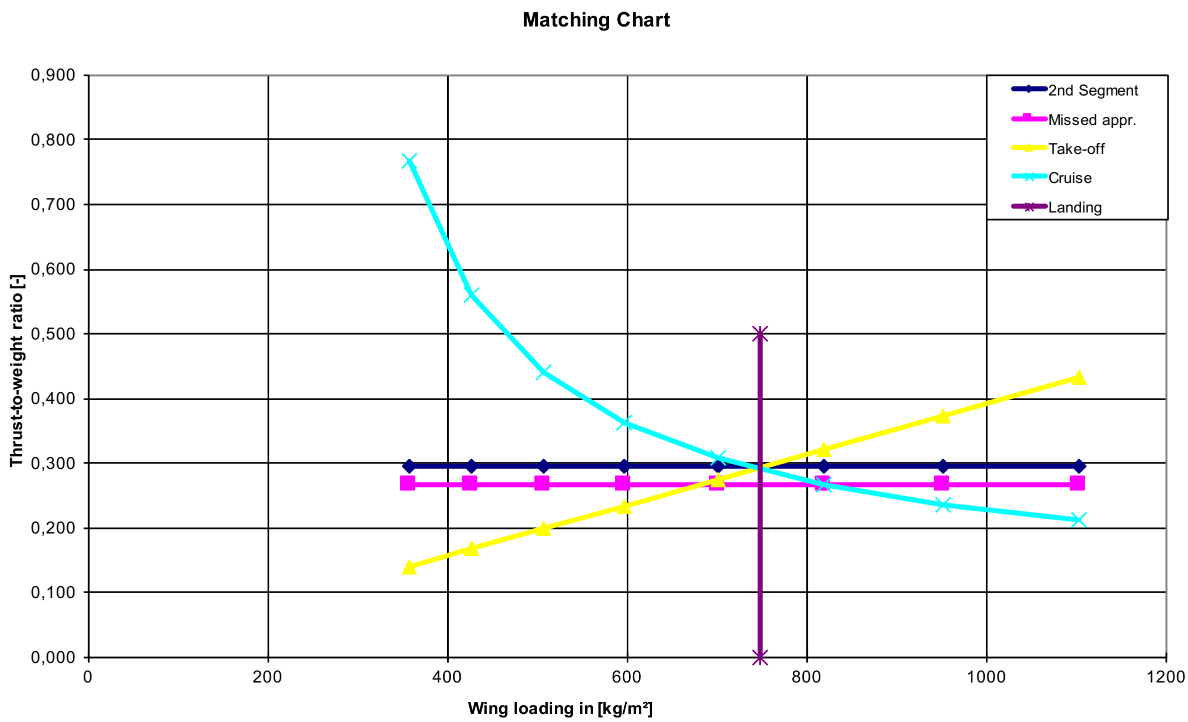
Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**3,21**
RE value maximum lift coefficient, landing		3,56
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,42**
RE value maximum lift coefficient, take-off		2,68
-10%		

Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
No winglets	$k_{e,WL}$	1,00	
Span	b_W	28,88	m
Winglet height	h	**2,7**	m
Aspect ratio	A	9,16	
Effective aspect ratio	A_{eff}	9,16	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**18,2**	
RE value maximum aerodynamic efficiency		15,19	
20%			

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,745	
Cruise altitude	h_{CR}	10668	m
By Pass Ratio	μ	5,90	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	97,86	kN
Overall Pressure ratio	OAPR	**24,30**	
Turbine entry temperature	TET	**1438,25**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,94	
Ventilator efficiency	$\eta_{ventilator}$	0,87	
Compressor efficiency	$\eta_{compresor}$	0,86	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,98	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,81	K
Dimensionless turbine entry temperature	ϕ	6,57	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,11	
Temperature function	χ	1,65	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,12	
Verification value specific fuel consumption	SFC	0,58	kg/daN/h
Verification value specific fuel consumption	SFC	**1,62E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,73E-05	kg/N/s
-6%			


Matching Chart
2nd Segment
Missed appr.
Take-off
Cruise
Landing
Thrust-to-weight ratio [-]
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
200
400
600
800
1000
1200
Wing loading in [kg/m²]

