Hochschule für Angewandte Wissenschaften Hamburg
*Hamburg University of Applied Sciences*

**Master Thesis**

**Department of Automotive and Aeronautical Engineering**

# Preliminary Sizing of FAR Part 23 and Part 25 Aircraft

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# Abstract

This thesis covers the subject of preliminary sizing together with the development of the SAS Optimizations tool for Part 23 and Part 25 certification requirements. Preliminiary sizing is a very important step in the process of designing an airplane as it decides if the airplane will be further developed or not. The design of an airplane is defined by different specifications and requirements that can follow from a mission specification or market research, etc. The goal of preiminary sizing is translating these requirements and specifications into design and performance parameters. Most of these requirements and specifications are defined by certification requirements. Therefore Part 23, Part 25 and CS-VLA have been analysed to see which requirements affect the design. In order to translate these requirements and specifications to performance parameters, the mechanics behind each flight phase have to be analysed. With these equations resulting from these mechanics, a tool is developed that allows students to perform preliminary sizing by use of a set of input parameters and then perform an optimization on this design for a chosen design goal. In order to build the tool for Part 25, OPerA was dismantled and deconstructed to a more simple version that could perform the optimization by using the algorithms used in OPerA. After this a more detailed Oswald Factor calculation was implemented. This tool could now be used to build a tool for Part 23 as well by making the necessary changes according to the certification requirements. With the tool finished, it was decided to write a general users guide to SAS Optimization.

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## Background

At the University of Applied Sciences Hamburg (HAW Hamburg) several tools are available for aircraft design. The tool PreSTo (Preliminary Sizing Tool) was developed within the Aero Research Group at HAW Hamburg, based on sizing calculations presented in the lecture "Aircraft Design" by Prof. D. Scholz. This tool is now called SAS Classic. Another tool that was designed is OPerA, which is far more complicated and detailed, which means it is not really student friendly. Both of these tools are developed for Part 25 requirements. All this led to the idea of developing a tool, which is in the middle of these tools and for other certification bases.

## Task

The task of this thesis consists of developing the SAS Optimization tools for Part 25, Part 23 and (if possible) EASA CS-VLA by completing following subtasks as a guidance:

Perform a study on the certification requirements for Part 25, Part 23 and CS-VLA aircraft.
Get from OPerA to SAS Optimization for FAR Part 25 Jet aircraft.
Get from SAS Optimization Part 25 Prop to SAS Optimization Part 23 Prop and if possible to SAS Optimization for EASA CS-VLA Prop.

This thesis will be written in English according to German or international standards on report writing.

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# List of Symbols

| | |
|---|---|
| B | width |
| C | coefficient |
| d | diameter |
| e | Oswald Efficiency Factor |
| E | glide ratio |
| k | statistical constant |
| m | mass |
| M | Mach |
| n | load factor |
| P | power |
| q | dynamic pressure |
| s | distance |
| S | aerodynamic reference wing area |
| T | thrust |
| V | speed |
| W | airplane gross weight |

## Greek Symbols

| | |
|---|---|
| $\lambda$ | taper ratio |
| $\varphi$ | sweep angle |
| $\eta$ | efficiency |
| $\rho$ | density |
| $\mu$ | friction coefficient |
| $\gamma$ | climb gradient |

## Indices

| | |
|---|---|
| 0 | sea level, zero lift |
| 25 | 25% mean chord line |
| a | airborne |
| APP | approach |
| CL | landing configuration |
| comp | compression |
| CR | cruise |

| | |
|---|---|
| D | drag |
| E | engine |
| f | friction |
| F | fuselage |
| g | ground |
| L | landing, lift |
| LFL | landing field length |
| LG | landing ground |
| LO | lift-off |
| M | Mach |
| MAX | maximum |
| mcg | minimum control ground |
| mca | minimum control airborne |
| MIN | minimum |
| MTO | maximum take-off |
| mu | minimum unstick |
| R | rotate |
| S | stall |
| SR | reference stall speed |
| theo | theoretical |
| TO | take-off |
| TOFL | take-off field length |
| W | wing |

# List of Abbrevations

| | |
|---|---|
| AEO | all engines operating |
| AR | aspect ratio |
| CS | Certification Specifications |
| CAS | calibrated airspeed |
| DP | design point |
| EASA | European Aviation Safety Agency |
| FAA | Federal Airworthiness Association |
| FAR | Federal Airworthiness Regulations |
| ISA | International Standard Atmosphere |
| MC | matching chart |
| MTOW | maximum take-off weight |
| OEI | one engine inoperative |
| PS | preliminary sizing |

| | |
|---|---|
| SAS | simple aircraft sizing |
| SFC | specific fuel consumption |
| sin | sinus |
| cos | cosinus |
| VLA | very light aircraft |

# 1 Introduction

## 1.1 Motivation

Preliminary sizing is a very important step in the aircraft design process as it will decide if the proposed design will be developed or not. Therefore it is important for students to get a feel on what exactly preliminiary sizing is and how it works. This was the reason that SAS Classic was developed for Part 25. With this tool, students could play around with values and see the effect of it on the performances of the airplane. After the development of this tool, another tool was produced: OPerA. This tool was a lot more detailed and complicated than the SAS Classic tool, but allowed the user to perform an Optimization. The idea and decision was made by Prof. D. Scholz to develop a tool that could be used by students for simple aircraft sizing but with the main advantages of OPerA such as the SFC calculation and of course the ability to perform automatic optimization. This tool would be developed for the different certificates.

## 1.2 Objectives

The aim of this thesis is to develop tools for simple aircraft sizing for different certification bases that can perform an optimization on the resulting design and can be used for preliminary sizing done by students. Therefore a torough study of these certification requirements is performed in order to know which requirements will affect the design of an airplane.

In order to develop these tools, a theoretical foundation on the mechanics behind every flight phase is necessary. This foundation is mainly based on the lecture notes of Prof. D. Scholz **(Scholz 2012)** and literature that covers the domains of aircraft design and flight mechanics.

To develop the tool, first SAS Optimization Part 25 was built by deconstructing OPerA. This was done because SAS Optimization Part 25 could be used as a base platform to build the tools for other certification bases.

Initially it was planned to develop these tools for Part 25, Part 23 and CS-VLA but during the period of working on this thesis, it seemed that too much time had to be spent on building the tools and performing statistical studies in order to get to key values. Therefore a tool for CS-VLA is not built but a study of the certification requirements is performed already. For Part 23 a tool is build for propeller driven aircrafts, which means that the tool for small turbine engine powered airplanes still has to be developed. The choice was made to build the tools for Part 25 Jet and Part 23 Prop in order to cover both propeller driven and turbine-engine powered airplanes.

## 1.3 Structure of the Thesis

The chapters two to five describe the conducted investigations in order to gain a fundamental understanding of preliminary sizing and how it is influenced. The chapters six and seven describe the used method for developing the SAS Optimization tools. Finally in the appendices, the statistical data and the codes of the macros are given.

| | |
|---|---|
| **Chapter 2** | gives a short introduction preliminary sizing and its place in the aircraft design process. |
| **Chapter 3** | consists of the anaylis of the certification requirements for Part 23, Part 25 and CS-VLA |
| **Chapter 4** | gives an insight on the equations used for preliminary sizing I, mostly based on the lectures of Prof. D. Scholz **(Scholz 2012)**. |
| **Chapter 5** | gives a short theoretical background on airplane drag and explains the new method that is implemented in the tools for estimating the Oswald Factor. |
| **Chapter 6** | describes how SAS Optimization Part 25 Jet was build, starting from Opera and how SAS Optimization Part 25 Prop was modified to become SAS Optimization Part 23 Prop. |
| **Chapter 7** | should be regarded as a users guide to the developed tools where the structure of the tools is described with a suggested working method. |
| **Chapter 8** | contains the final conclusion |
| **Appendix A** | is an overview of the used and calculated statistical data |
| **Appendix B** | overviews the codes for the different macros for SAS Optimization Part 25 Jet |

# 2 Introduction to Preliminary Sizing

Preliminary Sizing is an important phase in airplane design, therefore this part will explain a bit more about the design process of an airplane.

Airplane design can be considered as an art and a science, which is closely connected to airplane performance. Airplane design and performance can almost be called twins. To get a good definition of airplane design, **Anderson 1999** states it as follows:

> *Airplane design is the intellectual engineering process of creating on paper (or on a computer screen) a flying machine to (1) meet certain specifications and requirements established by potential users (or as perceived by the manufacturer) and/or (2) pioneer innovative, new ideas and technology.*

## 2.1 Mission Specifications and Requirements

To design an airplane, a mission specification is needed. The mission specification defines certain requirements. These requirements are unique and different for each new airplane design. Typical requirements are:

- Range
- Take-off distance
- Stalling velocity
- Endurance
- Maximum velocity
- Fuel reserves
- Climb requirements
- Manoeuvring requirements
- Service ceiling
- Cost
- Maximum size
- **Certification Base**

…

## 2.2 Definition of Preliminary Sizing

These mission specifications will be translated into numerical definitions of critical airplane design parameters such as:

- maximum lift coefficient $C_{L,max}$;
- lift to drag ratio, *L/D*;
- wing loading, *W/S*;
- thrust-to-weight ratio, *T/W*;

This translation of mission specifications to numerical definitions of the design parameters is called preliminary sizing. Preliminary sizing gives a first abstract view on the overall shape, size, weight and performance of the new design. This means the output of the preliminary sizing is a first layout of the airplane configuration, which can still be slightly changed during the following design phase. After the preliminary sizing an important question should be asked: can this design meet the specifications? Therefore preliminary sizing is an important and decisive step in the airplane design process, as it will determine if the design will result in a full-scale design-development. If the design meets the specifications the next step will be optimization. Optimization is making sure that the design meets the specifications in the most optimal and economical way.

## 2.3 Preliminary Design

Next step in the airplane design process is the preliminary design phase. In this phase only minor changes are made to the configuration layout. Preliminary design is a more detailed design phase where questions are asked as: what systems are needed to control this airplane? How will the air flow around the airplane? Is there undesirable aerodynamic interference? What about stability? All these questions will define the precisely defined configuration or cancel the full-scale design development of the airplane.

**Figure 2.1** gives a visualization of the overall design process.

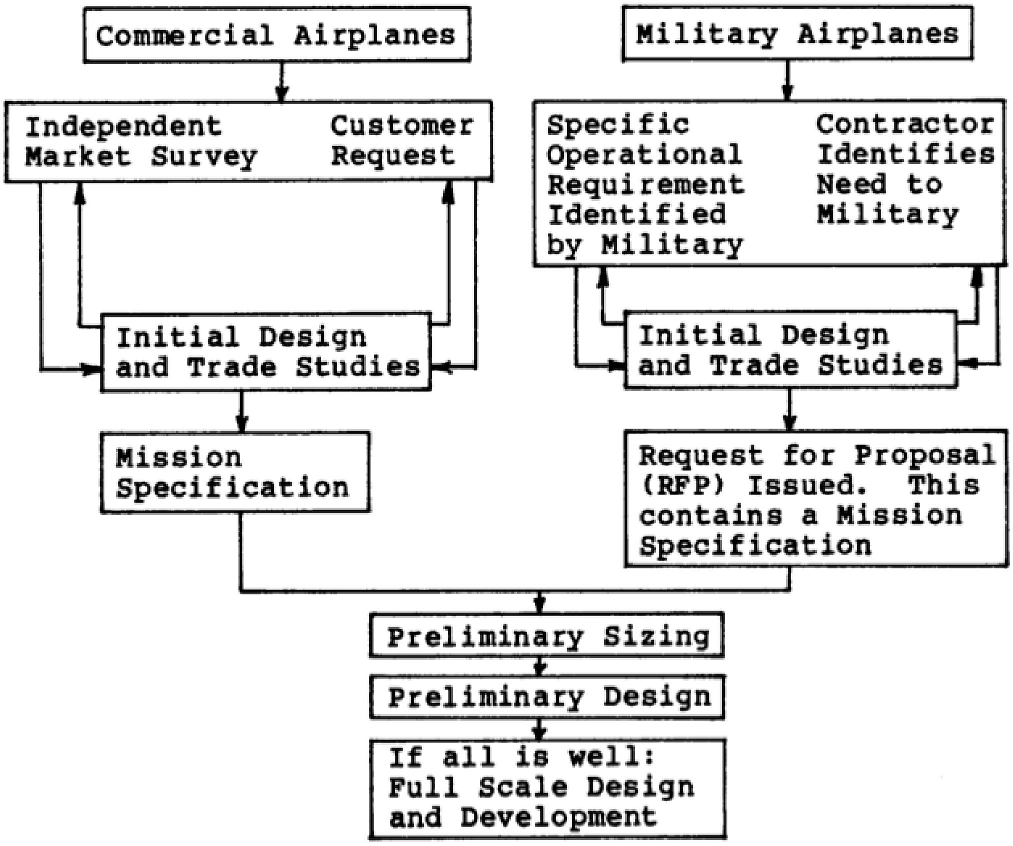


**Figure 2.1** Evolution of a design (**Roskam**)

# 3 Airworthiness Requirements

In this part of the thesis the limitations and requirements defined by the different certification rules will be discussed. It is important to remark that only those limitations or requirements will be discussed that will influence the preliminary sizing. Later on in this thesis the used equations will be explained based on this part of the thesis.

According to FAA regulations these requirements are defined in the different FAR parts, e.g. **FAR PART 23**. According to the European EASA regulations these requirements are stated in the different CS parts, e.g. **CS-23**. There are not too many differences between FAA or EASA regulations and therefore they will not be discussed separately.

## 3.1 Part 23

With Part 23, both **CS-23** and **FAR PART 23** is meant. Part 23 defines the certification requirements for airplanes in the normal, utility, aerobatic and commuter categories. It dictates the standards required for issuance and change of type certificates for airplanes in these categories.

### 3.1.1 Applicability

It is very important for further use of the requirements to know exactly which airplanes Part 23 defines. According to **FAR 23.1, FAR 23.3** and **CS 23.1**. Part 23 states its applicability to airplanes in the normal, utility and aerobatic categories with a maximum number of nine passengers, pilot(s) excluded, and a MTOW of not more than 5670 kg. In case the airplane is a propeller-driven twin engined airplane in the commuter category a maximum of nineteen passengers, pilot(s) excluded, is stated together with a MTOW of 8618 kg.

### 3.1.2 Stall Speed

The passage about stall speed according to CS-23 is quoted here, more details can be found in the regulations.

> **CS 23.49 Stalling speed**
>
> (c) Except as provided in sub-paragraph (d) of this paragraph, VSO at maximum weight must not exceed 113 km/h (61 knots) for –
> (1) Single-engined aeroplanes; and
> (2) Twin-engined aeroplanes of 2 722 kg (6 000 lb) or less maximum weight that cannot meet the minimum rate of climb specified in CS 23.67 (a) (1) with the critical engine inoperative.
> (d) All single-engined aeroplanes, and those twin-engined aeroplanes of 2722 kg (6 000 lb) or less maximum weight, with a VSO of more than 113 km/h (61 knots) at maximum weight that do not meet the requirements of CS 23.67(a)(1), must comply with CS 23.562(d).

The climb requirements defined in **FAR 23.67(a)(1)** and **CS 23.67(a)(1)** state that the airplane has to be able to maintain a minimum steady climb gradient of 1,5 % at a pressure altitude of 1524 m with the critical engine inoperative. In case this requirement can't be met, additional requirements regarding structural strength are stated in **CS 23.562(d)**. For single-engined airplanes it is of course impossible to meet the OEI requirement.

What can be decided is that for Part 23 there is not really a stall speed requirement because when it is not met, additional requirements are stated. Therefore there is a choice to meet or not meet this stall speed limit.

### 3.1.3 Take-off

For the normal, utility and aerobatic categories, the take take-off distance is defined according to **FAR 23.53** and **CS 23.53**, quoted here.

> **CS 23.53 Take-off performance**
>
> (b) For normal, utility and aerobatic category aeroplanes the distance required to take-off and climb to a height of 15 m (50 ft) above the take- off surface must be determined for each weight,
> altitude and temperature within the operational limits established for take-off with –
> (1) Take-off power on each engine;
> (2) Wing flaps in the take-off position(s); and
> (3) Landing gear extended.

In case of a commuter category airplane, it gets a bit more complicated. Key passages regarding the take-off distance requirements for the commuter category airplanes are given here according to **CS-23**, more details can be found in the regulations.

**CS 23.59 Take-off distance and take-off run**

For each commuter category aeroplane, the take-off distance must be determined. The determination of the take-off run is optional.

(a) The take-off distance is the greater of –
- (1) The horizontal distance along the take-off path from the start of the take-off to the point at which the aeroplane is 11 m (35 ft) above the take-off surface, determined under CS 23.57; or
- (2) 115% of the horizontal distance, with all engines operating, from the start of the take-off to the point at which the aeroplane is 11 m (35ft) above the take-off surface, determined by a procedure consistent with CS 23.57.

**CS 23.57 Take-off path**

For each commuter category aeroplane, the take-off path is as follows;

(a) ...
- (2) The aeroplane must be accelerated on the ground to VEF at which point the critical engine must be made inoperative and remain inoperative for the rest of the take-off; and
- (3) After reaching VEF, the aeroplane must be accelerated to V2.

(b) During the acceleration to speed V2, the nose gear may be raised off the ground at a speed not less than VR. However, landing gear retraction must not be initiated until the aeroplane is airborne.

(c) During the take-off path determination, in accordance with sub-paragraphs (a) and (b) –
- (1) The slope of the airborne part of the take-off path must not be negative at any point;
- (2) The aeroplane must reach V2 before it is 11m (35 ft) above the take-off surface and must continue at a speed as close as practical to, but not less than, V2, until it is 122 m (400 ft) above the take-off surface;

**CS 23.55 Accelerate-stop distance**

For each commuter category aeroplane, the accelerate-stop distance must be determined as follows:

(a) The accelerate-stop distance is the sum of the distances necessary to –
- (1) Accelerate the aeroplane from a standing start to VEF with all engines operating;
- (2) Accelerate the aeroplane from VEF to V1, assuming the critical engine fails at VEF; and
- (3) Come to a full stop from the point at which V1 is reached.

This key passage describes a situation where the critical engine becomes inoperative. This is also referred to as the *one engine inoperative* situation or *OEI*.

### 3.1.4 Climb Requirements, All Engines Operative

According to **FAR 23.65** and **CS 23.65** each normal, utility and aerobatic category reciprocating engine-powered airplane of 2722 kg or less MTOW must have a steady climb gradient at sea level of at least 8,3 %. This minimum climb gradient has to be met with the flaps in take-off position and with a climb speed of at least the greater of $1{,}10 \cdot V_{MC}$ or $1{,}20 \cdot V_S$ for single engined airplanes.