Appendix AP Airbus A300

Data Collection			A300-600		1	2	3	4	5	6	7	8	9
Parameter	Symbol	Units	Chosen value	Source:	Aircraft characteristics for airport planning	Jane's	Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collection	Webs
PAX			361		269		375-266-228			308	361		
Landing field length	s_{LFL}	m	1489		1850		1489			1536	1489	1635	
Approach speed	V_{APP}	m/s	70		71		69,96			69,17		67,39	
Temperature above ISA (288,15K)	ΔT_L	K	0		0		0			0			
Relative density	s												
Take-off field length	s_{TOFL}	m	2280		2300		2280				2280	2850	2325
Temperature above ISA (288,15K)	ΔT_{TO}	K	0		0		0						
Relative density	s												
Range (max payload)	R	km	3283		4500		3283			5000	4040		6670
Cruise Mach number	M_{CR}		0,78		0,78			0,8			0,78	0,79	0,78
Wing area	S_W	m²	260				260			260	260		260
Wing span	b_W	m	44,84		44,83		44,84			44,84	44,84	44,8	44,85
Aspect ratio	A		7,7				7,733175385			7,7	7,73		
Maximum take-off mass	m_{MTO}	kg	170500		165000		170500			165000	165000	165000	165000
Payload mass	m_{PL}	kg	43273		37495		41100				43273		
Mass ratio, payload - take-off	m_{PL}/m_{MTO}						0,241055718				0,262		
Maximum landing mass	m_{ML}	kg	136000		136000		140000			138000	138000		
Mass ratio, landing - take-off	m_{ML}/m_{MTO}						0,82111437						
Operating empty mass	m_{OE}	kg	86727		88505		88900				86727		90060
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}						0,521407625				0,526		
Wing loading	m_{MTO}/S_W	kg/m²	635				655,7692308				635		
Maximum zero fuel mass	m_{MZF}	kg	130000		126000		130000				130000		
Number of engines	n_E		2				2				2	2	2
Engine type	GE CF6 (84%), PW4000		CF6-80C2A1		GE CF6—50	CF6-80C2A5	P&W 4158	CF6-50C2			CF6-80C2A1	GE CF6-50-C2	
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	257				257	233,532			257,4	233	
Total take-off thrust	T_{TO}	kN	514										
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,32				0,307305072				0,32		
Bypass ratio	μ		5,2					4,31			5,2		
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s	1,05E-05					1,05E-05			9,46E-06		
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s	1,78E-05					1,78E-05			1,63E-05		
Available fuel volume	$V_{fuel,available}$	m³	62		62		68,150-75,350				62		62,9
Cruise speed	V_{CR}	m/s	241,79				234,59-246,93					241,79	
Cruise altitude	h_{CR}	m	10668				10668-9448,8	10668			9449		
Sweep angle	ϕ_{25}	°	28				28				28		
Mean aerodynamic chord	c_{MAC}	m	6,61				6,437				6,61		
Position of maximum camber	$x_{(y\_c),max}$	%c											
Camber	$(y_c)_{max}/c$	%c											
Position of maximum thickness	$x_{t,max}$	%c											
Relative thickness	t/c	%	10,5				10,5				10,5		
Taper	λ		0,292				0,3				0,292		
Overall pressure ratio	OAPR		30,4					30,4					
Turbine entry temperature	TET	K											

Aeroplane Specifications

Data to apply reverse engineering

					LL	UL
Landing field length	**Known**	s_{LFL}	**1489**	m		
Approach speed	**Known**	V_{APP}	**70,00**	m/s	70,0	70,0
Temperature above ISA (288,15K)		ΔT_L	**0**	K		
Relative density		σ	**1**			
Take-off field length	**Known**	s_{TOFL}	**2280**	m	2280	2280
Temperature above ISA (288,15K)		ΔT_{TO}	**0**	K		
Relative density		σ	**1,000**			
Range (maximum payload)		R	**1773**	NM		
Cruise Mach number		M_{CR}	**0,78**			
Wing area		S_W	**260**	m²		
Wing span	**Known**	b_W	**44,84**	m²	44,84	44,84
Aspect ratio		A	7,73			
Maximum take-off mass		m_{MTO}	**170500**	kg		
Maximum payload mass		m_{PL}	**43273**	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,254			
Maximum landing mass		m_{ML}	**136000**	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,798			
Operating empty mass		m_{OE}	**86727**	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,509			
Wing loading		m_{MTO}/S_W	655,8	kg/m²		
Number of engines		n_E	**2**			
Take-off thrust for one engine		$T_{TO,one\ engine}$	**257**	kN		
Total take-off thrust		T_{TO}	514	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,307			
Bypass ratio		μ	**5,2**			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

					LL	UL
Cruise speed		V_{CR}	**242**	m/s		
Cruise altitude		h_{CR}	**10668**	m		
Speed ratio		V/V_{md}	**1,088**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**28**	°		
Mean aerodynamic chord		c_{MAC}	**6,61**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**11,6**	%		
Taper		λ	**0,292**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	1489	1489	m	0,00%
Approach speed	V_{APP}	70,00	70,0	m/s	0,00%
Take-off field length	s_{TOFL}	2280	2280	m	0,00%
Span	b_W	44,84	44,84	m	0,00%
Aspect ratio	A	7,73	7,73		0,00%
Cruise speed	V_{CR}	241,8	232	m/s	-4,23%
Cruise altitude	h_{CR}	10668	10600	m	-0,64%
Squared Sum					**1,83E-03**
Absolute maximum deviation					*4,2%*

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**3,28**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,19**	
Maximum aerodynamic efficiency	E_{max}	**14,08**	
Specific fuel consumption	SFC	**1,51E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	1489	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	70,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,80	
Wing loading at maximum take-off mass	m_{MTO}/S_W	655,8	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**3,28**	