Airplanes that have a MTOW of more than 2722 kg and turbine engine powered airplanes in the normal, utility and aerobatic categories have to meet a steady climb gradient of at least 4% with the same climb speed specified for those airplanes with a MTOW of less tan 2722 kg.

For all categories there is an en-route climb requirement that states a minimum climb speed of $1{,}3 \cdot V_S$.

**Table 3.1** Climb requirements with AEO, according to Part 23 specifications

| MTOW | Type of Engine | Climb Gradient | Climb Speed |
|---|---|---|---|
| ≤ 2722 kg | Reciprocating | 8,3 % | $1{,}10 \cdot V_{MC}$ or $1{,}20 \cdot V_S$ |
| ≤ 2722 kg | Turbine | 4 % | $1{,}10 \cdot V_{MC}$ or $1{,}20 \cdot V_S$ |
| ≥ 2722 kg | Reciprocating | 8,3 % | $1{,}10 \cdot V_{MC}$ or $1{,}20 \cdot V_S$ |
| ≥ 2722 kg | Turbine | 4 % | $1{,}10 \cdot V_{MC}$ or $1{,}20 \cdot V_S$ |

### 3.1.5 Climb Requirements, One Engine Inoperative

Both FAR and CS regulations specify a one engine inoperative situation for twin-engined airplanes, this is stated in **FAR 23.66** and **CS 23.66**.

Airplanes in the normal, utility and aerobatic categories with a MTOW of less than 2722 kg and a stall speed higher than 61 knots need to be able to maintain a steady climb gradient of at least 1,5 % at a pressure altitude of 1 524 m (5000 ft) with the critical engine inoperative, the remaining engine at not more than continuous allowed power and a climb speed of at least $1{,}20 \cdot V_S$.

For those airplanes in the normal, utility and aerobatic categories but with a MTOW of more than 2722 kg, the steady climb gradient has to be measurable positive but has to have a minimum value of 0,75 % at 1500 ft, with a climbspeed of $1{,}20 \cdot V_S$.

**Table 3.2** Climb requirements with OEI according to Part 23

| MTOW | Climb Gradient | Climb Speed |
|---|---|---|
| > 2722 kg | 0,75 % (1500 ft) | $1{,}20 \cdot V_S$ |
| ≤ 2722 kg | 1,5 % (5000 ft) | $1{,}20 \cdot V_S$ |

For the commuter category the one engine inoperative requirement requires a minimum climb speed during take-off of at least $V_2$. If the landing gear is retracted, a climb gradient of 2 % is required at a height of 122 m above take-off surface. En-route a steady climb grade of 1,2 % is required at a height of 457 m above take-off surface with a climb speed of not less than $1{,}20 \cdot V_S$

In case of a missed approach the steady climb gradient at a height of 122m above landing surface must not be less than 2,1 %

### 3.1.6 Landing

As defined in **FAR 23.73** and **CS 23.73** the landing approach for all categories should be at least 1,3·$V_S$.

A key passage concerning the landing distance and balked landing is quoted here. According to CS-23.

**CS 23.75 Landing distance**

The horizontal distance necessary to land and come to a complete stop from a point 15 m (50 ft) above the landing surface must be determined, for standard temperatures at each weight and altitude within the operational limits established for landing, as follows:

(a) A steady approach at not less than VREF, determined in accordance with CS 23.73 (a), (b) or (c) as appropriate, must be maintained down to 15 m (50 ft) height and –
  (1) The steady approach must be at a gradient of descent not greater than 5·2% (3°) down to the 15 m (50ft) height.

**CS 23.77 Balked landing**

(a) Each normal, utility and aerobatic category reciprocating engine-powered aeroplane of 2 722 kg (6 000 lb) or less maximum weight must be able to maintain a steady gradient of climb at sea-level of at least 3·3% with –
  (1) Take-off power on each engine;
  (2) The landing gear extended;
  (3) The wing flaps in the landing except that if the flaps may safely be in two seconds or less without loss of position, retracted altitude and without sudden changes of angle of attack, they may be retracted; and
  (4) A climb speed equal to VREF, as defined in CS 23.73 (a).
(b) For normal, utility and aerobatic category each reciprocating engine-powered aeroplane of more than 2 722 kg (6 000 lb) maximum weight and turbine engine-powered aeroplanes in the normal, utility and aerobatic category, the steady gradient of climb must not be less than 2·5% with –
  (1) Not more than the power or thrust that is available 8 seconds after initiation of movement of the power controls from the minimum flight-idle position;
  (2) The landing gear extended;
  (3) The wing flaps in the landing position; and
  (4) A climb speed equal to VREF, as defined in CS 23.73 (b).
(c) For each commuter category aeroplane, the steady gradient of climb must not be less than 3·2% with –
  (1) Not more than the power that is available 8 seconds after initiation of movement of the power controls from the minimum flight idle position;
  (2) Landing gear extended;
  (3) Wing flaps in the landing position; and
  (4) A climb speed equal to VREF, as defined in CS 23.73 (c).

## 3.2 Part 25

With Part 25, both **CS 25** and **FAR PART 25** are meant. There are differences between them but for a general approach these will not be discussed here. Part 25 defines the certification requirements for large airplanes in the normal, utility, aerobatic and commuter categories. It dictates the standards required for issuance and change of type certificates for large airplanes in these categories.

### 3.2.1 Applicability

As said before, it is important to know with which kind of airplanes we are dealing in the category we want to certify. Part 25 is applicable to large turbine powered airplanes. This doesn't say too much as the question could be asked: what is large? In a short manner this can be answered with all the airplanes that have more passenger seats or higher MTOW than those airplanes described by Part 23. This means for jets that once an airplane has more than 9 passenger seats or a MTOW higher than 5670 kg it should meet Part 25 requirements. For propeller-driven airplanes this means that once an airplane has more than 19 passenger seats or a MTOW of more than 8618 kg it should meet Part 25 requirements.

### 3.2.2 Stall Speed

Part 25 doesn't give an exact number for the stall speed but **FAR 25.103** and **CS 25.103** do state that the applicant should define a reference stall speed, $V_{SR}$. This reference stall speed may not be less than a 1-g stall speed and is expressed by following equation:

$$V_{SR} = \frac{V_{CL,MAX}}{\sqrt{n_{ZW}}} \tag{3.1}$$

$V_{CL,MAX}$ CAS obtained during following described manoeuvre with a load-factor corrected lift coefficient. Starting from a stabilized trim condition with the engines idling or zero thrust, longitudinal control has to be applied to decelerate the airplane in order to get a speed reduction of 1 knot per second;

$n_{ZW}$ Load factor normal to the flight path at this manoeuvre. The load factor corrected lift coefficient is given by equation (3.2):

$$C_{LSR} = \frac{n_{zw} \cdot W}{q \cdot S} \tag{3.2}$$

| | |
|---|---|
| $W$ | Gross weight of the airplane |
| $S$ | Aerodynamic reference wing area |
| $q$ | Dynamic pressure |

### 3.2.3 Take-off

Take-off performances will be influenced mostly by the take-off distance and climb requirements. Following part is a key passage quoting the CS-25 requirements influenceing the take-off performance.

**CS 25.113 Take-off distance and take-off run**

(a) Take-off distance is the greater of –
  (1) The horizontal distance along the take-off path from the start of the take-off to the point at which the aeroplane is 11 m (35 ft) above the take-off surface, determined under CS 25.111; or
  (2) 115% of the horizontal distance along the take-off path, with all engines operating, from the start of the take-off to the point at which the aeroplane is 11 m (35 ft) above the take-off surface, as determined by a procedure consistent with CS 25.111. (See AMC 25.113(a)(2), (b)(2) and (c)(2).)

**CS 25.111 Take-off path**

(a) …
  (2) The aeroplanemust be accelerated on the ground to VEF, at which point the critical engine must be made inoperative and remain inoperative for the rest of the take-off; and
  (3) After reaching VEF, the aeroplane must be accelerated to V2.
(b) During the acceleration to speed V2, the nose gear may be raised off the ground at a speed not less than VR. However, landing gear retraction may not be begun until the aeroplane is airborne. (See AMC 25.111(b).)
(c) During the take-off path determination in accordance with sub-paragraphs (a) and (b) of this paragraph –
  (2) The aeroplane must reach V2 before it is 11 m (35 ft) above the take-off surface and must continue at a speed as close as practical to, but not less than V2 until it is 122 m (400 ft) above the take-off surface;

**CS 25.109 Accelerate-stop distance**

(a) The accelerate-stop distance is..
  (2) The sum of the distances necessary to-
    (i) Accelerate the aeroplane from a standing start with all engines operating to the highest speed reached during the rejected take-off, assuming the pilot takes the first action to reject the take-off at the V1 for take-off from a dry runway; and
    (ii) With all engines still operating, come to a full stop on a dry runway from the speed reached as prescribed in sub-paragraph (a)(2)(i) of this paragraph; plus
    (iii) A distance equivalent to 2 seconds at the V1 for take-off from a dry runway.

### 3.2.4 Climb Requirements, All Engines Operative

Both **FAR PART 25** and **CS-25** regulations specify the climb gradient with all engines working only for the landing configuration.

As specified by **FAR 25.119** and **CS 25.119** the climb gradient may not be less than 3,2 % for the landing configuration with the engines at the power or thrust that is available 8 seconds after the moment that the power or thrust controls are changed from the minimum flight idle to the go-around power or thrust setting.

### 3.2.5 Climb Requirements, One Engine Inoperative

Both FAR and CS regulations specify the one engine inoperative requirement for different configurations. These requirements have to be met with the critical engine inoperative and are described in **FAR 25.121** and **CS 25.121**.

For take-off configuration with the landing gear extended, the steady climb gradient must be positive for two-engined airplanes, may not be less than 0,3 % for three-engined airplanes and not less than 0,5 % for four-engined airplanes.

For take-off configuration with the landing gear retracted the steady climb, gradient must be at least 2,4 % for two-engined airplanes, may not be less than 2,7 % for three-engined airplanes and not less than 3 % for four-engined airplanes.

In the en-route configuration, the climb gradient must have a minimum value of 1,2 % for two-engined airplanes, 1,5 % for three-engined airplanes and 1,7 % for four-engined airplanes.

When the airplane is in the approach configuration, the steady gradient of climb may not be less than 2,1 % for two-engined airplanes, 2,4 % for three-engined airplanes and 2,7 % for four-engined airplanes.

An overview is given in **Table 3.3**.

**Table 3.3** Climb gradient in function of configuration and number of engines according to Part 25 specifications.

| Configuration | Number of engines | Climb gradient |
|---|---|---|
| Take-off, landing gear extended | 2 | Positive |
| | 3 | 0,3 % |
| | 4 | 0,5 % |
| Take-off, landing gear retracted | 2 | 2,4 % |
| | 3 | 2,7 % |
| | 4 | 3,0 % |
| En-route | 2 | 1,2 % |
| | 3 | 1,5 % |
| | 4 | 1,7 % |
| Approach | 2 | 2,1 % |
| | 3 | 2,4 % |
| | 4 | 2,7 % |

### 3.2.6 Landing

**FAR 25.125** and **CS 25.125** both define the landing distance as the horizontal distance necessary to land and to come to a complete stop from a point 15 m above the landing surface. This distance has to be determined in landing configuration with an approach speed of at least $1{,}23 \cdot V_{SR}$ that must be maintained till the 15 m height point. The landing must be made without excessive vertical acceleration, tendency to bounce, nose over or ground loop and may not require exceptional piloting skill or alertness.

## 3.3 CS-VLA

The CS-VLA requirements are a lot more compact than the previous discussed certification bases. The key points of CS-VLA have been studied and are explained here. For more information, a look at the full version is suggested and can be downloaded from the EASA site.

### 3.3.1 Applicability

CS VLA airplanes are airplanes with a single engine (spark- or compression-ignition) that have a maximum number of 2 seats, with a MTOW of not more than 750 kg and a stalling speed in landing configuration of not more than 83 km/h (45 knots) CAS. Important notice is that these airplanes may not be used for aerobatic use.

### 3.3.2 Stall Speed

**CS-VLA 49** states that the stall speed may not exceed 83 km/h (45 knots). This requirement will specify a maximum wing loading by use of equation (4.1).

### 3.3.3 Take-off

According to **CS-VLA 51** the take-off distance is defined as the distance necessary to take-off from a dry, level, hard surface and climb over an obstacle of 15 m high. This distance is limited to a maximum of 500 m.

After clearing this obstacle of 15 m high the airplane should have reached a speed of at least $1{,}3 \cdot V_{SR}$.

### 3.3.4 Climb Requirements

A steady climb rate of 2 m/sec is required by **CS VLA 65.** This climb rate has to be met with no more than take-off power, landing gear retracted and flaps in take-off position.

## 3.3.5 Landing

**CS VLA 75 Landing distance**

The horizontal distance necessary to land and come to a complete stop from a point 15 m (50 ft) above the landing surface must be determined, for standard temperatures at each weight and altitude within the operational limits established for landing, as follows:

(a) A steady gliding approach with a calibrated airspeed of at least 1.3 VS1 must be maintained down to the 15 m height.

(c) It must be shown that a safe transition to the balked landing conditions of CS-VLA 77 can be made from the conditions that exist at the 15 m height.

**CS VLA 77 Balked landing**

For balked landings, it must be possible to maintain -

(a) A steady angle of climb at sea level of at least 1:30; or

(b) Level flight at an altitude of 915 m (3 000 ft) and at a speed at which the balked landing transition has been shown to be safe, with –

(1) Take-off power;

(2) The landing gear extended; and

(3) The wing flaps in the landing position, except that if the flaps may be safely retracted in two seconds or less, without loss of altitude and without sudden changes of angle of attack or exceptional piloting skill, they may be retracted.

# 4 Calculating Key Parameters

Following part will give some methods for calculating following parameters that will affect the performance of the airplane:

- Stall speed, $V_s$;
- Take-off distance, $s_{TO}$;
- Approach speed, $V_{APP}$;
- Landing field length, $s_{LFL}$;
- Wing loading, W/S;
- Thrust-to-weight ratio, T/W or power-to-weight ratio, P/W.

The sizing methods will define a range of values for the wing loading, W/S, thrust loading, T/W (or power loading, P/W), which fulfil the required certification specifications. From these values usually the combination of the highest possible wing loading and the lowest possible thrust loading (or power loading) results in an aircraft with the lowest weight and the lowest cost. Therefore these parameters will define the design point.

This part only describes the structures of the equations used in the tools, based on the lecture notes of Prof. D. Scholz **(Scholz 2012)**. These equations are based mostly on Part 25 requirements, later on in this thesis and explanation will be given about the changes that were made in the tool for Part 23. Exact values of the constants for Part 25 and Part 23 are also given there.

## 4.1 Sizing to Stall Speed Requirements

A low stall speed means good field performance but a decrease in stall speed also means a more sophisticated, and therefore more expensive, flap system and/or the wing loading should be lowered. But of course a lower wingloading means bigger wings **(Torenbeek 1986)**.

With a given stall speed a maximum value of the wing loading W/S for a given value of $C_{L,MAX}$ can be calculated **(Roskam)**:

$$\frac{W}{S} = \frac{\rho}{2} \cdot C_{L,MAX} \cdot V_S^2 \tag{4.1}$$

| | |
|---|---|
| $V_S$ | Stall speed |
| $\rho$ | Density |
| $C_{L,MAX}$ | Maximum lift coefficient in landing configuration |

**Table 4.1** can be used as a reference for $C_{L,MAX}$ values.

The wing loading is a very important design parameter, as it will decide the size of the wings. Low wing loading is required to sustain low speed at lift-off and touchdown, whereas high wing loading is suitable at cruise because high speeds generate the required lift on a smaller wing area. The large wing area for take-off and landing results in excess wing for high-speed cruise. To obtain the minimum wing area and satisfy all requirements, a compromise for sizing of the wing area must be found

When choosing the wing loading, the lowest value should be chosen to make sure that the wings are big enough for every flight phase. It is important that all wing loadings are converted to take-off conditions in order to have a correct comparison **(Raymer 1989)**

**Table 4.1** lift coefficient values according to **Roskam** .

| Airplane type | $C_{L,MAX}$ | $C_{L,MAX,TO}$ | $C_{L,MAX,L}$ |
|---|---|---|---|
| Homebuilt | 1.2 – 1.8 | 1.2 – 1.8 | 1.2 - 2.0 |
| Single Engine Propeller Driven | 1.3 – 1.9 | 1.3 – 1.9 | 1.6 - 2.3 |
| Twin Engine Propeller Driven | 1.2 – 1.8 | 1.4 – 2.0 | 1.6 - 2.5 |
| Agricultural | 1.3 – 1.9 | 1.3 – 1.9 | 1.3 – 1.9 |
| Business Jets | 1.4 – 1.8 | 1.6 – 2.2 | 1.6 - 2.6 |
| Regional TBP | 1.5 – 1.8 | 1.7 – 2.1 | 1.9 – 3.3 |
| Transport Jets | 1.2 – 1.8 | 1.6 – 2.2 | 1.8 - 2.8 |
| Military Trainers | 1.2 – 1.8 | 1.4 – 2.0 | 1.6 - 2.2 |
| Fighters | 1.2 – 1.8 | 1.4 – 2.0 | 1.6 - 2.6 |
| Mil. Patrol, Bomb and Transports | 1.2 – 1.8 | 1.6 – 2.2 | 1.8 – 3.0 |
| Flying Boats, Amphibious and Float Airplanes | 1.2 – 1.8 | 1.6 – 2.2 | 1.8 – 3.4 |
| Supersonic Cruise Airplanes | 1.2 – 1.8 | 1.6 – 2.0 | 1.8 - 2.2 |

## 4.2 Sizing to Take-Off Distance Requirements

Take-off distances of airplanes are determined by the following factors:

- Take-off weight, $W_{TO}$
- Take-off speed, $V_{TO}$ (also called lift-off speed)
- Thrust-to-weight ratio at take-off, $(T/W)_{TO}$ (Or weight-to-power ratio, $(P/W)_{\mathrm{TO}}$ and the corresponding propeller characteristics)
- Aerodynamic drag coefficient, $C_{D,G}$ and ground friction coefficient, $\mu_r$
- Pilot technique

Take-off requirements are usually take-off field length requirements. The total take-off distance consists of a ground phase and an airborne phase, illustrated on **Figure 4.1**. The distance covered by the airplane along the runway is called the ground roll, $s_g$, the extra distance covered over the ground after the airplane is airborne but before it clears an obstacle of a specified height is denoted by $s_a$.