Take-off

Take-off field length	s_{TOFL}	2280	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,307	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,19**	

2nd Segment

Aspect ratio	A	7,733
Lift coefficient, take-off	$C_{L,TO}$	1,52
Lift-independent drag coefficient, clean	$C_{D,0}$ (2^{nd} Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,021
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,041
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	8,59
Number of engines	n_E	2
Climb gradient	$\sin(\gamma)$	0,024
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,281

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,94
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,042
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,077
Glide ratio in landing configuration	E_L	6,50
Climb gradient	$\sin(\gamma)$	0,021
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,279

2) Maximum Aerodynamic Efficiency

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications

Mach number, cruise	M_{CR}	0,78	
Aspect ratio	A	7,73	
Bypass ratio	μ	5,20	
Wing loading	m_{MTO}/S_W	656	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,307	

Variables

	V/V_{md}	**1,1**

Calculations

Zero-lift drag coefficient	$C_{D,0}$	0,026
Lift coefficient at E_{max}	$C_{L,md}$	0,73
Ratio, lift coefficient	$C_L/C_{L,md}$	0,845
Lift coefficient, cruise	C_L	0,620
Actual aerodynamic efficiency, cruise	E	13,88
Max. glide ratio, cruise	E_{max}	**14,08**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	-0,27	-0,01	0,00
f'(x)	-0,15	-0,14	-0,14
E_{max}	16	14,14	14,08

3) Specific Fuel Consumption

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications			
Range	R	1773	NM
Mach number, cruise	M_{CR}	0,78	
Bypass ratio	μ	5,20	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,307	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	170500	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,254	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,509	

Calculated values			
Actual aerodynamic efficiency, cruise	E	13,88	
Cruise altitude	h_{CR}	10600	m
Cruise speed	V_{CR}	232	m/s

Mission fuel fraction			
Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations			
Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,238	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,762	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,112	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,906	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**yes**	
	international	**no**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	370400	m
Loiter time	t_{loiter}	2700	s
Specific fuel consumption	SFC	**1,51E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	44,84	m
Structural wing span	$b_{W,struct}$	50,78	m
Wing area	S_W	260,0	m²
Aspect ratio	A	7,73	
Sweep	φ_{25}	28	°
Mean aerodynamic chord	c_{MAC}	6,61	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	11,6	%
Taper	λ	0,292	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	70,00	m/s
Mach number, landing	M_{APP}	0,21	
Mach number, cruise	M_{CR}	0,78	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	2,1	%c
Leading edge sweep	φ_{LE}	32,1	°
Reynoldsnumber	Re	3,3E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,26	
Correction term, camber	$\Delta_1 c_{L,max}$	0,40	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,050	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,714	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,86	
Correction term, Mach number	$\Delta C_{L,max}$	-0,02	
Lift coefficient, wing	$C_{L,max}$	1,46	

Calculations increase of lift coefficient due to flaps			**1 flap type**
Correction factor, sweep	K_φ	0,85	
• Flap group A			
0,3c Single-slotted fowler flap	$\Delta c_{L,max,fA}$	1,73	
Use flapped span	b_W,fA	**35,9**	m
Percentage of flaps allong the wing		71%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	1,04	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,74	
Use flapped span	b_W,fB	**0**	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	1,04	

Calculations increase of lift coefficient due to slats			**1 slat type**
Sweep angle of the hinge line	$\varphi_{H.L.}$	**31**	°
• Slat group A			
0,1c Kruger flap	$\Delta c_{L,max,sA}$	0,67	
Use slatted span	b_W,sA	**40,4**	m
Percentage of slats allong the wing		80%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,45	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**0**	m
Percentage of slats allong the wing		0%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,00	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,45	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,90**
RE value maximum lift coefficient, landing		3,28
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**1,93**
RE value maximum lift coefficient, take-off		2,19