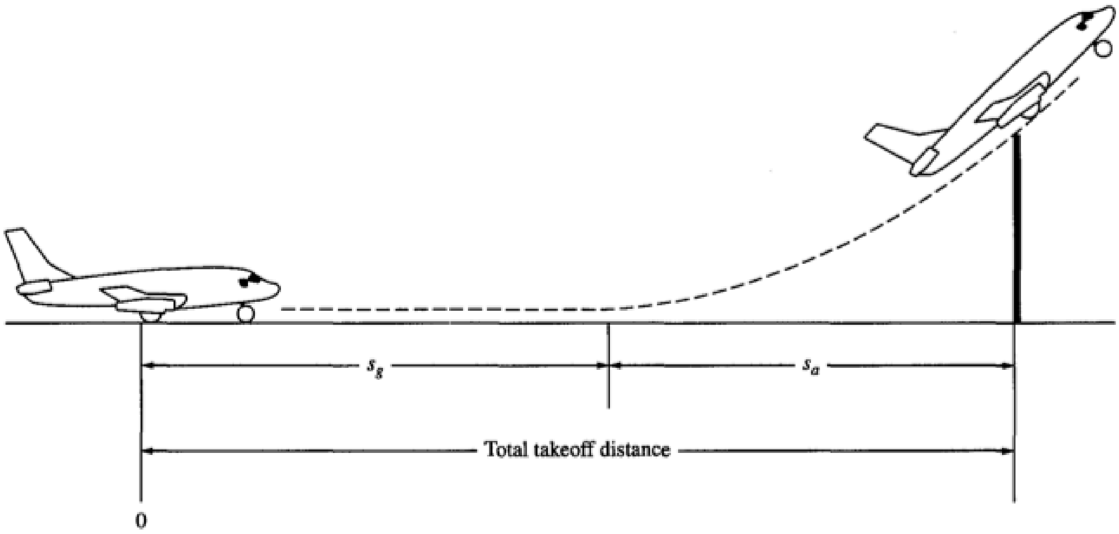


**Figure 4.1** Illustration of the total take-off field length **(Anderson 1999)**

The ground roll $s_g$ can be further divided into intermediate segments, which are defined by various velocities; this is illustrated in **Figure 4.2**.

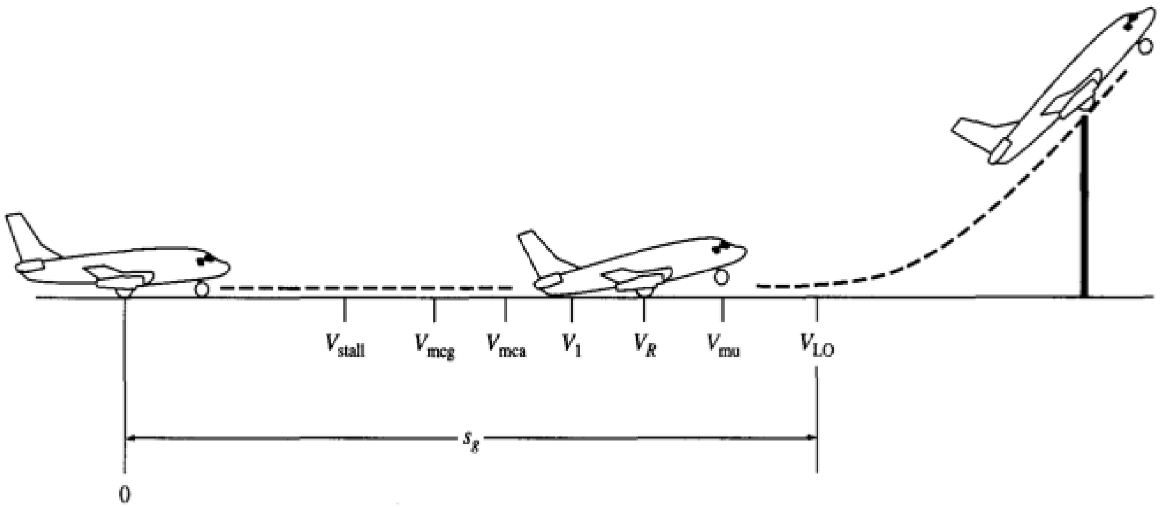


**Figure 4.2** Detailed illustration of the total take-off field length **(Anderson 1999)**

$V_{stall}$ the stalling velocity;

$V_{mcg}$ minimum control speed on the ground, enough aerodynamic force can be generated on the vertical fin with rudder deflection to produce a yawing moment sufficient to counteract that produced when there is an engine failure for a multiengine airplane;

$V_{mca}$ minimum control speed in the air, minimum speed required for yaw control in case of engine failure.

$V_1$ decision speed, speed at which the pilot can successfully continue takeoff even if an engine failure would occur at that point. It is also called critical engine failure speed, if an engine fails before $V_1$ is reached, the take-off must be cancelled;

$V_R$ take-off rotational speed. At this velocity the pilot initiates by elevator deflection a rotation of the airplane, in order to increase the angle of attack and thus $C_L$;

$V_{mu}$ minimum unstick speed;

$V_{LO}$ lift-off speed, this is the point at which the airplane actually lifts off the ground.

Important parameter in defining the accelerate-stop distance is the decision speed $V_1$. This speed can be set arbitrarily but there is only one decision speed where the following applies **(Scholz 2012)**:

| Accelerate-stop distance = Take-off distance OEI |
|---|

The take-off distance resulting from this equality is called the *balanced field length*. This is illustrated in Figure 4.3

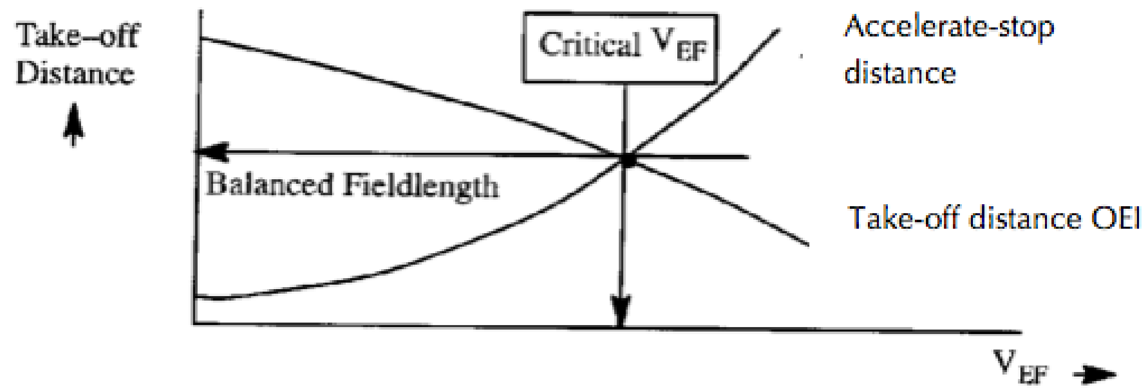


**Figure 4.3** Illustration of the balanced field length **(Roskam 1997)**

The take-off ground roll can be calculated with following equation **(Scholz 2012)**:

$$s_{TOG} = \frac{1}{2} \cdot \frac{m_{TO} \cdot (v_{LOF} - v_W)^2}{T_{TO} - D_{TO} - \mu \cdot (m \cdot g - L_{TO}) - m_{TO} \cdot g \cdot \sin\gamma} \tag{4.2}$$

This equation is simplified in order to get an equation that results in a ratio take-off thrust to weight over wing loading. As a result following equation is obtained and gives a ratio between the thrust-to-weight ratio and the wing loading **(Scholz 2012)**:

$$\frac{\frac{T_{TO}}{m_{MTO} \cdot g}}{\frac{m_{MTO}}{S_W}} = \frac{k_{TO}}{s_{TOFL} \cdot \frac{\rho}{\rho_0} \cdot c_{L,max,TO}} \tag{4.3}$$

| | |
|---|---|
| $k_{TO}$ | proportionality factor for take-off derived from statistical data; |
| $s_{TOFL}$ | take-off field length; |
| $\frac{\rho}{\rho_0}$, | density ratio; |
| $C_{L,max,TO}$ | maximum lift coefficient in take-off configuration. |

In case of a propeller driven airplane equation 4.4 is used:

$$\frac{\frac{P_{TO}}{m_{MTO}}}{\frac{m_{MTO}}{S_W}} = \frac{k_{TO}}{s_{TOFL} \cdot \sigma^{3/2} \cdot c_{L,max,TO}{}^{3/2} \cdot \eta_{Truckenbrodt}} \tag{4.4}$$

| | |
|---|---|
| $\eta_{Truckenbrodt}$ | Truckenbrodt propeller efficiency. |

## 4.3 Sizing to Landing Distance and Approach Speed Requirements

The landing field performance consists of a ground roll and a landing field length. The landing field length is defined as the horizontal distance from a point on which the airplane is 50 ft above the ground to a point on the runway where the airplane is fully stopped. Following factors influences the landing distance of an airplane:

- Landing Weight;
- Approach speed;
- Deceleration method used;
- Flying qualities of the airplane;
- Pilot technique

The approach speed has a square effect on the total landing distance, this is expressed by equation 4.5 (**Loftin 1980)**:

$$V_{APP} = k_{APP} \cdot \sqrt{s_{LFL}} \tag{4.5}$$

In case an approach speed is given, this equation can be transformed to calculate the landing field length:

$$s_{LFL} = (\frac{V_{APP}}{k_{APP}})^2 \tag{4.6}$$

The proportionality factor $k_{APP}$ is derived from statistical data depending on the chosen category. This will be explained further in this thesis as said before.

As the landing field length is related to the approach speed and the approach speed is related to the stall speed, the landing requirements define a maximum wing loading, $(\frac{m_{MTO}}{S_W})$, which can be calculated from four basic equations:

- Equilibrium:

$$m_{ML} \cdot g = \frac{\rho}{2} \cdot V_{S,L}^2 \cdot C_{L,MAX,L} \cdot S_W \tag{4.7}$$

- Loftin statistic:

$$V_{APP} = k_{APP} \cdot \sqrt{s_{LFL}} \tag{4.8}$$

- Minimum approach speed:

$$V_{APP} = 1{,}3 \cdot V_{S,L} \tag{4.9}$$

- Mass ratio:

$$\frac{m_{MTO}}{S_W} = \frac{\frac{m_{ML}}{S_W}}{\frac{m_{ML}}{m_{MTO}}} \tag{4.10}$$

Combining these four equations we get equation 4.11 **(Scholz 2012)**.

$$\frac{m_{MTO}}{S_W} = \frac{k_L \cdot \frac{\rho}{\rho_0} \cdot C_{L,max,L} \cdot s_{LFL}}{\frac{m_{ML}}{m_{MTO}}} \tag{4.11}$$

| | |
|---|---|
| $k_L$ | proportionality factor derived from statistical data; |
| $\frac{\rho}{\rho_0}$, | the density ratio; |
| $C_{L,max,L}$ | maximum lift-coefficient in landing configuration; |
| $s_{LFL}$ | landing field length; |
| $\frac{m_{ML}}{m_{MTO}}$ | mass ratio of maximum landing weight to maximum takeoff weight. |

The density ratio differs from 1 depending on at which temperature (higher or lower than the temperature defined by ISA at sea level) the landing requirements have to be met. The mass ratio has to be chosen and may not be too low, otherwise this might result in a landing mass greater than the maximum landing mass.

## 4.4 Sizing to Climb Requirements

Figure 4.4 shows a detailed image of the climb paths. In this section, the 2nd segment sizing will be discussed.

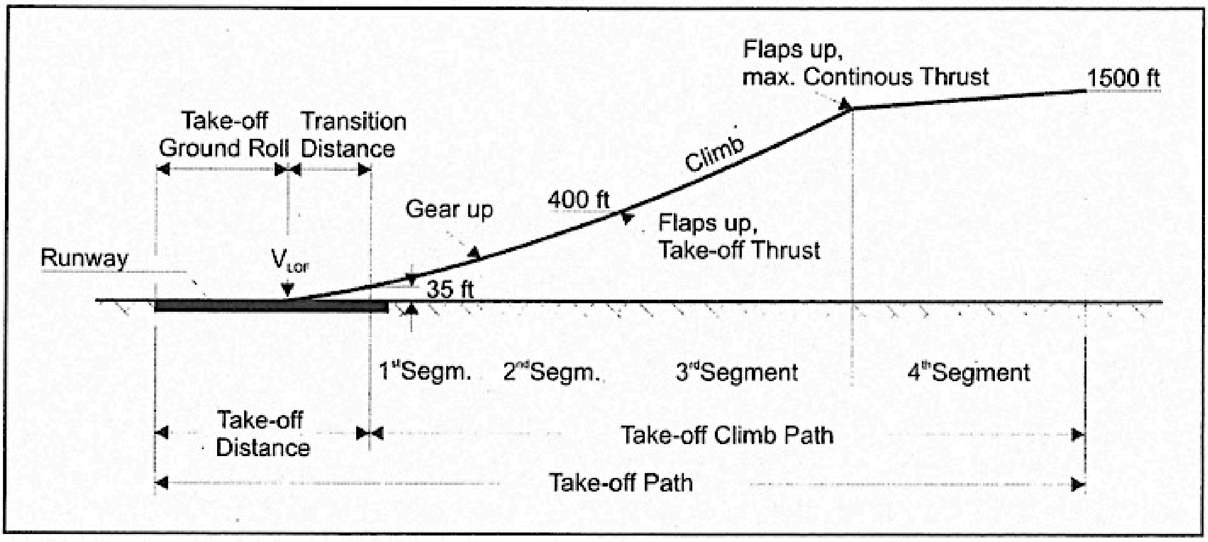


**Figure 4.4** Illustration of the climb paths **(Scholz 2012)**

For the 2nd segment requirement, the certification states a situation where one engine of the airplane is inoperative. In this situation the thrust of the remaining engine(s) still has to be enough in order to climb as required.

To find an equation that can be used in preliminary sizing, the equilibrium condition is analysed. This equilibrium is defined by following two equations:

$$T = D + m \cdot g \cdot \sin \gamma \tag{4.12}$$

$$L = m \cdot g \cdot \cos \gamma \tag{4.13}$$

Because the climb gradient γ is rather small, we can state:

$$L = m \cdot g \cdot cos\gamma \ \approx m \cdot g \tag{4.14}$$

And:

$$sin\gamma \approx \frac{climb\ gradient}{100} \tag{4.15}$$

With all engines operative and by use of previous two equations, the thrust-to-weight ratio is defined by equation 4.16.

$$\frac{T}{m_{TO} \cdot g} = \frac{1}{L/_D} + sin\gamma \tag{4.16}$$

Because of the one engine inoperative statement in Part 25 and Part 23 regulations, the thrust at take-off for all engines has to be higher with a factor $n_E/(n_E\text{-}1)$:

$$\frac{T}{m_{TO} \cdot g} = \left(\frac{n_E}{n_E - 1}\right) \cdot \left(\frac{1}{L/_D} + sin\gamma\right) \tag{4.17}$$

| | |
|---|---|
| $n_E$ | number of engines; |
| $L/_D$ | lift to drag ratio; |
| $\gamma$ | the climb gradient. |

In case of a propeller driven airplane, equation 4.18 is used:

$$\frac{P_{S,TO}}{m_{MTO} \cdot g} = \left(\frac{n_E}{n_E - 1}\right) \cdot \left(\frac{1}{E_{TO}} + sin\gamma\right) \cdot \left(\frac{V_2 \cdot g}{n_{P,CL}}\right) \tag{4.18}$$

## 4.5 Sizing to Missed Approach Requirement

The missed approach situation is similar to the second segment climb requirement with one engine inoperative. After the missed approach, the airplane has to have enough thrust to be able to climb again as required. Therefore equation 4.19 is similar to equation 4.17, only now a mass ratio is added.

$$\frac{T}{m_{TO} \cdot g} = \left(\frac{n_E}{n_E - 1}\right) \cdot \left(\frac{1}{L/_D} + sin\gamma\right) \cdot \frac{m_{ML}}{m_{MTO}} \tag{4.19}$$

Again, the same simplifications for the climb gradient can be made:

$$sin\gamma \approx \frac{climb\ gradient}{100} \tag{4.15}$$

In case of a propeller driven airplane, equation 4.20 is used:

$$\frac{P_{S,TO}}{m_{MTO} \cdot g} = \left(\frac{n_E}{n_E - 1}\right) \cdot \left(\frac{1}{E_{TO}} + sin\gamma\right) \cdot \frac{m_{ML}}{m_{MTO}} \cdot \left(\frac{V_2 \cdot g}{n_{P,CL}}\right) \tag{4.20}$$

# 5 Maximum Glide Ratio in Cruise and Oswald Efficiency Factor

In this part there will be a brief explanation on the calculation of the maximum glide ratio in cruise, $E_{max}$ and the estimation of the Oswald factor, $e$. But in order to understand all this better, there will be a brief theoretical background on airplane drag.

## 5.1 Brief Theoretical Background on Airplane Drag

In airplane design, it is not only important to produce lift, it is also important to produce this lift as efficient as possible. The ratio of lift to drag, *L/D*, gives us an idea on how aerodynamically efficient the lift is produced. The more drag, the less efficient of course.

In order to minimize the drag, the amount of drag that will be produced has to be estimated first. Equation (5.1) gives a simple idea on the amount of drag produced:

$$C_D = C_{D,o} + \frac{C_L^2}{\pi e AR} \tag{5.1}$$

| | |
|---|---|
| $C_D$ | total drag coefficient for the entire airplane; |
| $C_{D,o}$ | parasite drag coefficient for entire airplane at zero lift; |
| $C_L$ | lift coefficient for entire airplane; |
| $AR$ | aspect ratio; |
| $e$ | Oswald efficiency factor. |

The term $C_L^2/(\pi e AR)$ is the drag coefficient due to lift including both induced drag and the contribution to parasite drag due to lift (**Anderson 2011)**. Now this is where the Oswald efficiency factor, $e$ comes in to play. The Oswald efficiency factor is a correction factor for the non-elliptical distribution of lift. For preliminary sizing it is important to get a good estimation of this factor. Therefore a more detailed calculation according to **Nita 2012** is implemented in SAS Optimization.

## 5.2 Estimating the Oswald Efficiency Factor

Following method for estimating the Oswald efficiency factor is the method proposed by M. Nita and D. Scholz (**Nita 2012**).