-12%

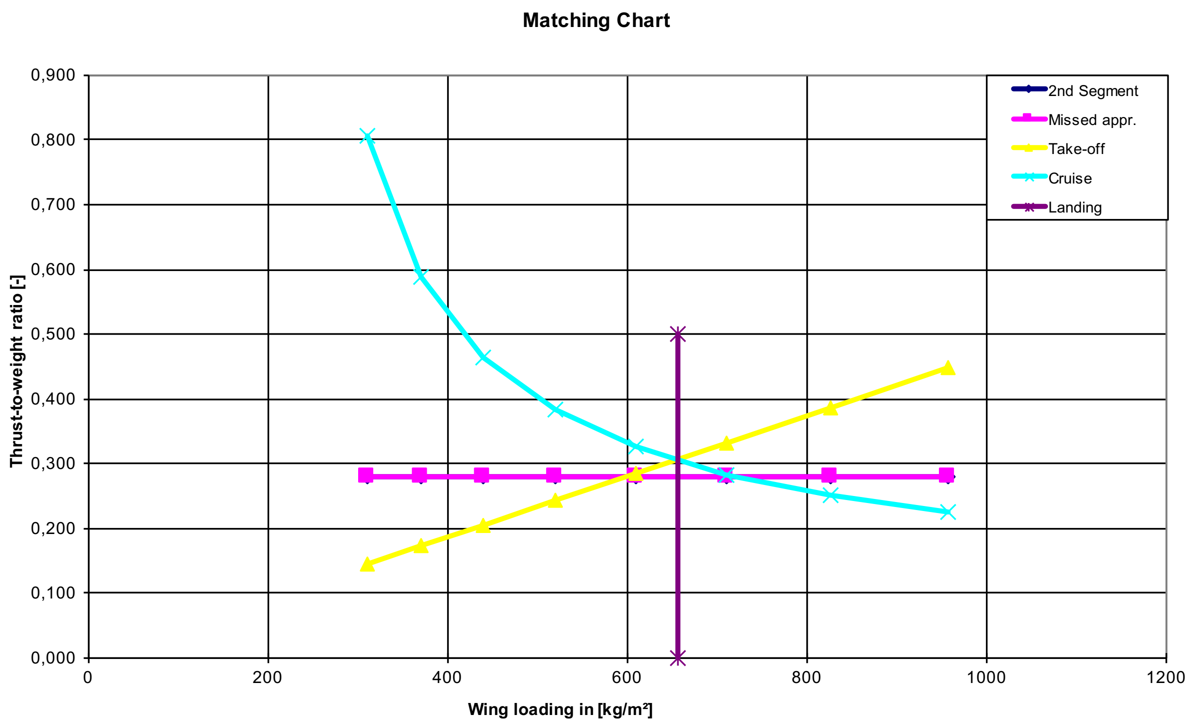
Aerodynamic efficiency

Real aircraft average	k_{WL}	2,83	
No winglets	$k_{e,WL}$	1,00	
Span	b_W	44,84	m
Winglet height	h	**2,7**	m
Aspect ratio	A	7,73	
Effective aspect ratio	A_{eff}	7,73	
Efficiency factor, short range	k_E	15,15	
Relative wetted area	S_{wet}/S_W	**6,35**	
Verification value maximum aerodynamic efficiency	E_{max}	**16,7**	
RE value maximum aerodynamic efficiency		14,08	

19%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,780	
Cruise altitude	h_{CR}	10668	m
By Pass Ratio	μ	5,20	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	257,00	kN
Overall Pressure ratio	OAPR	**30,40**	
Turbine entry temperature	TET	**1488,87**	
Inlet pressure loss	$\Delta P/P$	2%	
Inlet efficiency	η_{inlet}	0,95	
Ventilator efficiency	$\eta_{ventilator}$	0,89	
Compressor efficiency	$\eta_{compresor}$	0,87	
Turbine efficiency	$\eta_{turbine}$	0,91	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,81	K
Dimensionless turbine entry temperature	ϕ	6,80	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,12	
Temperature function	χ	1,85	
Gas generator efficiency	η_{gasgen}	0,98	
Gas generator function	G	2,24	
Verification value specific fuel consumption	SFC	0,56	kg/daN/h
Verification value specific fuel consumption	SFC	**1,55E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,51E-05	kg/N/s
2%			


Matching Chart
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
Thrust-to-weight ratio [-]
0
200
400
600
800
1000
1200
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing

Appendix AQ Boeing 747-8

Data Collection			747-8	Source: 1	2	3	4	5	6	7	8	9	
Parameter	Symbol	Units	Chosen value	Aircraft characteristics for airport planning	Jane's	Jenkinson	Engine	Scholz	Paul Müller	Elodie Roux	Data collectior	Webs	
PAX			654	48+467	467					654-467			467-581
Landing field length	s_{LFL}	m	2130	1981,2	2072					2130	2680		
Approach speed	V_{APP}	m/s	74								74,594444		
Temperature above ISA (288,15K)	ΔT_L	K	0										
Relative density	s												
Take-off field length	s_{TOFL}	m	3300	3302	3230					3310	3190		
Temperature above ISA (288,15K)	ΔT_{TO}	K	0	0	15								
Relative density	s												
Range (max payload)	R	km	10949,95	10949,95	14816					11437			15000
Cruise Mach number	M_{CR}		0,855	0,855	0,855					0,855	0,855		0,855
Wing area	S_W	m²	525							525			
Wing span	b_W	m	68,5	68,4	68,45					68,5	68,45		68,5
Aspect ratio	A		8,94							8,94			
Maximum take-off mass	m_{MTO}	kg	447696	447696	439985					439985	447696		447696
Payload mass	m_{PL}	kg	76340	76067	76340					76340			
Mass ratio, payload - take-off	m_{PL}/m_{MTO}									0,174			
Maximum landing mass	m_{ML}	kg	306175	312072	306175					306175			309000
Mass ratio, landing - take-off	m_{ML}/m_{MTO}												
Operating empty mass	m_{OE}	kg	211691	220128	211690					211691			
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}									0,481			
Wing loading	m_{MTO}/S_W	kg/m²	838							838			
Maximum zero fuel mass	m_{MZF}	kg	288031	295289	288030					288031			
Number of engines	n_E		4							4	4		
Engine type	GEnx-2B		Genx-2B67	GEnx-2B67	Genx-2B67					Genx-2B67	GEnx-2B67	Genx-2B67B	Genx
Take-off thrust for one engine	$T_{TO,one\ engine}$	kN	296		296					298	296	295,80676	296
Total take-off thrust	T_{TO}	kN											
Thrust to weight ratio	$T_{TO}/(m_{MTO}*g)$		0,28		0,274303					0,28			
Bypass ratio	μ		8							8		8,0-7,4	
Specific Fuel Comsumption (dry)	SFC (dry)	kg/N s											
Specific Fuel Comsumption (cruise)	SFC (cruise	kg/N s											
Available fuel volume	$V_{fuel,available}$	m³	241,619	238,61	243,111					241,619			254,722
Cruise speed	V_{CR}	m/s	255								262,36667		254,722
Cruise altitude	h_{CR}	m	10668							10668			10668
Sweep angle	ϕ_{25}	°	37,5							37,5			
Mean aerodynamic chord	c_{MAC}	m	9,68							9,68			
Position of maximum camber	$x_{(y\_c),max}$	%c											
Camber	$(y_c)_{max}/c$	%c											
Position of maximum thickness	$x_{t,max}$	%c											
Relative thickness	t/c	%	9,4							9,4			
Taper	λ		0,275							0,275			
Overall pressure ratio	OAPR		44,7									44,7-52,4	44,7
Turbine entry temperature	TET	K											

Aeroplane Specifications

Data to apply reverse engineering					LL	UL
Landing field length	Known	s_{LFL}	2130	m		
Approach speed	Known	V_{APP}	74,00	m/s	74,0	74,0
Temperature above ISA (288,15K)		ΔT_L	0	K		
Relative density		σ	1			
Take-off field length	Known	s_{TOFL}	3300	m	3300	3300
Temperature above ISA (288,15K)		ΔT_{TO}	0	K		
Relative density		σ	1,000			
Range (maximum payload)		R	5912	NM		
Cruise Mach number		M_{CR}	0,855			
Wing area		S_W	525	m²		
Wing span	Known	b_W	68,5	m²	68,5	68,5
Aspect ratio		A	8,94			
Maximum take-off mass		m_{MTO}	447696	kg		
Maximum payload mass		m_{PL}	76340	kg		
Mass ratio, payload - take-off		m_{PL}/m_{MTO}	0,171			
Maximum landing mass		m_{ML}	306175	kg		
Mass ratio, landing - take-off		m_{ML}/m_{MTO}	0,684			
Operating empty mass		m_{OE}	211691	kg		
Mass ratio, operating empty - take-off		m_{OE}/m_{MTO}	0,473			
Wing loading		m_{MTO}/S_W	852,8	kg/m²		
Number of engines		n_E	4			
Take-off thrust for one engine		$T_{TO,one\ engine}$	296	kN		
Total take-off thrust		T_{TO}	1184	kN		
Thrust to weight ratio		$T_{TO}/(m_{MTO}*g)$	0,270			
Bypass ratio		μ	8			
Available fuel volume		$V_{fuel,available}$	23,86	m³		

Data to optimize V/V_{md}

				LL	UL
Cruise speed	V_{CR}	**255**	m/s		
Cruise altitude	h_{CR}	**10668**	m		
Speed ratio	V/V_{md}	**1,000**	-	1	1,316

Data to execute the verification

					Range	
Sweep angle		φ_{25}	**25**	°		
Mean aerodynamic chord		c_{MAC}	**4,2**	m		
Position of maximum camber		$x_{(y\_c),max}$	**30**	%c	15 - 50	%c
Camber		$(y_c)_{max}/c$	**4**	%c	2 - 6	%c
Position of maximum thickness		$x_{t,max}$	**30**	%c	30 - 45	%c
Relative thickness	**Unknown**	t/c	**10,6**	%		
Taper		λ	**0,24**			

Reverse Engineering

Reverse engineering & optimization of V/Vmd

	Quantity	*Original value*	RE value	*Unit*	*Deviation*
Landing field length	s_{LFL}	2130	2130	m	0,00%
Approach speed	V_{APP}	74,00	74,0	m/s	0,00%
Take-off field length	s_{TOFL}	3300	3300	m	0,00%
Span	b_W	68,5	68,5	m	0,00%
Aspect ratio	A	8,94	8,94		0,00%
Cruise speed	V_{CR}	255,0	254	m/s	-0,35%
Cruise altitude	h_{CR}	10668	10525	m	-1,34%
Squared Sum					**1,92E-04**
Absolute maximum deviation					1,3%