First step in estimating the Oswald factor is calculating a theoretical Oswald factor, $e_{theo}$. The theoretical Oswald factor is an Oswald factor that is not yet corrected for fuselage interference, zero lift drag influence and Mach number influence **(Nita 2012)**. This theoretical Oswald factor is calculated by use of following equation:

$$e_{theo} = \frac{1}{1+f(\lambda-\Delta\lambda)\cdot AR} \tag{5.2}$$

$f(\lambda - \Delta\lambda)$ is the Hörner function that is corrected by the factor $\Delta\ \lambda$ so that it is useable for swept wings as well. The Hörner function accounts for the viscous component of the Oswald factor and is given by.

$$f(\lambda-\Delta\lambda) = \mathbf{0,0524}(\lambda-\Delta\lambda)^4 - \mathbf{0,15}(\lambda-\Delta\lambda)^3 + \mathbf{0,1658}(\lambda-\Delta\lambda)^2 - \mathbf{0,0706}(\lambda-\Delta\lambda) + \mathbf{0,0119} \tag{5.3}$$

**Figure 5.1** is a plot of the un-shifted Hörner function.

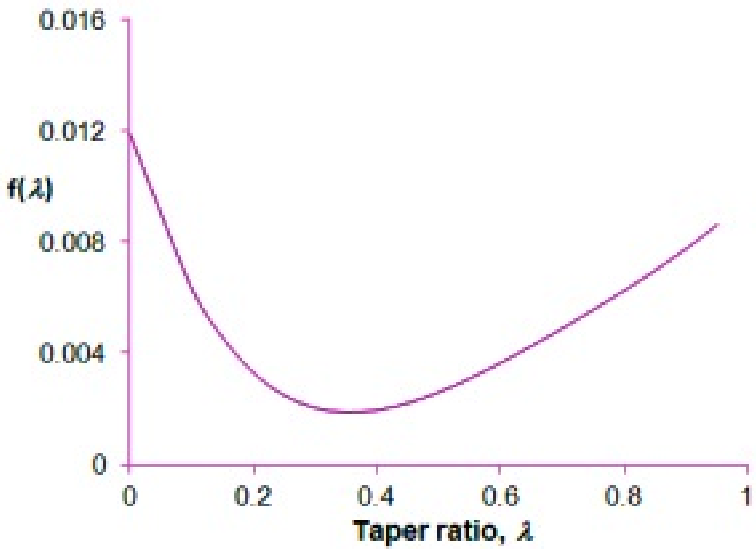


**Figure 5.1** Plot of the Hörner function **(Nita 2012)**

The swept wing shifting correction is given as (**Nita 2012)**:

$$\Delta\lambda = -0{,}375 + 0{,}45 \cdot e^{-0{,}0375\varphi_{25}} \tag{5.4}$$

For each sweep, there is an optimal taper ratio that minimizes the induced drag. This suggested taper ratio for an approximate elliptical wing loading is given as:

$$\lambda_{opt} = 0{,}45 \cdot e^{-0{,}0375\varphi_{25}} \tag{5.5}$$

With $e$ as the Euler number and $\varphi_{25}$ as the wingsweep at 25 % chord line in degrees. For unswept wings, 0,45 is the ideal taper ratio.

As previously said, the theoretical Oswald factor is not yet corrected for fuselage interference, zero-lift drag influence and Mach number influence. Hence, some correction factors have to be added that account for these influences. Following equation for calculating the Oswald efficiency factor is obtained:

$$e = e_{theo} \cdot k_{e,F} \cdot k_{e,D_o} \cdot k_{e,M} \tag{5.6}$$

According to **Nita 2012** $k_{e,F}$ can be obtained if the ratio between fuselage diameter and span is known. $k_{e,D_o}$ is a statistical factor accounting for the change of Oswald Factor based on a change of zero-lift drag depending on the airplane category. Values for these correction factors according to **Nita 2012** are given in **Table 5.1.** Following equation should be used:

$$k_{e,F} = 1 - 2 \cdot \left(\frac{d_F}{b}\right) \tag{5.7}$$

**Table 5.1** Correction factors according to **Nita 2012**

| Airplane Category | $d_F/b$ | $k_{e,F}$ | $k_{e,Do}$ |
|---|---|---|---|
| All | 0,114 | 0,974 | - |
| Jet | 0,116 | 0,973 | 0,873 |
| Business Jet | 0,120 | 0,971 | 0,864 |
| Turboprop | 0,102 | 0,979 | 0,804 |
| General Aviation | 0,119 | 0,971 | 0,804 |

For the Mach number correction $k_{e,M}$ is given as followed by **Nita 2012**:

$$k_{e,M} = \begin{cases} a_e \cdot \left(\frac{M}{M_{comp}} - 1\right)^{b_e} + 1, M \geq M_{comp} \\ 1, M \leq M_{comp} \end{cases} \tag{5.8}$$

Where $a_e$ and $b_e$ are statistically determined factors. For commercial transport airplanes **Nita 2012** gives following values: $a_e$ = -0,001521 and $b_e$ = 10,82.

## 5.3 Estimating Maximum Glide Ratio in Cruise

The glide ratio is an indication on how aerodynamical efficient an airplane is and is visualised in **Figure 5.2** and calculated by use of equation 5.9 **(Scholz 2012)**.

$$E_{max} = k_E \cdot \sqrt{\frac{AR}{S_{WET}/S_W}} \tag{5.9}$$

It is obvious from this equation that the lift-to-drag ratio increases with a higher aspect ratio and a smaller ratio of wetted area to total wing area.

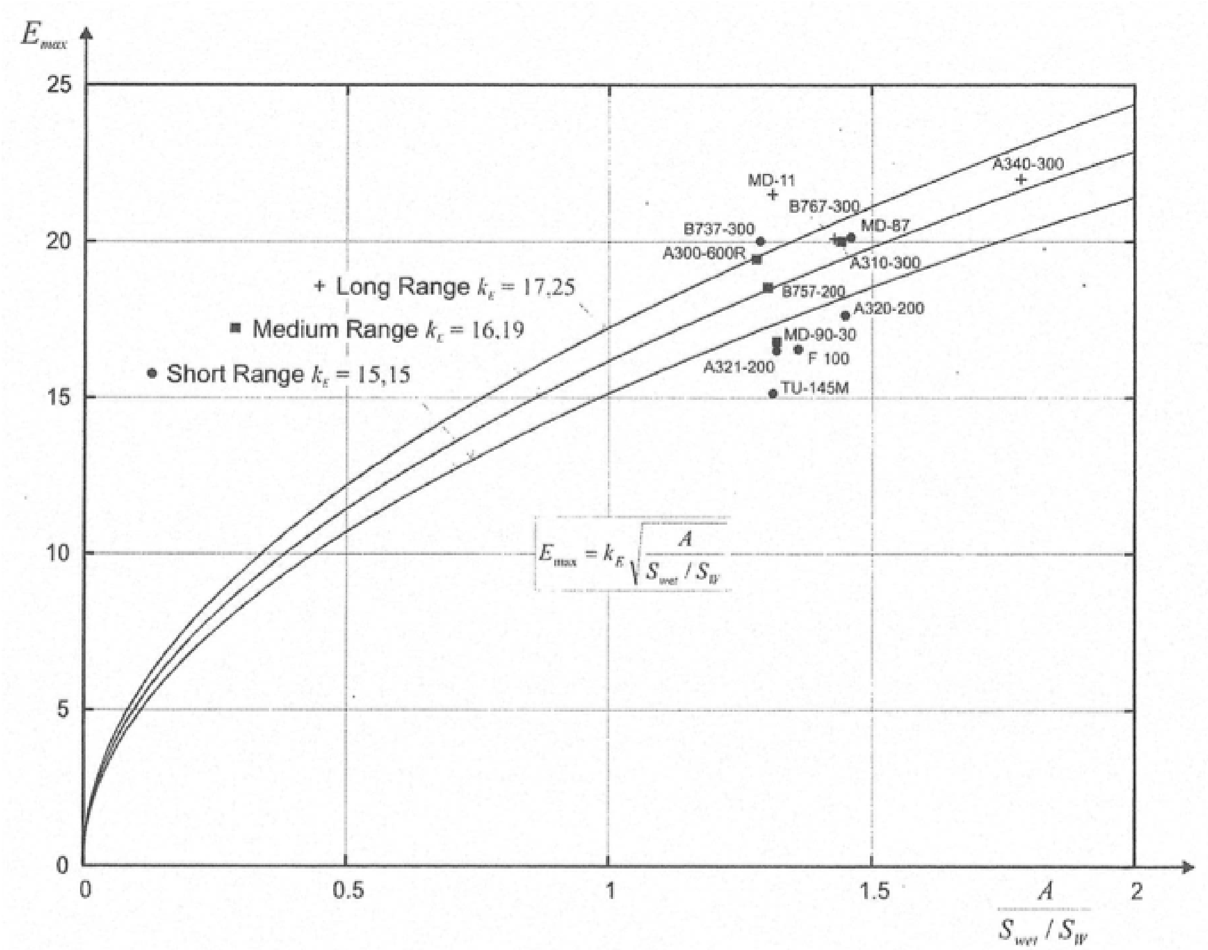


**Figure 5.2** Estimation of glide ratio, wetted area and wing area **(Scholz 2012)**

$k_E$ can be calculated as follows

$$k_E = \frac{1}{2}\sqrt{\frac{\pi e}{C_f}} \tag{5.10}$$

# 6 Building the SAS Optimization Tool for Part 25 and Part 23

This part of the thesis will explain the way of work that is done to build the SAS optimization tool for Part 25. First the general approach will be discussed followed by the changes and extra implementations compared to the SAS Classic tool. An exact copy of the codes of the different algorithms is given in **Appendix B.**

The idea behind building SAS Optimization was to develop a tool that is not that big and complex as OPerA but not that simple as the SAS Classic tool. There was a need for a tool that students could use for simple airplane sizing but with the extra abilities to calculate the Oswald Factor more accurate, calculate the Specific Fuel Consumption and most important do an optimization on the calculated results. The OPerA tool can do all this but is far too detailed for students in order to be able to fully understand the parameters and play around with them without getting confused with parameters where students have no knowledge of.

## 6.1 Getting From OPerA to a Basic Version of SAS Optimization for Part 25

The decision was made to start from the OPerA tool and do top-to-bottom deconstruction of the tool. First idea was to start deleting tab per tab small amounts of cells and see if the tool still works, if not a more detailed look would have been done to see which cell made the tool crash. When this was started, it seemed that this would take a long time, as it was difficult to see what the effect was of deleting one cell because of the big amount of tabs and cells. Therefore a new idea for this deconstruction was used.

In order to get an efficient deconstruction of the tool, a mapping was performed. By mapping following technique is meant.

First step was analysing which tabs should be kept in the final tool and which ones could be deleted. Next step was giving all the tabs each a different colour or patron. After this, each tab that had to stay in the final tool was analysed cell by cell in order to see what was the source for the formula or input in each cell and given the colour of the tab where the data came from. When this was finally finished for all the tabs that had to stay, there was a clear overview on what could be deleted without problem and what had to be made independent from the tabs that would be deleted. **Figure 6.1** gives an example of the mapping view

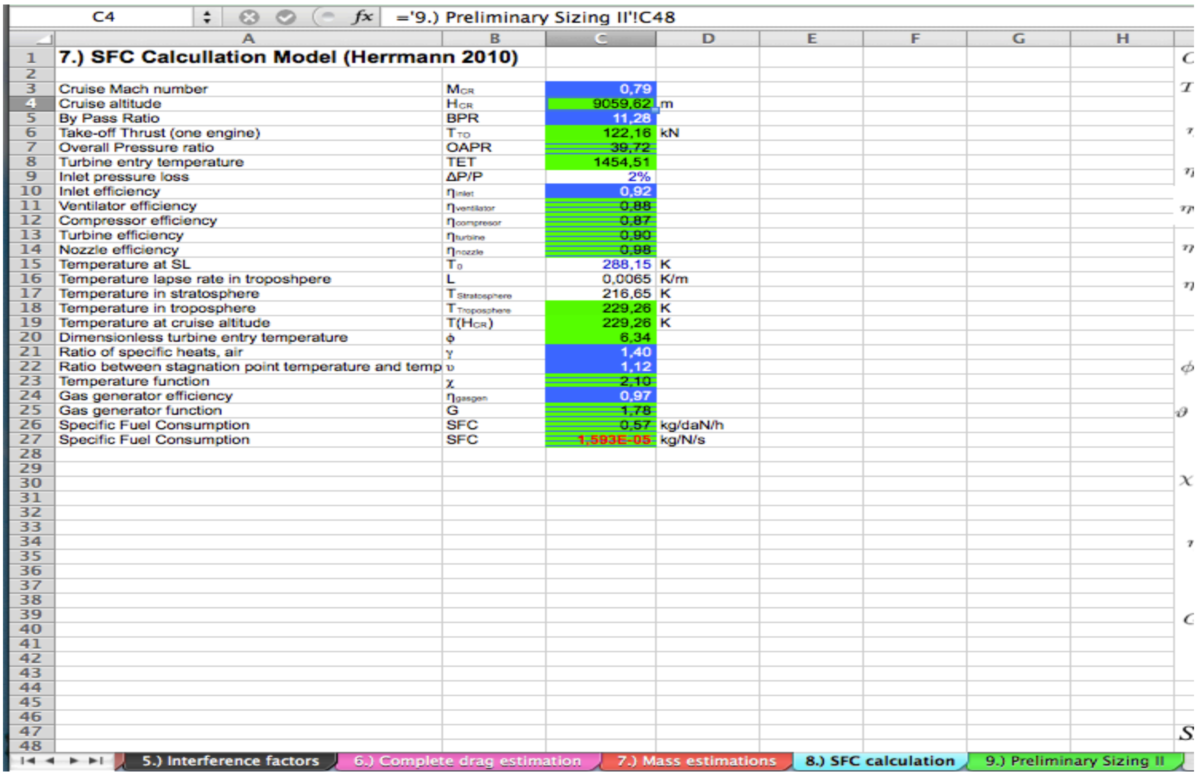


**Figure 6.1** Mapping of the SFC tab

After making these cells independent, the tabs could be deleted entirely instead of cell per cell. This way, it was made sure that the tool would keep on working all the time and no times was lost trying to find what caused the tool to crash.

The result of all this was a basic version of the SAS Optimization tool with already a SFC calculation. Next step would implement the improvements such as the more accurate Oswald factor calculation and making the optimizer work.

## 6.2 Upgrading the Basic SAS Optimization Tool for Part 25 to the Final Version

In order to make the SAS Optimization tool user friendly the idea was brought up of collecting all input and output parameters together with the action buttons on one tab. This meant that the user is able to control the entire tool just with the INPUT tab but can still make relations between input parameters for example the lift coefficients for landing and take-off could be made dependent on each other.

Therefore first step in building the INPUT tab was making sure that all the cells that needed an input before were linked to the INPUT tab.

The user is now also informed on what the lower and upper limit are for the input values. These limits are also used in the optimization algorithm together whit check boxes for optimization parameter selection.

On the input side following extra parameters were added: choosing the design goal, choosing the method for Oswald factor calculation, selection if fuselage outer diameter is known, value for the fuselage outer diameter, selection for the $k_E$ value, selection for method of relative wetted area calculation, selection of the relative empty mass and finally the value for the relative empty mass. **Figure 6.2** shows an image of the input parameters.

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | Parameter | Value | Low | High | | yes/no |
| 2 | S_LFL | 1447,8 | 1400 | 2000 | | no |
| 3 | S_TOFL | 1767,83 | 1500 | 2000 | | no |
| 4 | CL_maxL | 3,392638372 | 2,5 | 3,4 | | no |
| 5 | CL_maxTO | 2,95268798 | 2,5 | 3,4 | | no |
| 6 | mML_to_mMTO | 0,87755102 | 0,86 | 1 | | no |
| 7 | AR | 8,899210334 | 8 | 12 | | yes |
| 8 | n_E | 2 | 2 | 4 | | no |
| 9 | n_PAX | 180 | 100 | 250 | | no |
| 10 | m_cargo | 2516 | 0 | 3000 | | no |
| 11 | Phi_25 | 25 | 0 | 35 | | no |
| 12 | Lambda | 0,213 | 0,15 | 0,5 | | no |
| 13 | t_to_c | 0,119 | 0,1 | 0,2 | | no |
| 14 | BPR | 6 | 7 | 18 | | no |
| 15 | M_CR | 0,714025374 | 0,55 | 0,85 | | yes |
| 16 | Range | 1510 | 1208 | 1812 | | no |
| 17 | Range_type | 1 | 1 | 2 | | no |
| 18 | Reserve_type | 2 | 1 | 2 | | no |
| 19 | Design_goal | 1 | 1 | 6 | | no |
| 20 | Reference_values | 1 | 0 | 1 | | |
| 21 | $k_{APP}$ | 1,79 | | | | |
| 22 | $k_{TO}$ | 2,43 | | | | |
| 23 | $DC_{D,slat,2Seg}$ | 0 | | | | |
| 24 | $k_{a,2Seg}$ | 0,96 | | | | |
| 25 | $DC_{D,slat,MA}$ | 0 | | | | |
| 26 | Choose: Certification basis | FAR Part 25 | | | | |
| 27 | $k_{a,MA}$ | 0,98 | | | | |
| 28 | Select method for oswald factor | Own value | | | | |
| 29 | Own value | 0,783648447 | | | | |
| 30 | Fuselage outer diameter known? | no | | | | |
| 31 | $d_{F,o}$ | --- | | | | |
| 32 | Select method for $k_E$ | Own value | | | | |
| 33 | $k_E$ | 13 | | | | |
| 34 | Select method for relative wetted area | From statistics | | | | |
| 35 | $S_{wet}$ / $S_w$ | --- | | | | |
| 36 | $s_{to\_alternate}$ | 200 | | | | |
| 37 | $M_{ff,taxi}$ | 0,997 | | | | |
| 38 | $M_{ff,TO}$ | 0,993094905 | | | | |
| 39 | $M_{ff,CLB}$ | 0,993094905 | | | | |
| 40 | $M_{ff,DES}$ | 0,993094905 | | | | |
| 41 | $M_{ff,L}$ | 0,993094905 | | | | |
| 42 | Relative operating empty mass, chosen | Own value | | | | |
| 43 | $m_{OE}/m_{MTO}$ (own value) | 0,561142857 | | | | |
| 44 | Select airfoil type | Supercritical | | | | |
| 45 | | | | | | |

**Figure 6.2** Input parameters on the INPUT tab.

After adjusting the INPUT tab, the tab for calculating the maximum glide ratio, $E_{max}$ was changed by calculating the Oswald factor according to **Section 5.2** and the glide ratio according to **Section 5.3**.