Results reverse engineering

Maximum lift coefficient, landing	$C_{L,max,L}$	**2,56**	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,24**	
Maximum aerodynamic efficiency	E_{max}	**18,03**	
Specific fuel consumption	SFC	**1,39E-05**	kg/N/s

Reverse Engineering

1) Maximum Lift Coefficient for Landing and Take-off

Landing

Landing field length	s_{LFL}	2130	m
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1,000	
Factor, approach	k_{APP}	1,70	$(m/s^2)^{0.5}$
Approach speed	V_{APP}	74,00	m/s
Factor, landing	k_L	0,107	kg/m³
Mass ratio, landing - take-off	m_{ML}/m_{TO}	0,68	
Wing loading at maximum take-off mass	m_{MTO}/S_W	852,8	kg/m²
Maximum lift coefficient, landing	$C_{L,max,L}$	**2,56**	

Take-off

Take-off field length	s_{TOFL}	3300	m
Temperatur above ISA (288,15K)	ΔT_{TO}	0	K
Relative density	σ	1,00	
Factor	k_{TO}	2,34	m³/kg
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,270	
Maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,24**	

2nd Segment

Aspect ratio	A	8,938
Lift coefficient, take-off	$C_{L,TO}$	1,56
Lift-independent drag coefficient, clean	$C_{D,0}$ (2nd Segment)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,023
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Profile drag coefficient	$C_{D,P}$	0,043
Oswald efficiency factor; landing configuration	e	0,7
Glide ratio in take-off configuration	E_{TO}	9,37
Number of engines	n_E	4
Climb gradient	$\sin(\gamma)$	0,030
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,182

Missed approach

Lift coefficient, landing	$C_{L,L}$	1,51
Lift-independent drag coefficient, clean	$C_{D,0}$ (Missed approach)	0,020
Lift-independent drag coefficient, flaps	$\Delta C_{D,flap}$	0,021
Lift-independent drag coefficient, slats	$\Delta C_{D,slat}$	0,000
Choose: Certification basis	JAR-25 resp. CS-25	**no**
	FAR Part 25	**yes**
Lift-independent drag coefficient, landing gear	$\Delta C_{D,gear}$	0,015
Profile drag coefficient	$C_{D,P}$	0,056
Glide ratio in landing configuration	E_L	8,79
Climb gradient	$\sin(\gamma)$	0,027
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,128

2) Maximum Aerodynamic Efficiency

Constant parameters			
Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Oswald eff. factor, clean	e	0,85	

Specifications			
Mach number, cruise	M_{CR}	0,855	
Aspect ratio	A	8,94	
Bypass ratio	µ	8,00	
Wing loading	m_{MTO}/S_W	853	kg/m²
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,270	

Variables		
	V/V_{md}	**1,0**

Calculations		
Zero-lift drag coefficient	$C_{D,0}$	0,018
Lift coefficient at E_{max}	$C_{L,md}$	0,66
Ratio, lift coefficient	$C_L/C_{L,md}$	1,000
Lift coefficient, cruise	C_L	0,662
Actual aerodynamic efficiency, cruise	E	18,03
Max. glide ratio, cruise	E_{max}	**18,03**

Newton-Raphson for the maximum lift-to-drag ratio

Iterations	1	2	3
f(x)	0,21	-0,01	0,00
f'(x)	-0,10	-0,11	-0,11
E_{max}	16	18,11	18,03

3) Specific Fuel Consumption

Constant parameters

Ratio of specific heats, air	γ	1,4	
Earth acceleration	g	9,81	m/s²
Air pressure, ISA, standard	p_0	101325	Pa
Fuel density	ρ_{fuel}	800	kg/m³

Specifications

Range	R	5912	NM
Mach number, cruise	M_{CR}	0,855	
Bypass ratio	μ	8,00	
Thrust-to-weight ratio	$T_{TO}/(m_{MTO}*g)$	0,270	
Available fuel volume	$V_{fuel,available}$	23,86	m³
Maximum take-off mass	m_{MTO}	447696	kg
Mass ratio, landing - take-off	m_{PL}/m_{MTO}	0,171	
Mass ratio, operating empty - take-off	m_{OE}/m_{MTO}	0,473	

Calculated values

Actual aerodynamic efficiency, cruise	E	18,03	
Cruise altitude	h_{CR}	10525	m
Cruise speed	V_{CR}	254	m/s

Mission fuel fraction

Type of aeroplane (according to Roskam)	**Transport jet**		
Fuel-Fraction, engine start	$M_{ff,engine}$	0,990	
Fuel-Fraction, taxi	$M_{ff,taxi}$	0,990	
Fuel-Fraction, take-off	$M_{ff,TO}$	0,995	
Fuel-Fraction, climb	$M_{ff,CLB}$	0,980	
Fuel-Fraction, descent	$M_{ff,DES}$	0,990	
Fuel-Fraction, landing	$M_{ff,L}$	0,992	