Next step taken was making sure the codes of the macros were working again like they used to work on OPerA. In order to do this, not a lot of changes had to be made. Basically the declaration and position defining of what was an input and what was an output value had to be changed. When this was done, decisions were made to add some extras and improvements in the macros.

First macro that was changed was the DP_Fast macro, also known as the macro for finding the design point. This macro is now working according to the design goal that is selected. This macro basically uses the solver to vary the value of $V/V_m$ in order to get a minimum value of the design goal that is selected and by doing this it moves the cruising line on the matching chart.

In SAS Optimization the diagonal macro now also works according to the selected design goal, it will plot a graph of the results, giving the chosen design goal in function of the chosen input parameter that is varied. This way the user gets a general view that shows if the results make sense or not.

In OPerA the differential evolution only gave the results by writing down all the possible airplanes in the Results DE tab, but it did not show what was the optimum airplane according to the chosen output parameter that was varied. In SAS Optimization this is changed. In the new tool it gives an optimum output value based on the design goal that was chosen and a graph that plots the value of the output parameter that is varied according to each iteration. Therefore it is important that in order to get a correct view on the results, the user selects the same output parameter as the design goal.

## 6.3 From SAS Optimization Part 25 Prop to SAS Optimization Part 23 Prop

The tool for Part 23 Prop is build by changing the tool for Part 25 Prop where it was needed. These changes were necessary because of different certification requirements or change in statistical factors. All these changes are explained and discussed here.

### 6.3.1 Stall Speed

As discussed in **Section 3.1.2** the stall speed is not a real requirement, as other requirements can be met instead. But the decision was made to make sure that the tool will work with the 61 knots limitation for single-engined airplanes and twin-engined airplanes with a MTOW equal to or less than 2 722 kg.

In order to implement this requirement in the tool, a stall speed check is added on the PS I tab. If the airplane is a single-engined airplane or a twin-engined airplane with a MTOW equal to or less than 2 722 kg, it will check if the stall speed is not exceeded. When it does not exceed 61 kt it will give a check value of "1" in the output parameters on the INPUT tab, which is used for the optimization. If the airplane is twin-engined with a MTOW of more than 2 722 kg, the check value will also be "1" and the stall speed check on the PS I tab will show "OK" as this requirement does not have to be met for these airplanes.

With a given stall speed, a maximum wingloading can be calculated according to **Section 4.1**. Therefore this is done in the tool now according to equation (4.1) and shown in the Matching Chart.

The wing loading for the design point is defined either by the stall speed requirement or by the landing requirement. The tool will automaticly choose the lower value of these two as the lowest value defines the limit.

### 6.3.2 Approach

**Figure 6.3** shows an illustration of the landing distance defined by Part 23 and discussed in **Section 3.1.9**.

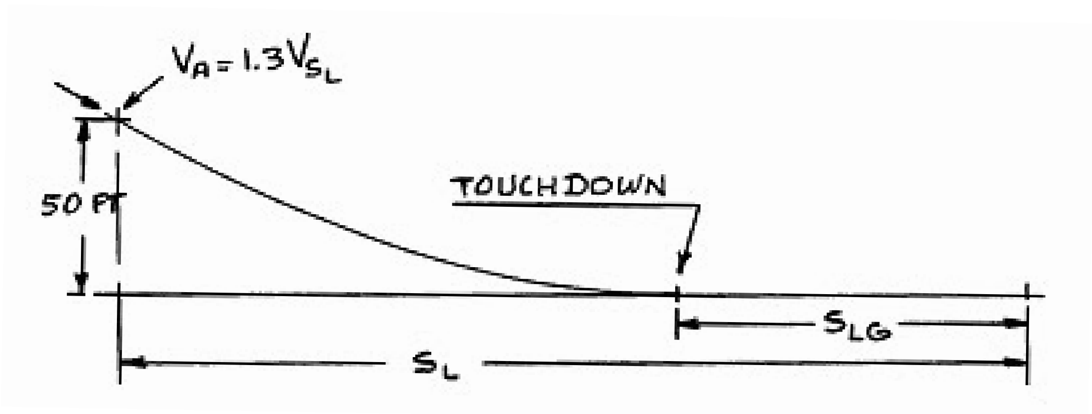


**Figure 6.3** Landing distance according to Part 23 (**Roskam)**

As described in **Section 4.3** by equation 4.5, the approach speed has a square effect on the landing field length, $s_L$:

$$V_{APP} = k_{APP} \cdot \sqrt{s_{LFL}} \tag{4.5}$$

In order to find $k_{APP}$ the most logic thing to do would be to plot the landing field length in function of the square of the approach speed. But as it was very difficult to find complete and useful data of different airplanes, another method was used according to **Roskam.** In this method the first step is defining the relationship between the landing ground run and the square of the stall speed in landing configuration. After this, the relationship between the landing field length and the landing ground run is analysed. The data used, can be viewed in Appendix A

**Figure 6.4** is a graph showing the relationship between the landing ground run (ft) and the square of the stall speed in landing configuration ($\sqrt{m/s}$). This graph suggests following relationship:

$$s_{LG} = 0{,}2711 \cdot V_{SL}^2 \tag{6.1}$$

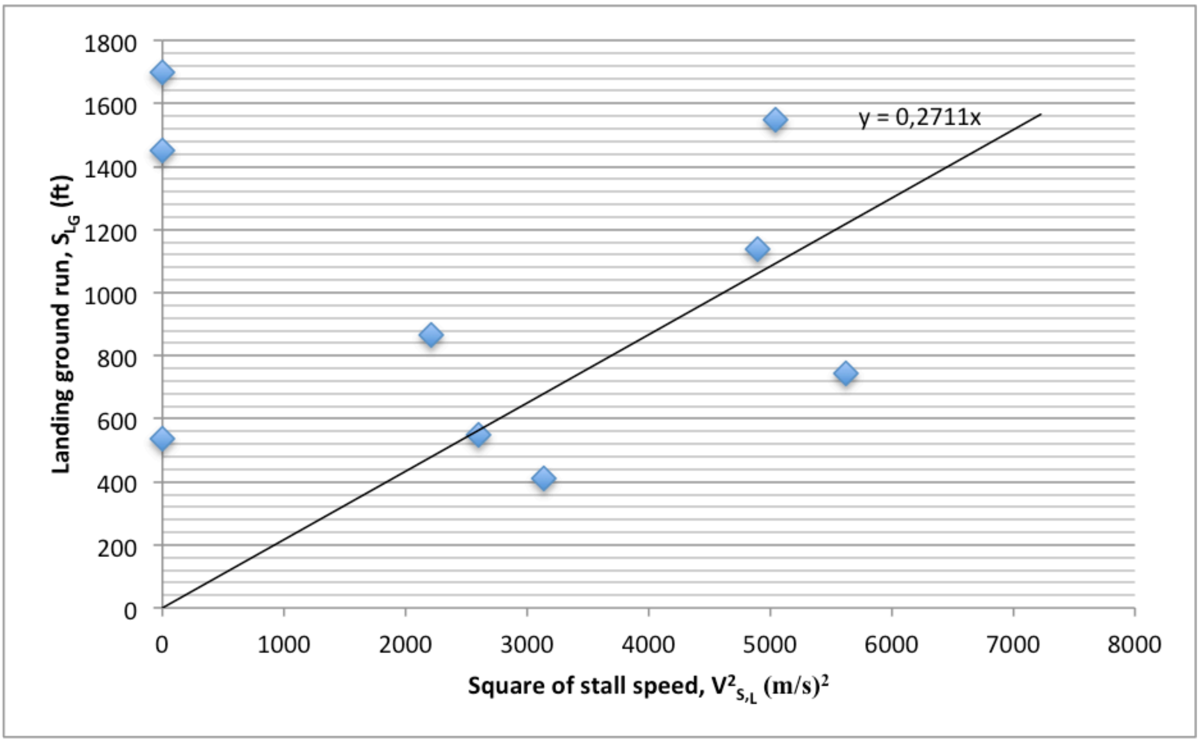


**Figure 6.4** Landing ground run in function of the square of the stall speed

**Figure 6.5** shows the relationship between the total landing field length and the ground run. Following relationship is suggested:

$$s_{LG} = 1{,}855 \cdot s_{LFL} \tag{6.2}$$

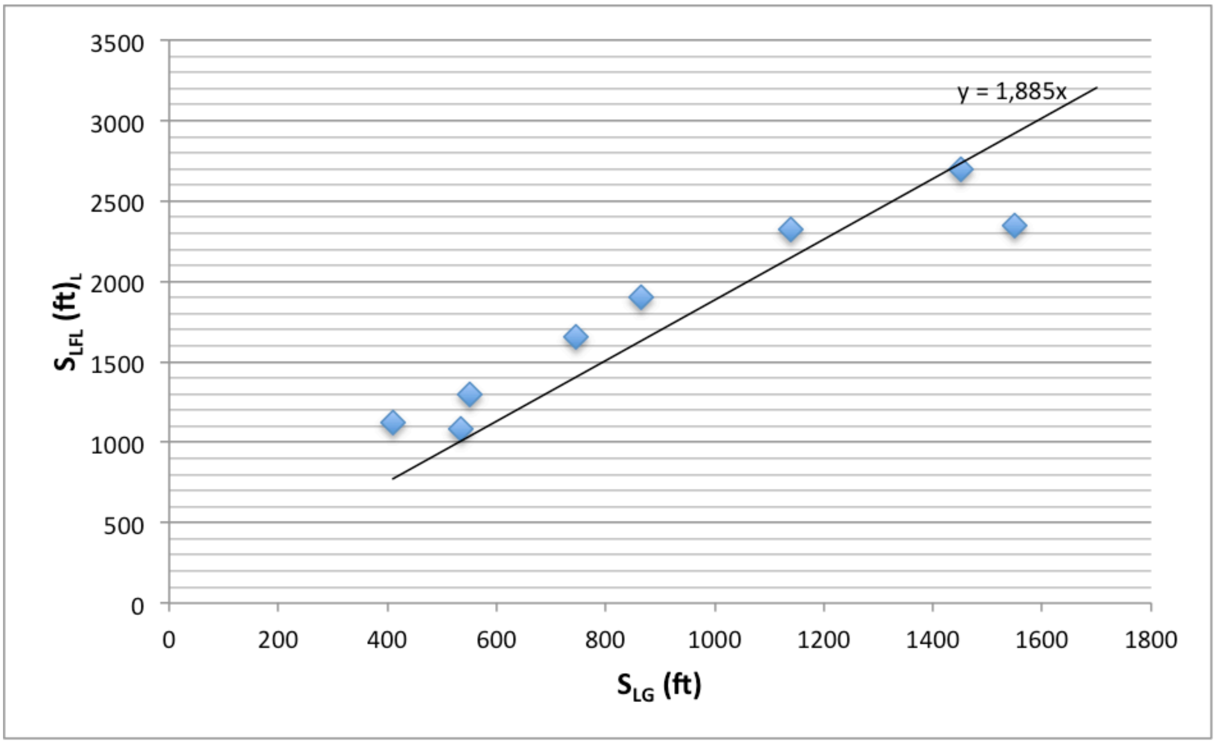


**Figure 6.5** Landing field length in function of landing ground run

Combining equations (4.5), (6,1) and (6,2) and transforming knots into m/s and ft into m, we get following equation:

$$V_{APP} = 1{,}694 \cdot \sqrt{s_{LFL}} \tag{6.3}$$

This value for $k_{APP}$ is based on own statistical research for airplanes defined by Part 23. **Roskam** suggests a value of 1,690. This is an indication that the statistical analysis is correct.

### 6.3.3 Take-off

As shown in **Section 4.2**, equation 4.4 can be used to calculate the wingloading. To do this, it has to be multiplied by the wing loading, which is calculated in the landing section of the tool. But in order to use equation 4.4, a value is needed for $k_{TO}$.

$$\frac{\frac{P_{TO}}{m_{MTO}}}{\frac{m_{MTO}}{S_W}} = \frac{k_{TO}}{s_{TOFL} \cdot \sigma^{3/2} \cdot c_{L,max,TO}{}^{3/2} \cdot \eta_{Truckenbrodt}} \tag{4.4}$$

By re-arranging equation 4.4 to $k_{TO}$, equation 6.4 is obtained:

$$k_{TO} = \left(\frac{P_{TO}/m_{MTO}}{m_{MTO}/S_W}\right) \cdot s_{TOFL} \cdot \sigma^{3/2} \cdot C_{L,MAX,TO}^{3/2} \cdot \eta_{TRUCKENBRODT} \tag{6.4}$$

This equation suggests that we can find an average value of $k_{TO}$ by plotting $\left(\frac{P_{TO}/m_{MTO}}{m_{MTO}/S_W}\right)$ in function of $\frac{1}{s_{TOFL} \cdot \sigma^{3/2} \cdot C_{L,MAX,TO}^{3/2} \cdot \eta_{TRUCKENBRODT}}$. By doing this, **Figure 6.5** is obtained. Out of this figure a value of $k_{TO}$ =75,615 $Wm^4/kg^{5/2}$ is suggested. The data used can be viewed in Appendix A.

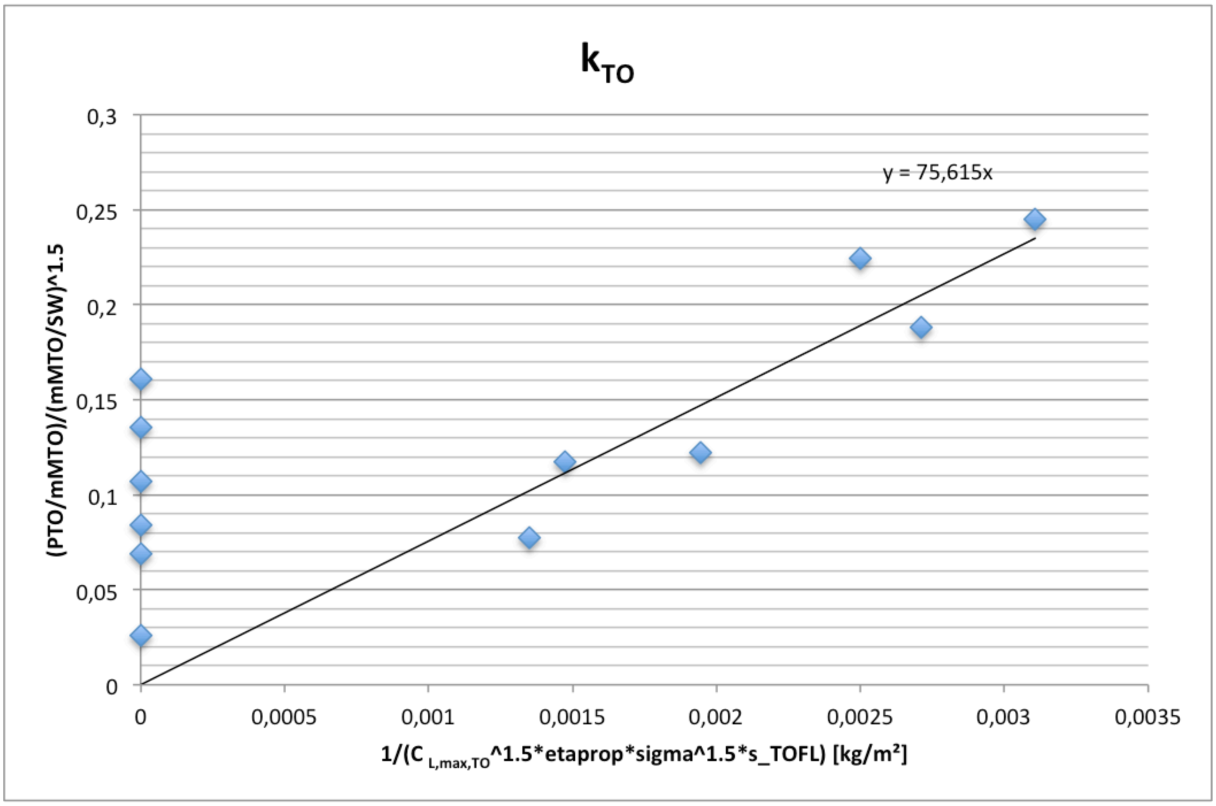


**Figure 6.6** Graph for obtaining $k_{TO}$

In order to check if this value is correct, $k_{TO}$ was calculated for different airplanes in the Part 23 category. These calculations suggest an average value of 72,92 $Wm^4/kg^{5/2}$.

## 6.4 2nd Segment

As described in **Section 3.1.4** for single-engined airplanes there is not a one engine inoperative requirement but there is an all engines operative requirement that requires a climb gradient of 8,3 % for airplanes with a MTOW of less than 2 722 kg and 4 % for airplanes with a MTOW higher than 2 722 kg. To implement this in the tool, the powerloading is calculated for these climb gradients depending on the MTOW and with all engines operative.

For twin-engined airplanes the tool changes the value oft the one engine inoperative climb gradient according to the chosen category. In case of a commuter category airplaine, the value of the one engine inoperative climb gradient is 2 %. For those twin-engined airplanes not in the commuter category, the value is decided to be 0,75 % according to **Section 3.1.5**.

## 6.5 Missed Approach

According to **Section 3.1.5**, the certification requirements specify a missed approach requirement for commuter category airplanes. This requirement is not specified for twin-engined airplanes in the normal, utility and aerobatic categories but is calculated in the tool.

The required climb gradient for commuter category airplanes with one engine inoperative must be at least 2,1 %. This gradient is also used for twin engined airplanes not defined by the commuter category.

In case of a one-engined airplane, the calculated power to mass ratio will have a value of 0, this means the line on the matching chart will shift down.

## 6.6 Engine Choice

In SAS Optimization Part 23 Prop the user can choose a normal piston engine or a turbocharged engine. For the normal piston engine, the tool will keep in account the loss of power due to the fact that the cruise altitude is higher than sea level. The available power can be calculated with following formula:

$$P_{CR} = P_{SL} \cdot [\sigma(1 + C_H) - C_H] \tag{6.5}$$

$P_{SL}$ Power at sea-level

$\sigma$ relative density

$C_H$ constant according to altitude, suggested value: 0,132.

In case of a turbo-charged engine, the tool assumes that the engine is designed in a way that the same power is available at cruise-altitude as at sea level.

# 7 Users Guide to SAS Optimization

In this chapter of the thesis, an explanation will be given on what exactly SAS Optimization is and what it is used for. After this explanation, a users guide is provided in order to be able to work with the tool as a new user.