Calculations

Mission fuel fraction (acc. to PL and OE)	m_F/m_{MTO}	0,357	
Mission fuel fraction (acc. to PL and OE)	M_{ff}	0,643	
Available fuel mass	$m_{F,available}$	19088	kg
Relative fuel mass (acc. to fuel capacity)	$m_{F,available}/m_{MTO}$	0,043	
Mission fuel fraction (acc. to fuel capacity)	M_{ff}	0,977	
Distance to alternate	$s_{to\_alternate}$	200	NM
Distance to alternate	$s_{to\_alternate}$	370400	m
Choose: FAR Part121-Reserves	domestic	**no**	
	international	**yes**	
Extra-fuel for long range		5%	
Extra flight distance	s_{res}	917851	m
Loiter time	t_{loiter}	1800	s
Specific fuel consumption	SFC	**1,39E-05**	kg/N/s

4) Verification Specifications

Maximum lift coefficients

General wing specifications	*Airfoil type:*	**NACA 66 series**	
Wing span	b_W	68,5	m
Structural wing span	$b_{W,struct}$	75,58	m
Wing area	S_W	525,0	m²
Aspect ratio	A	8,94	
Sweep	φ_{25}	25	°
Mean aerodynamic chord	c_{MAC}	4,2	m
Position of maximum camber	$x_{(y\_c),max}$	30	%c
Camber	$(y_c)_{max}/c$	4	%c
Position of maximum thickness	$x_{t,max}$	30	%c
Relative thickness	t/c	10,6	%
Taper	λ	0,24	
General aircraft specifications			
Temperature above ISA (288,15K)	ΔT_L	0	K
Relative density	σ	1	
Temperature, landing	T_L	273,15	K
Density, air, landing	ρ	1,225	kg/m³
Dynamic viscosity, air	μ	1,72E-05	kg/m/s
Speed of sound, landing	a_{APP}	331	m/s
Approach speed	V_{APP}	74,00	m/s
Mach number, landing	M_{APP}	0,22	
Mach number, cruise	M_{CR}	0,855	
Calculations maximum clean lift coefficient			
Leading edge sharpness parameter	Δy	1,9	%c
Leading edge sweep	φ_{LE}	28,9	°
Reynoldsnumber	Re	2,2E+07	
Maximum lift coefficient, base	$c_{L,max,base}$	1,17	
Correction term, camber	$\Delta_1 c_{L,max}$	0,38	
Correction term, thickness	$\Delta_2 c_{L,max}$	0,00	
Correction term, Reynolds' number	$\Delta_3 c_{L,max}$	0,067	
Maximum lift coefficient, airfoil	$c_{L,max,clean}$	1,617	
Lift coefficient ratio	$C_{L,max}/c_{L,max}$	0,91	
Correction term, Mach number	$\Delta C_{L,max}$	-0,01	
Lift coefficient, wing	$C_{L,max}$	1,46	

Calculations increase of lift coefficient due to flaps		**1 flap type**	
Correction factor, sweep	K_φ	0,87	
• Flap group A			
Double-slotted flap	$\Delta c_{L,max,fA}$	1,43	
Use flapped span	b_W,fA	**43,8**	m
Percentage of flaps allong the wing		58%	
Increase in maximum lift coefficient, flap group A	$\Delta C_{L,max,fA}$	0,72	
• Flap group B			
0,3c Plain flap	$\Delta c_{L,max,fB}$	0,75	
Use flapped span	b_W,fB	0	m
Percentage of flaps allong the wing		0%	
Increase in maximum lift coefficient, flap group B	$\Delta C_{L,max,fB}$	0,00	
Increase in maximum lift coefficient, flap	$\Delta C_{L,max,f}$	0,72	

Calculations increase of lift coefficient due to slats		**2 slat types**	
Sweep angle of the hinge line	$\varphi_{H.L.}$	**42**	°
• Slat group A			
0,1c Kruger flap	$\Delta c_{L,max,sA}$	0,67	
Use slatted span	b_W,sA	**9,3**	m
Percentage of slats allong the wing		12%	
Increase in maximum lift coefficient, slat group A	$\Delta C_{L,max,sA}$	0,06	
• Slat group B			
0,3c Nose flap	$\Delta c_{L,max,SB}$	0,90	
Use slatted span	b_W,sB	**34,8**	m
Percentage of slats allong the wing		46%	
Increase in maximum lift coefficient, slat group B	$\Delta C_{L,max,sB}$	0,31	
Increase in maximum lift coefficient, slat	$\Delta C_{L,max,s}$	0,37	

Wing		
Verification value maximum lift coefficient, landing	$C_{L,max,L}$	**2,51**
RE value maximum lift coefficient, landing		2,56
Verification value maximum lift coefficient, take-off	$C_{L,max,TO}$	**2,20**
RE value maximum lift coefficient, take-off		2,24

-2%

Aerodynamic efficiency

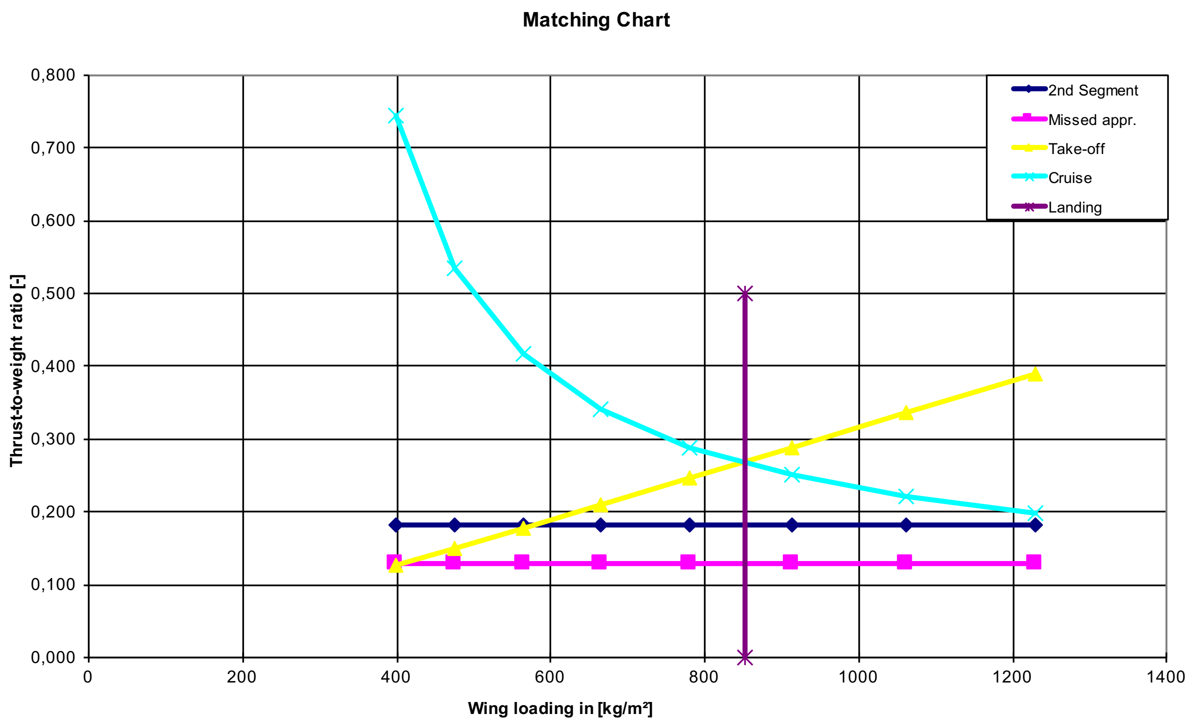
Real aircraft average	k_{WL}	2,83	
End plate	$k_{e,WL}$	1,03	
Span	b_W	68,5	m
Winglet height	h	**1,6**	m
Aspect ratio	A	8,94	
Effective aspect ratio	A_{eff}	9,24	
Efficiency factor, short range	k_E	17,25	
Relative wetted area	S_{wet}/S_W	**6,30**	
Verification value maximum aerodynamic efficiency	E_{max}	**20,9**	
RE value maximum aerodynamic efficiency		18,03	

16%

Specific fuel consumption (Herrmann 2010)

Cruise Mach number	M_{CR}	0,855	
Cruise altitude	h_{CR}	10668	m
By Pass Ratio	μ	8,00	
Take-off Thrust (one engine)	$T_{TO,one\ engine}$	296,00	kN
Overall Pressure ratio	OAPR	**44,70**	
Turbine entry temperature	TET	**1492,97**	
Inlet pressure loss	ΔP/P	2%	
Inlet efficiency	η_{inlet}	0,93	
Ventilator efficiency	$\eta_{ventilator}$	0,89	
Compressor efficiency	$\eta_{compresor}$	0,87	
Turbine efficiency	$\eta_{turbine}$	0,90	
Nozzle efficiency	η_{nozzle}	0,99	
Temperature at SL	T_0	288,15	K
Temperature lapse rate in troposhpere	L	0,0065	K/m
Temperature (ISA) at tropopause	T_S	216,65	K
Temperature at cruise altitude	T(H)	218,81	K
Dimensionless turbine entry temperature	ϕ	6,82	
Ratio of specific heats, air	γ	1,40	
Ratio between stagnation point temperature and temperature	υ	1,15	
Temperature function	χ	2,25	
Gas generator efficiency	η_{gasgen}	0,97	
Gas generator function	G	2,06	
Verification value specific fuel consumption	SFC	0,55	kg/daN/h
Verification value specific fuel consumption	SFC	**1,54E-05**	kg/N/s
RE value specific fuel consumption	SFC	1,39E-05	kg/N/s

11%


Matching Chart
Thrust-to-weight ratio [-]
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
200
400
600
800
1000
1200
1400
Wing loading in [kg/m²]
2nd Segment
Missed appr.
Take-off
Cruise
Landing