SAS Optimization is developed mainly for students because of the need to have a tool that can perform simple aircraft sizing like the SAS Classic tool, with the main advantages of the OPerA tool. The OPerA tool is far too complex to understand for students while the SAS Classic tool, doesn't allow automatic optimization and therefore something in the middle was needed.

## 7.1 What is SAS Optimization?

SAS Optimization is a Simple Aircraft Sizing tool with the ability to perform optimization on the preliminary sizing results with a more detailed glide ratio calculation and SFC calculation. It is a Microsoft Excel based tool that uses the Excel Solver and Visual Basic macros.

The main goal of using the tool is to perform the automatic optimization by use of the genetic algorithm used in the OPerA tool. The tool should be used as a sort of reference if the design makes sense, by looking at the matching chart.

## 7.2 Structure of the Tool

To get an overview on how the tool looks like the structure of the tool will be discussed in this section.

When the user opens the tool he or she will see that there are several tabs. These tabs are included in the tool: *INPUT*, *DP*, *PS I*, *Emax Cr*, *PS II*, *SFC*, *MC*, *Results DE* and *Res. DOE Diag*. **Figure 7.1** shows these different tabs in the tool. Each tab has its purpose of course and this will be explained now.

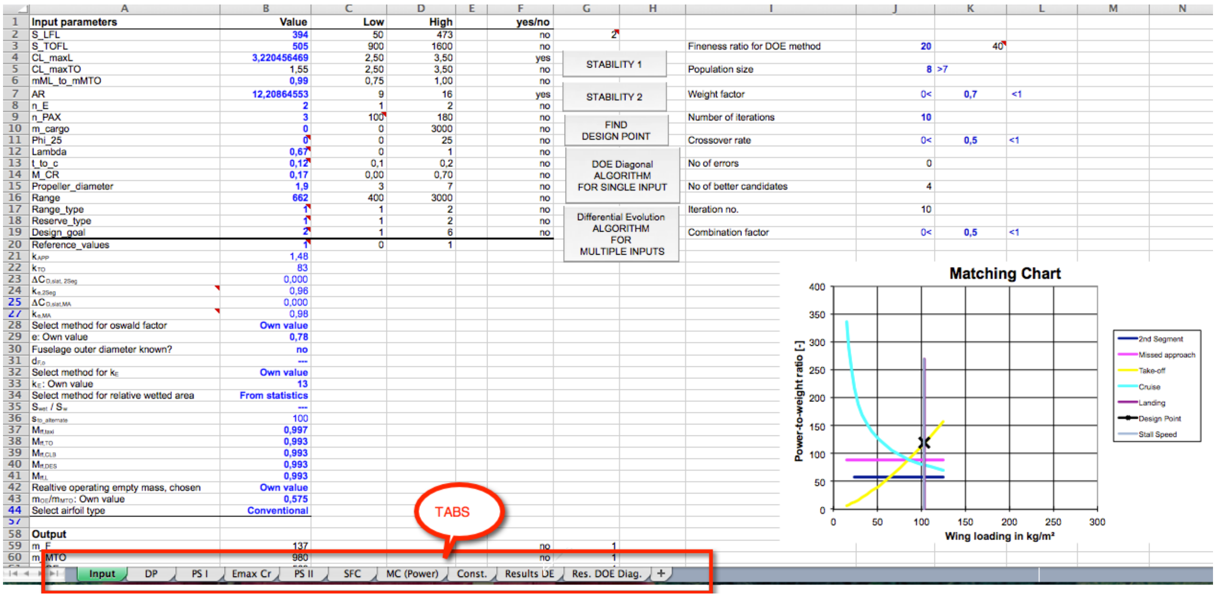


**Figure 7.1** Overview of the different tabs in the tool

### 7.2.1 The Input Tab

First tab, and probably the most important one, is the Input tab. A major advantage of the SAS Optimization tool compared to the SAS Classic tool is the fact that the user completely controls the program from the Input tab. On the Input tab, all input values, the most important output values, the matching chart, optimization set-up and action buttons are gathered. Following blocks can be distinguished on this tab: Input, Output, Matching Chart, Optimization Set-up and the action buttons.

In the Input block, the user fills in the values for the asked parameters. The Low and High columns provide the user with an indication of minimum and maximum values. An important Input is the design goal parameter. This parameter gives the user a choice for an optimization goal, for example the maximum take-off mass can be minimized. Choosing the design goal is done by numbers, each number has a design goal and the different options are given as a comment in this cell. It is important that the user only changes values on the Input tab, by changing values in other tabs, the formulas in the respective cell will be deleted and this might cause an error in the calculation process done by the tool. The user will also notice a column with yes/no, this column is used to select which parameters can be varied for the optimization. **Figure 7.2** shows the Input block.

| Parameter | Value | Low | High | | yes/no |
|---|---|---|---|---|---|
| S_LFL | 1447,8 | 1400 | 2000 | | no |
| S_TOFL | 1767,83 | 1500 | 2000 | | no |
| CL_maxL | 3,392638372 | 2,5 | 3,4 | | no |
| CL_maxTO | 2,95268798 | 2,5 | 3,4 | | no |
| mML_to_mMTO | 0,87755102 | 0,86 | 1 | | no |
| AR | 12 | 8 | 12 | | yes |
| n_E | 2 | 2 | 4 | | no |
| n_PAX | 180 | 100 | 250 | | no |
| m_cargo | 2516 | 0 | 3000 | | no |
| Phi_25 | 25 | 0 | 35 | | no |
| Lambda | 0,213 | 0,15 | 0,5 | | no |
| t_to_c | 0,119 | 0,1 | 0,2 | | no |
| BPR | 6 | 7 | 0 | | no |
| M_CR | [illegible]25374 | 0,55 | 0,85 | | no |
| Range | 1510 | 1208 | 1812 | | no |
| Range_type | 1 | 1 | 2 | | no |
| Reserve_type | 2 | | | | no |
| Design_goal | 2 | | | | no |
| Reference_values | 1 | | | | |
| $k_{APP}$ | 1,79 | | | | |
| $k_{TO}$ | 2,43 | | | | |
| $DC_{D,slat,2Seg}$ | 0 | | | | |
| $k_{e,2Seg}$ | 0,96 | | | | |
| $DC_{D,slat,MA}$ | 0 | | | | |
| Choose: Certification basis | FAR Part 25 | | | | |
| $k_{e,MA}$ | 0,98 | | | | |
| Select method for oswald factor | Own value | | | | |
| Own value | 0,784 | | | | |
| Fuselage outer diameter known? | no | | | | |
| $d_{F,o}$ | --- | | | | |
| Select method for $k_E$ | Own value | | | | |
| $k_E$ | 13 | | | | |
| Select method for relative wetted area | From statistics | | | | |
| $S_{wet} / S_w$ | --- | | | | |
| $s_{to\_alternate}$ | 200 | | | | |
| $M_{ff,taxi}$ | 0,997 | | | | |
| $M_{ff,TO}$ | 0,993 | | | | |
| $M_{ff,CLB}$ | 0,993 | | | | |
| $M_{ff,DES}$ | 0,993 | | | | |
| $M_{ff,L}$ | 0,993 | | | | |
| Relative operating empty mass, chosen | Own value | | | | |
| $m_{OE}/m_{MTO}$ (own value) | 0,5611 | | | | |
| Select airfoil type | Supercritical | | | | |

Design goal

Minimize:
1) Maximum take-off mass
2) Mission fuel mass
3) Operating empty mass
4) Take-off thrust
5) Wing area
6) Adjust the cruise line in the matching chart

**Figure 7.2** Input block on the Input tab

Next block is the Output block; here the most important output values are gathered together with some check values. These check values are an indication for the user if the airplane can actually exist and are used for the optimization in order to only give realistic airplanes in the results. It is important that these checks have a value of “1”. **Figure 7.3** shows the Output block.

| Output | |
|---|---|
| m_F | 12682 |
| m_MTO | 72775 |
| Swet_to_SW | 6,3 |
| m_OE | 40837 |
| SFC | 1,561E-05 |
| V_to_Vmd | 0,96 |
| mMTO_to_SW | 600 |
| T_to_W | 0,329 |
| h_CR | 12337 |
| V_CR | 211 |
| m_ML | 63864 |
| S_W | 121 |
| T_TO | 117419 |
| E | 17,9 |
| C_L | 0,90 |
| E_max | 17,94 |
| Bs | 24589250 |
| CL_maxL_swept | 3,07 |
| Osw | 0,784 |
| Lambda_opt | 0,18 |
| CL_maxTO_swept | 2,68 |
| b_geo | 38,14 |
| mML_Airbus | 64300 |
| check_DP | 1 |
| check_fuel-tank-size | 1 |
| check_fuel | 1 |

Check values

**Figure 7.3** Output block on the Input tab

In the Optimization Set-up block, the user can change the preferences for the Differential Evolution algorithms. **Figure 7.4** shows the set-up parameters.

| | | | |
|---|---|---|---|
| Fineness ratio for DOE method | 15 | 15 | |
| Population size | 8 | >7 | |
| Weight factor | 0< | 0,25 | <1 |
| Number of iterations | 5 | | |
| Crossover rate | 0< | 0,5 | <1 |
| No of errors | 0 | | |
| No of better candidates | 5 | | |
| Iteration no. | 8 | | |
| Combination factor | 0< | 0,75 | <1 |

**Figure 7.4** Optimization Set-up Block on the Input tab

The user should only change following parameters: *Fineness ratio*, *Population size* and *Number of iterations*. The Fineness ratio defines in how many steps the chosen input value will be divided. The population size defines the number of starting values that will be randomized and should have a minimum value of 7. Finaly the number of iterations defines how many iterations the optimizer will perform. Of course the higher these values are, the better the result will be. But this will also take more time for the solver.

The Matching Chart shows the visualisation of the performance parameters. In this chart the design point will be found, which provides the user with the most logic design. More will be explained when the MC tab is discussed. **Figure 7.5** shows an example of the Matching Chart.

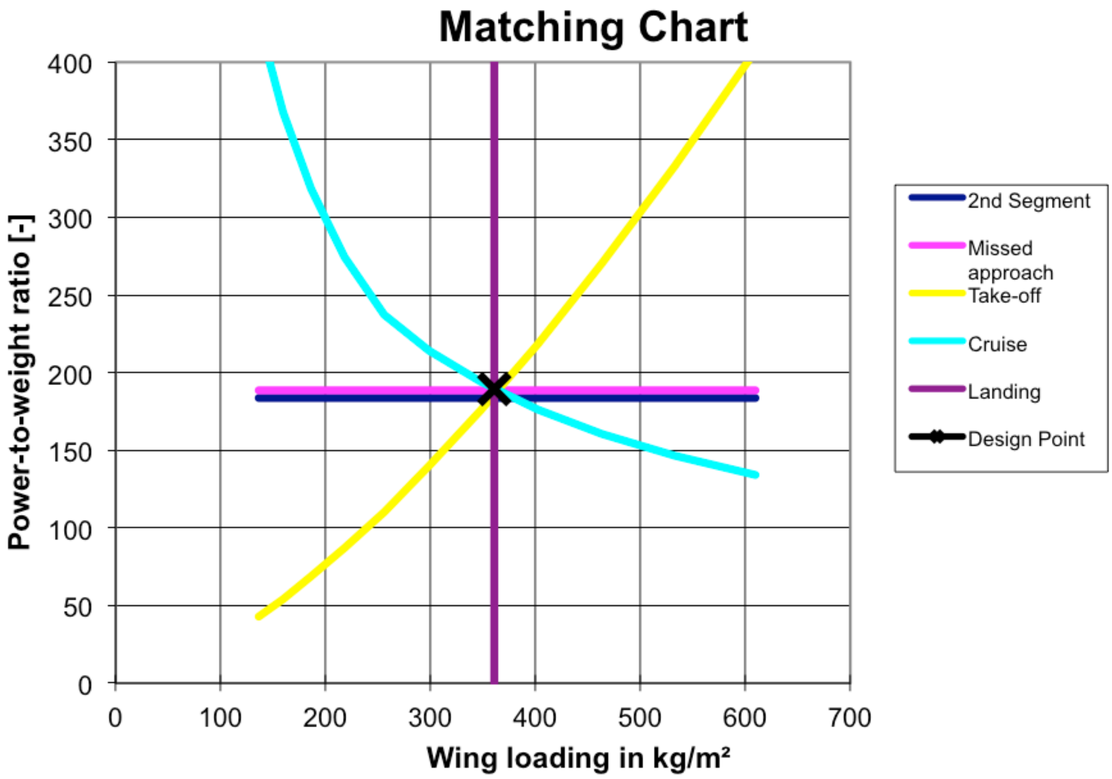


**Figure 7.5** Matching Chart in the Input tab

Final block of the Input tab discussed is the action button block. This block allows the user to perform different actions. Five buttons can be distinguished: *STABILITY 1*, *STABILITY 2*, *FIND DESIGN POINT*, *RUN DOE Diagonal ALGORITHM FOR SINGLE INPUT*, *RUN Differential Evolution ALGORITHM FOR MULTIPLE INPUTS*. **Figure 7.6** shows these buttons.

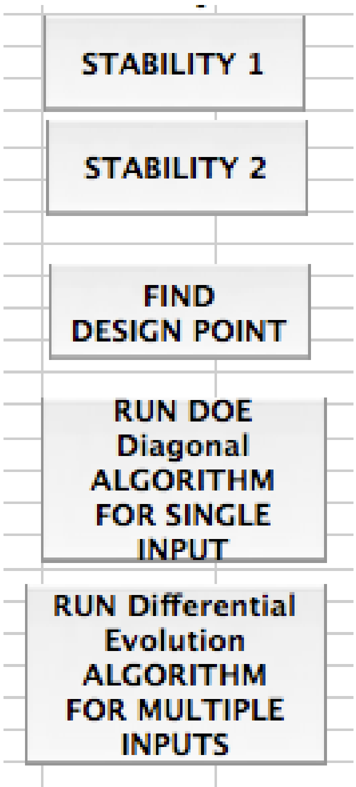


**Figure 7.6** Action Buttons on the Input tab

The *STABILITY 1* and *STABILITY 2* buttons are needed in case the tool "crashes". The tool calculates all the parameters but there are loops in it. This means that when one input value causes an error, for example a Mach number that is too high, most of the calculated values will get an error as well. In order to get out of this loop *STABILITY 1* puts constant values in key cells. By doing this, the tool gets out of the loop, giving the user the chance to change the input value back to a value that is allowed. Because *STABILTY 1* puts these constant values in the key cells, it is necessary to get the formulas back in these cells; this is done by *STABILITY 2*.

*FIND DESIGN POINT* is used to find the most logical design point in the Matching Chart; it does this by shifting the cruise line.

*RUN DOE Diagonal ALGORITHM FOR SINGLE INPUT* is used when the user wants to see the effect of varying one input parameter on one output parameter.

Now the most valuable button probably is the *RUN Differential Evolution ALGORITHM FOR MULTPLE INPUTS* button, as it allows the user to optimize the design by variating multiple input parameters. Here the relationship between input and output randomizes a set of values (the population) to find an optimum combination.

### 7.2.2 The DP Tab

The DP tab is not really useful for the user, but is used by the *FIND DESIGN POINT* macro and the *DIFFERENTIAL EVOLUTION* macro. The design point is defined by the minimum required Thrust- or Power-to-Weight ratio and the maximum allowable wing loading. Therefore the tool looks for the maximum value of Thrust- or Power-to-Weight ratio and the minimum value of wing loading.

The *DIFFERENTIAL EVOLUTION* macro varies the value of *V/Vm* in order to find miminum value for the chosen design goal. These design goals are shown as well in the DP tab. **Figure 7.7** gives an overview on the DP tab

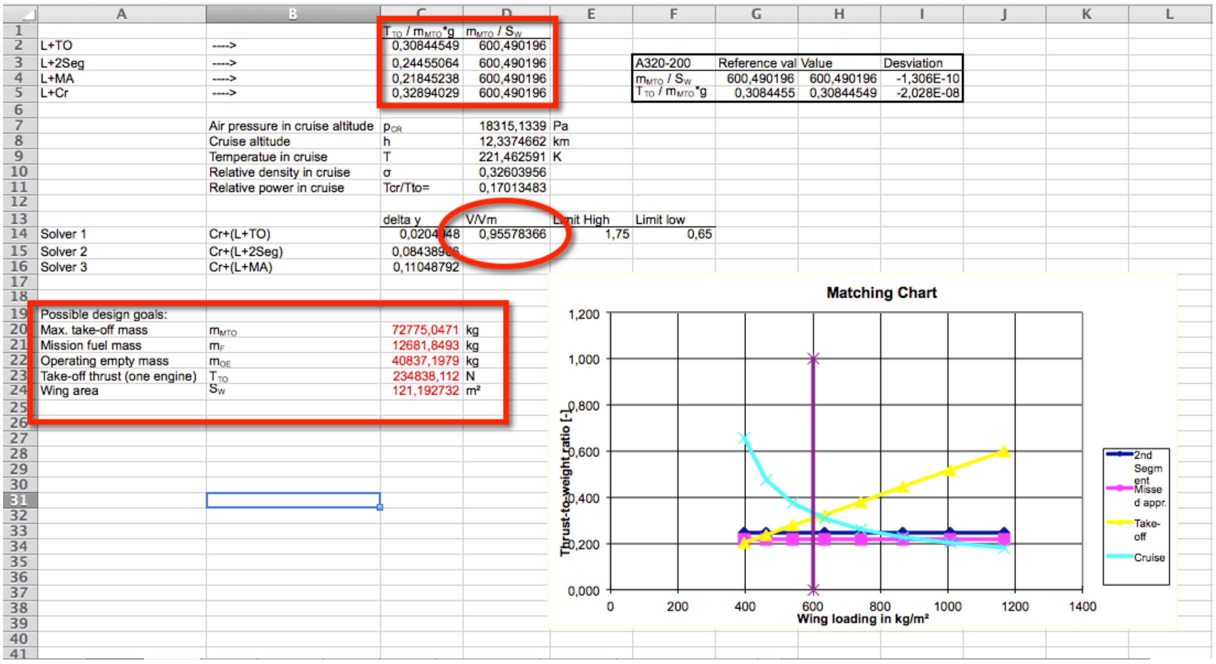


**Figure 7.7** Overview of the DP tab

### 7.2.3 The PS I Tab

The PS I tab, is the tab where the preliminary sizing I is performed, based on **Scholz 2012** and mostly described in **Chapter 4**. Several blocks can be distinguished again: Approach and landing field length calculations, Landing and Take-off calculations and the 2$^{nd}$ Segment block with the climb and missed approach calculations.

| | | | |
|---|---|---|---|
| **Approach** | | | |
| Factor | $k_{APP}$ | 1,79 | $(m/s^2)^{0.5}$ |
| Conversion factor | | 1,944 | kt / m/s |
| | | | |
| **Landing field length** | | | |
| Landing field length | $s_{LFL}$ | 1447,8 | m |
| Approach speed | $V_{APP}$ | 68,1 | m/s |
| Approach speed | $V_{APP}$ | 132,394 | kt |

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

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

**Figure 7.8** Approach and landing field length block on the PS I tab

| | | | |
|---|---|---|---|
| **Landing** | | | |
| Landing field length | $s_{LFL}$ | 1448 | m |
| Temperature above ISA (288,15K) | $DT_L$ | 0 | K |
| Relative density | s | 1,000 | |
| Factor | $k_L$ | 0,118 | kg/m³ |
| Max. lift coefficient, landing for unswept wing | $C_{L,max,L,unswept}$ | 3,393 | |
| Sweep angle, at 25% of chord | $Phi_{25}$ | 25 | ° |
| Max. lift coefficient, landing, as a function of sweep | $C_{L,max,L,swept}$ | 3,07 | |
| Mass ratio, landing - take-off | $m_{ML} / m_{TO}$ | 0,88 | |
| Wing loading at max. landing mass | $m_{ML} / S_W$ | 526,96 | kg/m² |
| Wing loading at max. take-off mass | $m_{MTO} / S_W$ | 600,49 | kg/m² |
| | | | |
| **Take-off** | | | |
| Take-off field length | $s_{TOFL}$ | 1767,83 | m |
| Temperatur above ISA (288,15K) | $DT_{TO}$ | 0 | K |
| Relative density | s | 1,000 | |
| Factor | $k_{TO}$ | 2,43 | m³/kg |
| Max. lift coefficient, take-off for unswept wing | $C_{L,max,TO,unswept}$ | 2,95 | |
| Exprience value for $C_{L,max,TO}$ | 0.87 * $C_{L,max,L,swept}$ | 2,68 | |
| Max. lift coefficient, take-off, as a function of sweep | $C_{L,max,TO,swept}$ | 2,68 | |
| Slope | a | 0,0005137 | kg/m³ |
| Thrust-to-weight ratio | $T_{TO}/m_{MTO}$*g at $m_{MTO}/S_W$ calculated from land | 0,308 | |

| | | |
|---|---|---|
| k_L = | 0,03694455 | * k_App^2 |

$$k_L = 0,03694 \; k_{APP}^2$$

| |
|---|
| A320-200 |
| 3,409 |
| 0,87755102 |
| 526,960784 |
| 600,490196 |

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

$$m_{MTO} / S_W = \frac{m_{ML} / S_W}{m_{ML} / m_{MTO}}$$

$$a = \frac{T_{TO} /(m_{MTO} \cdot g)}{m_{MTO} / S_W} = \frac{k_{TO}}{s_{TOFL} \cdot \sigma \cdot C_{L,max,TO}}$$

**Figure 7.9** Landing and Take-off block on the PS I tab

| | | | |
|---|---|---|---|
| **2nd Segment** | | | |
| | | | |
| **Calculation of glide ratio** | | | |
| Aspect ratio | $A_{eff}$ | | 12,0 |
| Lift coefficient, take-off | $C_{L,TO}$ | | 1,86 |
| Lift-independent drag coefficient, clean | $C_{D,0}$ (bei calcullation: 2. Segment) | | 0,023 |
| Lift-independent drag coefficient, flaps | $DC_{D,flap}$ | | 0,038 |
| Lift-independent drag coefficient, slats | $DC_{D,slat}$ | | 0,000 |
| Profile drag coefficient | $C_{D,P}$ | | 0,061 |
| Oswald efficiency factor; landing configuration | e | | 0,8 |
| Glide ratio in take-off configuration | $E_{TO}$ | | 10,18 |
| Factor for Oswald factor | $k_{e,2Seg}$ | | 0,96 |
| Calculation of thrust-to-weight ratio | | | |
| Number of engines | $n_E$ | | 2 |
| Climb gradient | sin(γ) | | 0,024 |
| Thrust-to-weight ratio | $T_{TO} / m_{MTO}$*g | | 0,245 |
| | | | |
| **Missed approach** | | | |
| Calculation of the glide ratio | | | |
| Lift coefficient, landing | $C_{L,L}$ | | 1,82 |
| Lift-independent drag coefficient, clean | $C_{D,0}$ (bei calcullation: Missed Approach) | | 0,023 |
| Lift-independent drag coefficient, flaps | $DC_{D,flap}$ | | 0,035969662 |
| Lift-independent drag coefficient, slats | $DC_{D,slat}$ | | 0,000 |
| Choose: Certification basis | JAR-25 bzw. CS-25 | no | |
| | FAR Part 25 | yes | |
| Lift-independent drag coefficient, landing gear | $DC_{D,gear}$ | | 0,015 |
| Profile drag coefficient | $C_{D,P}$ | | 0,074 |
| Glide ratio in landing configuration | $E_L$ | | 9,66 |
| Factor for Oswald Factor | $k_{e,MA}$ | | 0,98 |
| Oswald efficiency factor | e | | 0,77 |
| Calculation of thrust-to-weight ratio | | | |
| Climb gradient | sin(γ) | | 0,021 |
| Thrust-to-weight ratio | $T_{TO} / m_{MTO}$*g | | 0,218 |

| $n_E$ | sin(γ) |
|---|---|
| 2 | 0,024 |
| 3 | 0,027 |
| 4 | 0,03 |

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

| | JAR-25 bzw. C | FAR Part 25 |
|---|---|---|
| $DC_{D,gear}$ | 0 | 0,015 |

| $n_E$ | sin(γ) |
|---|---|
| 2 | 0,021 |
| 3 | 0,024 |
| 4 | 0,027 |

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

**Figure 7.10** 2nd Segment block on the PS I tab

### 7.2.4 The Emax Cr Tab

This tab is used for calculating the maximum glide ratio in cruise and is included with a new and more detailed Oswald Factor calculation compared to the SAS Classic tool. The user will notify that there are four main blocks: the estimation of the Oswald Factor, estimation of $k_E$, estimation of the relative wetted area and finally the estimation of the maximum glide ratio in cruise, $E_{MAX,CR}$. Following figures show these blocks.

**Oswald Factor and Max. Glide Ratio in Cruise**

| | | | |
|---|---|---|---|
| **Estimation of Oswald Factor, e** | | | |
| 1.) Own value | e | 0,78 | |
| 2.) Statistical value | e | xxx | |
| 3.) Calculated value | | | |
| Wing aspect ratio | $A_{eff}$ | 12,0 | |
| Suggestion for the wing taper ratio (from Torenbeek) | $l_{sug}$ | 0,176 | |
| Wing taper ratio | l | 0,213 | |
| Corrected Hörner function | f(λ−Δλ) | 0,00192 | |
| | Δλ | -0,180 | |
| Suggestion for the wing sweep angle (from Raymer) | $Phi_{25,sug}$ | 15,9 | ° |
| Wing sweep | $Phi_{25}$ | 25 | |
| Oswald factor, theoretical | $e_{theo}$ | 0,98 | |
| Fuselage outer diameter known? | | no | <<< Select! |
| Fuselage outer diameter | $d_{F,o}$ | --- | m |
| Geometrical span | $b_{geo}$ | 38,14 | m |
| | $d_{F,o}/b_{geo}$ | 0,12 | |
| | $k_{e,F}$ | 0,97 | |
| Factor for zero-lift drag effect | $k_{e,D\_0}$ | 0,873 | |
| Highest Mach number without compressibility effects | $M_{comp}$ | 0,3 | |
| Coefficients of equation | $a_e$ | -0,00270 | <<< from Nita 2012 |
| | $b_e$ | 8,60 | <<< from Nita 2012 |
| | $c_e$ | 1 | |
| Cruise Mach number | M | 0,71 | |
| Ratio: $M/M_{comp}$ | $M/M_{comp}$ | 2,380 | |
| Factor for compresibility effect | $k_{e,M}$ | 0,957 | |
| Oswald Factor, calculated | e | 0,79 | |
| Select method for oswald factor | | Own value | |
| Oswald Factor, chosen | | 0,784 | |

$$e_{theo} = \frac{1}{1 + f(\lambda - \Delta\lambda) \cdot A}$$

$$f(\lambda) = 0.0524\lambda^4 - 0.15 \cdot \lambda^3 + 0.1659\lambda^2 - 0.0706\lambda + 0.0119$$

$$\Delta\lambda = -0.35659 + 0.45 \cdot e^{-0.0375\varphi_{25}}$$

$$k_{e,M} = \begin{cases} a_e\left(\frac{M}{M_{comp}} - 1\right)^{b_e} + c_e, & for\ M > M_{comp} \\ 1, & for\ M \le M_{comp} \end{cases}$$

$$a_e < 0; \quad c_e = 1$$

$$a_e = -0.0027; \quad b_e = 8.6017$$

$$k_{e,F} = 1 - 2 \cdot \left(\frac{d_{F,o}}{b_{geo}}\right)^2$$

$$e = e_{theo} \cdot k_{e,F} \cdot k_{e,D_0} \cdot k_{e,M}$$

**Figure 7.11** Estimation of the Oswald Factor on the Emax,Cr tab

| | | | |
|---|---|---|---|
| **Estimation of $k_E$** | | 0,784 | |
| 1.) From the theory | | | |
| Equivalent surface friction coefficient | $C_{f,eqv}$ | 0,003 | |
| Factor | $k_{E,calc}$ | 14,32 | |
| 2.) From Raymer | | | |
| Factor | $k_E$ | 15,8 | |
| 3.) From own value | | | |
| Faktor | $k_E$ | 13 | |
| Select method for $k_E$ | | Own value | |
| **$k_E$, chosen** | | 13 | |

$$E_{max} = \frac{1}{2}\sqrt{\frac{\pi \cdot A \cdot e}{C_{D,0}}}$$

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

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

$$k_E = \frac{1}{2}\sqrt{\frac{\pi \cdot e}{c_f}}$$

**Figure 7.12** Estimation of the $k_E$ on the Emax,Cr tab

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

| | | | |
|---|---|---|---|
| **Estimation of the relative wetted area** | | | |
| 1.) From statistics | | | |
| Relative wetted area | $(S_{wet}/S_w)_{stat}$ | 6,3 | <<<$S_{wet}/S_W$ = 6.0...6.2 |
| 2.) Own value | | | |
| Relative wetted area | $S_{wet}/S_w$ | --- | |
| Select method for relative wetted area | | From statistics | |
| Relative wetted area, chosen | | 6,3 | |
| **Estimation of Max Glide-Ratio in Cruise, $E_{max}$** | | | |
| Max glide-ratio | $E_{max}$ | 17,94 | |
| Zero-lift drag | $C_{D0}$ | 0,0229 | |

| A320-200 | |
|---|---|
| Emax | 17,6 |
| $S_{wet}/S_w$ | 6,3 |
| Swet | 71 |
| $k_E$ | 14,3 |

**Figure 7.13** Estimation of the relative wetted areas and Max Glide-Ratio in Cruise on the Emax,Cr tab

### 7.2.5 The PS II Tab

On the PS II tab, the user will find more detailed calculations such as the maximum take-off mass, zero fuel mass and take-off thrust. These calculations are highlighted in yellow, as they are important parameters for optimization. **Figure 7.14** shows these parameters on the PS II tab.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Max. Take-off mass | $m_{MTO, Loftin}$ | 72775 | kg | A320-200 | 73500 | kg | -0,00986 |
| Mass ratio, landing - take-off (from Sheet 1) | $m_{ML}$ / $m_{TO}$ | 0,878 | | | | | |
| Max. landing mass | $m_{ML}$ | 63864 | kg | A320-200 | 64500 | kg | -0,00986 |
| Mission fuel fraction, standard flight | $m_F$ | 12682 | kg | A320-200 | 13000 | kg | -0,02447 |
| Wing area | $S_w$ | 121,2 | m² | A320-200 | 122,4 | m² | -0,00986 |
| Take-off thrust | $T_{TO}$ | 234838 | | all engines together | | | |
| Number of engines (from Sheet 1) | $n_E$ | 2 | | | | | |
| T-O thrust of ONE engine | $T_{TO}$ / $n_E$ | 117419 | N | A320-200 | 111200 | N | 0,05593 |
| T-O thrust of ONE engine | $T_{TO}$ / $n_E$ | 26396 | lb | one engine | | | |
| Fuel mass, needed | $m_{F,erf}$ | 12862 | kg | | | | |
| Fuel density | $r_F$ | 800 | kg/m³ | | | | |
| Fuel volume, needed | $V_{F,erf}$ | 16,08 | m³ | | | | |
| Max. Payload | $m_{MPL}$ | 19256 | kg | | | | |
| Max. zero-fuel mass | $m_{MZF}$ | 60093 | kg | A320-200 | 60500 | kg | -0,00672 |
| Zero-fuel mass | $m_{ZF}$ | 60093 | kg | <<<< for information only | | | |
| Fuel mass, all reserves | $m_{F,res}$ | 3551 | kg | | | | |
| Maximum Landing mass: 1.07 * mMZF | $m_{ML,Airbus}$ | 64300 | kg | | | | |
| Check of mass assumptions | check: | $m_{ML}$ | | > | $m_{MZF}$ + $m_{F,res}$ | ? | |
| | | 63864 | kg | > | 63645 | kg | |
| | | | | yes | | | |
| | | | | Aircraft sizing finished! | | | |

**Figure 7.14** Important values for optimization on the PS II tab.

### 7.2.6 The SFC Tab

In the SFC tab, the specific fuel consumption is calculated. This tab is inherited from the OPerA tool and therefore something new compared to the SAS Classic tool. The final result of the calculation is marked in red.

**SFC Calcullation Model (Herrmann 2010)**

| | | | |
|---|---|---|---|
| Cruise Mach number | $M_{CR}$ | 0,71 | |
| Cruise altitude | $H_{CR}$ | 12337 | m |
| By Pass Ratio | BPR | 6 | |
| Take-off Thrust (one engine) | $T_{TO}$ | 117,419 | kN |
| Overall Pressure ratio | OAPR | 21,15 | |
| Turbine entry temperature | TET | 1452 | |
| Inlet pressure loss | ΔP/P | 2% | |
| Inlet efficiency | $\eta_{inlet}$ | 0,944 | |
| Ventilator efficiency | $\eta_{ventilator}$ | 0,879 | |
| Compressor efficiency | $\eta_{compresor}$ | 0,866 | |
| Turbine efficiency | $\eta_{turbine}$ | 0,909 | |
| Nozzle efficiency | $\eta_{nozzle}$ | 0,984 | |
| Temperature at SL | $T_0$ | 288,15 | K |
| Temperature lapse rate in troposhpere | L | 0,0065 | K/m |
| Temperature in stratosphere | $T_{Stratosphere}$ | 216,65 | K |
| Temperature in troposphere | $T_{Troposphere}$ | 207,96 | K |
| Temperature at cruise altitude | $T(H_{CR})$ | 216,65 | K |
| Dimensionless turbine entry temperature | $\phi$ | 6,701 | |
| Ratio of specific heats, air | g | 1,4 | |
| Ratio between stagnation point temperature and temp | u | 1,102 | |
| Temperature function | $\chi$ | 1,533 | |
| Gas generator efficiency | $\eta_{gasgen}$ | 0,98 | |
| Gas generator function | G | 2,25 | |
| Specific Fuel Consumption | SFC | 0,562 | kg/daN/h |
| Specific Fuel Consumption | SFC | 1,561E-05 | kg/N/s |

$$OAPR = 0{,}0266785 \cdot S_{0TW} + 3{,}5168 \cdot BPR + 0{,}0556628$$

$$TET = \frac{-8000}{S_{0TW}} + XXXX$$

$$\eta_{Bläser} = \frac{-5{,}978}{5{,}978 + S_{0TW}} - Ma \cdot 0{,}1479 - \frac{0{,}133498}{0{,}133498 + BPR} + 1{,}05489$$

$$\eta_{Verdichter} = \frac{-2}{2 + S_{0TW}} - \frac{0{,}1171127}{0{,}1171127 + BPR} - Ma \cdot 0{,}0541 + 0{,}9407245$$

$$\eta_{Turbine} = \frac{-3{,}403}{3{,}403 + S_{0TW}} + 1{,}04826 - Ma \cdot 0{,}15533$$

$$\eta_{Düse} = \frac{-2{,}0319}{2{,}0319 + S_{0TW}} + 1{,}00764 - Ma \cdot 0{,}009868$$

$$\phi = \frac{\text{Turbineneintrittstemperatur}}{\text{statische Temperatur in der Höhe H}} = \frac{TET}{t}$$

$$\vartheta = \frac{\text{Staupunkttemperatur}}{\text{statische Außentemperatur}} = \frac{T}{t} = 1 + \frac{\kappa - 1}{2} \cdot Ma^2$$

$$\chi = \vartheta \cdot \left( OAPR^{\left(\frac{\kappa - 1}{\kappa}\right)} - 1 \right)$$

$$G = \left(\phi - \frac{\chi}{\eta_{Verdichter}}\right) \cdot \left( 1 - \frac{1{,}01}{\eta_{Gasgen}^{\frac{\kappa-1}{\kappa}} \cdot (\chi + \vartheta) \cdot \left(1 - \frac{\chi}{\phi \cdot \eta_{Verdichter} \cdot \eta_{Turbine}}\right)} \right)$$

$$SFC = \frac{0.697 \sqrt{\frac{t}{t_0}} \cdot \left(\phi - \vartheta - \frac{\chi}{\eta_{compressor}}\right)}{\sqrt{5 \cdot \eta_{nozzle} \cdot (1 + \eta_{ventilator} \cdot \eta_{turbine} \cdot BPR) \cdot \left(G + 0.2 \cdot M^2 \cdot BPR \cdot \frac{\eta_{compressor}}{\eta_{ventilator} \cdot \eta_{turbine}}\right) - M \cdot (1 + BPR)}}$$

**Figure 7.15** SFC calculation model

### 7.2.7 The MC Tab

An important tab for the user in order to evaluate the design result is the Matching Chart. The Matching Chart is a 2D graphical representation of the optimization problem. The two optimization parameters are: thrust-to-weigt ratio *($T_{TO}/m_{MTO}.g$)* or power-to-weight ratio ($P_{TO}/m_{MTO}.g$) and the wing loading *($m_{MTO}/S_W$)* **(Scholz 2012)**.

The user can distinguish following lines on the chart: 2nd Segment line, Missed approach line, Take-off line, Cruise line, Landing line and the design point. **Figure 7.16** is an example of a Matching Chart.

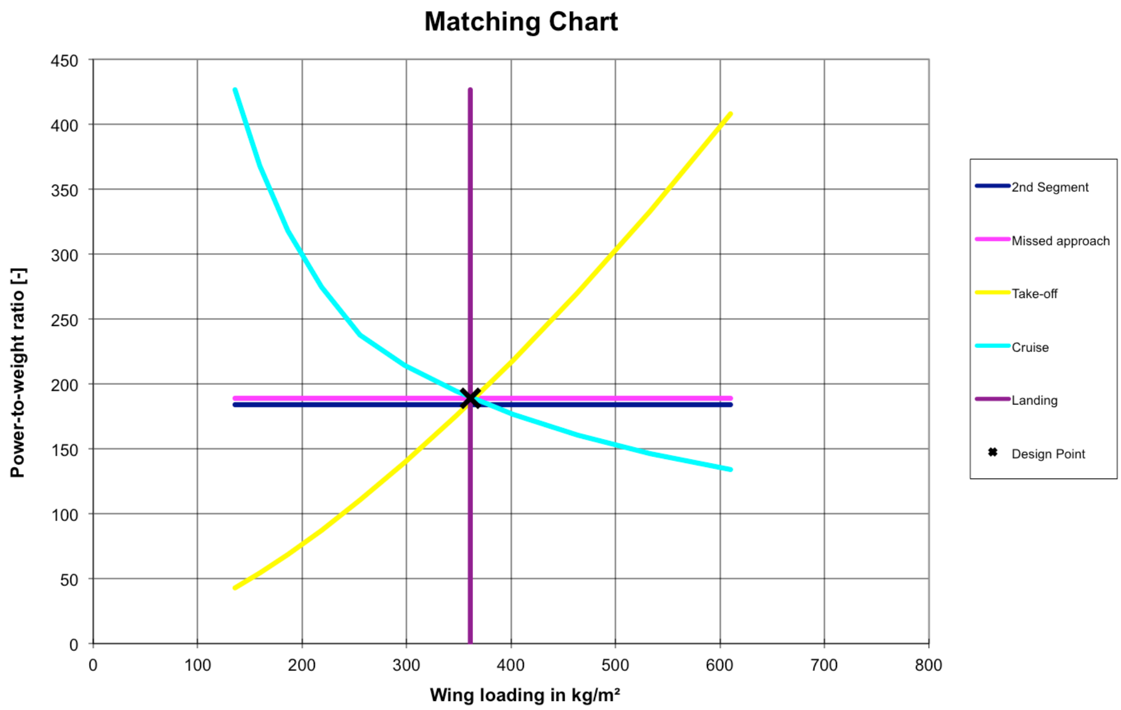


**Figure 7.16** Example of a Matching Chart

### 7.2.8 The Results DE Tab

In the Results DE tab, the user will find the results of the differential evolution. The tool displays all the parameters that define the possible aircraft that result of this differential evolution together with a graph that shows the evolution of the output parameter as function of the iterations. The user will also notice a cell with "output". This cell displays the optimal value for the chosen output parameter. It is important for the user to choose the same output value as the chosen design goal. If this is not done, the tool is not displaying the optimal aircraft for the chosen design goal in the output cell. **Figure 7.17** shows an example of some of the parameters resulting from the differential evolution for each iteration. **Figure 7.18** shows the graph and the output cell.

| A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Iteration | S_LFL | S_TOFL | CL_maxL | CL_maxTO | mML_to_mMT | AR | n_E | n_PAX | m_cargo | Phi_25 | Lambda | t_to_c | M_CR | Propeller_diam | Range | Range_type | Reserve_type | Design_goal |
| | no | no | yes | no | no | no | no | no | no | no | no | no | no | no | no | no | no | no |
| 0 | 1067 | 1290 | 3,245861232 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,44 | 3,93 | 890 | 1 | 1 | 6 |
| 0 | 1067 | 1290 | 3,163001657 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,44 | 3,93 | 890 | 1 | 1 | 6 |
| 0 | 1067 | 1290 | 2,942738831 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,44 | 3,93 | 890 | 1 | 1 | 6 |
| 0 | 1067 | 1290 | 3,337948084 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,44 | 3,93 | 890 | 1 | 1 | 6 |
| 0 | 1067 | 1290 | 3,152320325 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,44 | 3,93 | 890 | 1 | 1 | 6 |
| 0 | 1067 | 1290 | 2,974782825 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,44 | 3,93 | 890 | 1 | 1 | 6 |
| 0 | 1067 | 1290 | 3,241816103 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,44 | 3,93 | 890 | 1 | 1 | 6 |
| 0 | 1067 | 1290 | 3,440716267 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,44 | 3,93 | 890 | 1 | 1 | 6 |
| 4 | 1067 | 1290 | 3,152320325 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,444 | 3,93 | 890 | 1 | 1 | 6 |
| 5 | 1067 | 1290 | 3,152320325 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,444 | 3,93 | 890 | 1 | 1 | 6 |
| 8 | 1067 | 1290 | 3,197068214 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,444 | 3,93 | 890 | 1 | 1 | 6 |
| 10 | 1067 | 1290 | 3,159797257 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,444 | 3,93 | 890 | 1 | 1 | 6 |
| 11 | 1067 | 1290 | 3,120996803 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,444 | 3,93 | 890 | 1 | 1 | 6 |
| 14 | 1067 | 1290 | 3,21496737 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,444 | 3,93 | 890 | 1 | 1 | 6 |
| 15 | 1067 | 1290 | 3,174246791 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,444 | 3,93 | 890 | 1 | 1 | 6 |
| 16 | 1067 | 1290 | 3,150077246 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,444 | 3,93 | 890 | 1 | 1 | 6 |
| 18 | 1067 | 1290 | 3,13822872 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,444 | 3,93 | 890 | 1 | 1 | 6 |
| 19 | 1067 | 1290 | 3,156432638 | 2,66 | 0,99 | 12 | 2 | 68 | 0 | 1,3 | 0,62 | 0,14 | 0,444 | 3,93 | 890 | 1 | 1 | 6 |

**Figure 7.17** Result of differential evolution

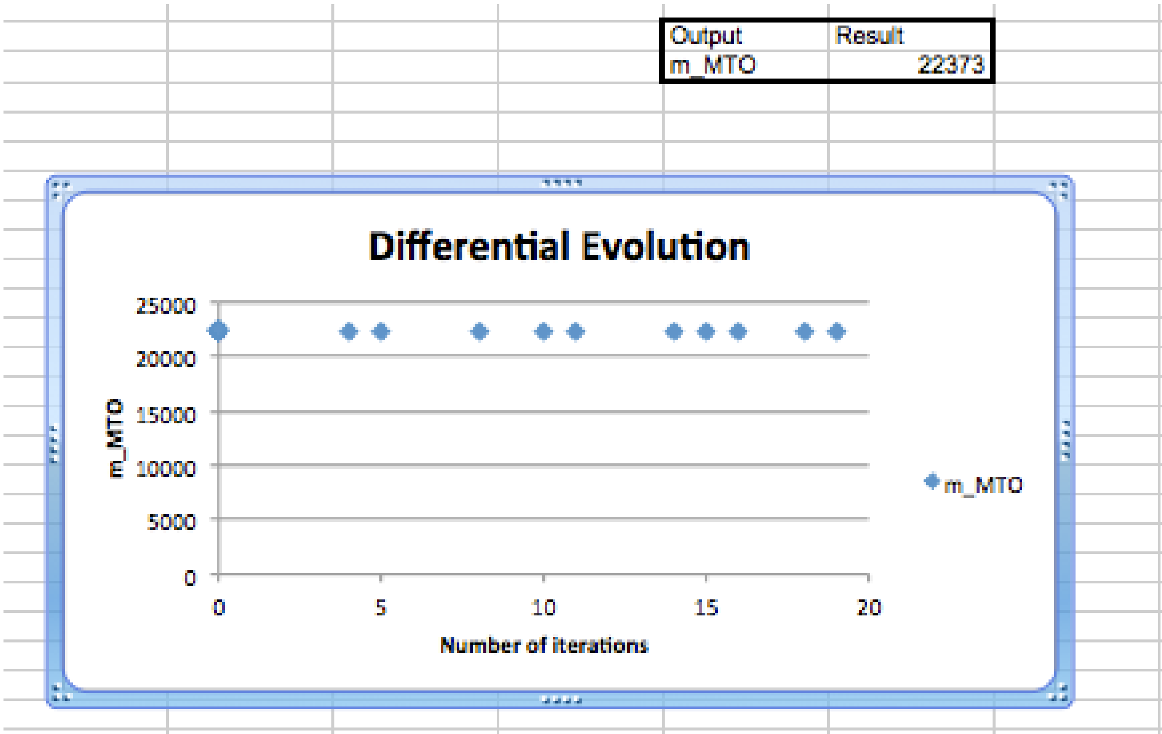


**Figure 7.18** Differential evolution graph and output cell

### 7.2.9 The Results DOE Diagonal Tab

Here the user wil find the results of the diagonal algorithm. Just as in the Results DE tab, the tool displays all the resulted airplanes according to each variation of the chosen input parameter together with a graph that shows the evolution of the output parameter in function of the varied input parameter. **Figure 7.19** shows the results and **Figure 7.20** shows the graph.

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Parameter | AR | m_MTO | | S_LFL | S_TOFL | CL_maxL | CL_maxTO | mML_to_mMT | AR | n_E | n_PAX | m_cargo | Phi_25 | Lambda | t_to_c | BPR | M_CR |
| 2 | 1 | 8 | 80787,6926 | | 1447,8 | 1767,83 | 3,39263837 | 2,95268798 | 0,87755102 | 8 | 2 | 180 | 2516 | 25 | 0,213 | 0,119 | 6 | 0,71402537 |
| 3 | 2 | 8,26666667 | 80029,6017 | | 1447,8 | 1767,83 | 3,39263837 | 2,95268798 | 0,87755102 | 8,26666667 | 2 | 180 | 2516 | 25 | 0,213 | 0,119 | 6 | 0,71402537 |
| 4 | 3 | 8,53333333 | 79316,7629 | | 1447,8 | 1767,83 | 3,39263837 | 2,95268798 | 0,87755102 | 8,53333333 | 2 | 180 | 2516 | 25 | 0,213 | 0,119 | 6 | 0,71402537 |
| 5 | 4 | 8,8 | 78644,9426 | | 1447,8 | 1767,83 | 3,39263837 | 2,95268798 | 0,87755102 | 8,8 | 2 | 180 | 2516 | 25 | 0,213 | 0,119 | 6 | 0,71402537 |
| 6 | 5 | 9,06666667 | 78010,4334 | | 1447,8 | 1767,83 | 3,39263837 | 2,95268798 | 0,87755102 | 9,06666667 | 2 | 180 | 2516 | 25 | 0,213 | 0,119 | 6 | 0,71402537 |
| 7 | 6 | 9,33333333 | 77409,973 | | 1447,8 | 1767,83 | 3,39263837 | 2,95268798 | 0,87755102 | 9,33333333 | 2 | 180 | 2516 | 25 | 0,213 | 0,119 | 6 | 0,71402537 |
| 8 | 7 | 9,6 | 76840,6792 | | 1447,8 | 1767,83 | 3,39263837 | 2,95268798 | 0,87755102 | 9,6 | 2 | 180 | 2516 | 25 | 0,213 | 0,119 | 6 | 0,71402537 |
| 9 | 8 | 9,86666667 | 76299,9951 | | 1447,8 | 1767,83 | 3,39263837 | 2,95268798 | 0,87755102 | 9,86666667 | 2 | 180 | 2516 | 25 | 0,213 | 0,119 | 6 | 0,71402537 |
| 10 | 9 | 10,1333333 | 75785,6438 | | 1447,8 | 1767,83 | 3,39263837 | 2,95268798 | 0,87755102 | 10,1333333 | 2 | 180 | 2516 | 25 | 0,213 | 0,119 | 6 | 0,71402537 |
| 11 | 10 | 10,4 | 75295,5909 | | 1447,8 | 1767,83 | 3,39263837 | 2,95268798 | 0,87755102 | 10,4 | 2 | 180 | 2516 | 25 | 0,213 | 0,119 | 6 | 0,71402537 |
| 12 | 11 | 10,6666667 | 74828,0121 | | 1447,8 | 1767,83 | 3,39263837 | 2,95268798 | 0,87755102 | 10,6666667 | 2 | 180 | 2516 | 25 | 0,213 | 0,119 | 6 | 0,71402537 |
| 13 | 12 | 10,9333333 | 74381,267 | | 1447,8 | 1767,83 | 3,39263837 | 2,95268798 | 0,87755102 | 10,9333333 | 2 | 180 | 2516 | 25 | 0,213 | 0,119 | 6 | 0,71402537 |
| 14 | 13 | 11,2 | 73953,8757 | | 1447,8 | 1767,83 | 3,39263837 | 2,95268798 | 0,87755102 | 11,2 | 2 | 180 | 2516 | 25 | 0,213 | 0,119 | 6 | 0,71402537 |
| 15 | 14 | 11,4666667 | 73544,4997 | | 1447,8 | 1767,83 | 3,39263837 | 2,95268798 | 0,87755102 | 11,4666667 | 2 | 180 | 2516 | 25 | 0,213 | 0,119 | 6 | 0,71402537 |
| 16 | 15 | 11,7333333 | 73151,9248 | | 1447,8 | 1767,83 | 3,39263837 | 2,95268798 | 0,87755102 | 11,7333333 | 2 | 180 | 2516 | 25 | 0,213 | 0,119 | 6 | 0,71402537 |
| 17 | 16 | 12 | 72775,0471 | | 1447,8 | 1767,83 | 3,39263837 | 2,95268798 | 0,87755102 | 12 | 2 | 180 | 2516 | 25 | 0,213 | 0,119 | 6 | 0,71402537 |

**Figure 7.19** Results on the Results DOE Diagonal tab

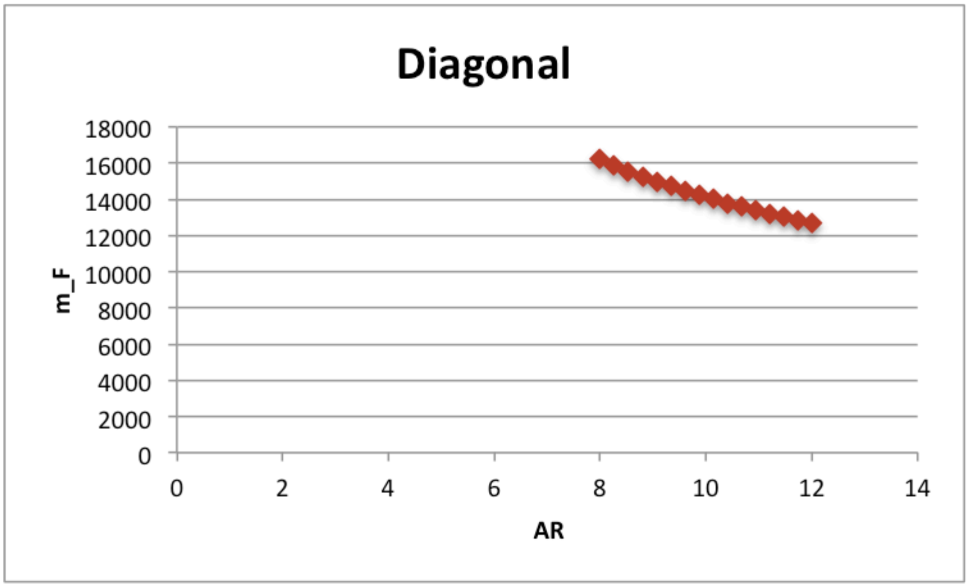


**Figure 7.20** Graph on the Results DOE Diagonal tab

## 7.3 Working Method

This part of the thesis will suggest a working method for working with the tool to the user. An important remark before starting, is that the user should only change values on the Input tab. This is very important as otherwise the formulas in the tabs will be deleted, which might affect the results of the tools in a negative way.

First step in working with the tool is gathering the data for the input parameters and filling them in in their respective cells. Some values for parameters depend on experience, if the user has no idea about these parameters, it is suggested to not change the standard values. Important input value is the design goal, in order to get the tool working as OPerA always did, the user should choose "6" (adjust the cruise line). If the user wants to minimize a certain optimization parameter, he/she can choose one of the five other options.

After filling in the input values, the user should always click the *FIND DESIGN POINT* action button. This way the output values will always be the correct ones according to the input values. Now it is up to the user to evaluate the output results and the Matching Chart. The user should ask him-/herself the question if the design makes sense.

Next step the user should decide what exactly he/she wants to do. If the user wants to see the effect of variating a single input, the *RUN DOE Diagonal ALGORITHM FOR SINGLE INPUT* action button should be clicked. If the user wants to see the effect of variating multiple inputs on a chosen output, the *RUN Differential Evolution ALGORITHM FOR MULTIPLE INPUTS* action button should be clicked. The second option should be chosen if the user wants to perform a real optimization. Important here is that the user should choose the same output value to optimize as the design goal.

When the user has decided what to do, he/she can evaluate the results in the Results DE or Results DOE Diagonal tabs. When the user chose the differential evolution, the optimal airplane can be found by looking in the graph at which iteration the output value is the lowest. If the user chose the same output value to optimize as the design goal, the lowest value can be found in the cell above the graph saying 'Output".

# 8 Summary and Outlook

Two tools were developed for Part 23 Prop and Part 25 Jet, to be used for simple aircraft sizing with the ability to perform an optimization on the resulting design. These tools are made with as main goal that they are understandable for students and can be used in classes.

In order to build these tools, first a study of the certification requirements was performed. There were some significant differences between the different certification bases that would affect the calculations that are done in the tools. Altought the tool for CS-VLA was not build because of a lack of time and data, the certification requirements have been analysed.

After analysing the certification requirements, a study was performed about the mechanics behind each flight phase in order to describe the equations that should be use in the tools in combination with the certification requirements.

Building the tool for Part 25 Jet started with deconstructing OPerA to a basic version that is less complex but with the main advantages from OPerA. When this was done the step to develop another tool for Part 23 Prop was made easier as I understood the structure and working of the tool now.

To build Part 23 Prop statistical research had to be done in order to get key values for constants. After getting these key values, the necessary changes were made to SAS Optimization Part 25 Prop to finally get SAS Optimization Part 23 Prop as a result.

When the tools were finished, it was decided to write a users guide with a suggested working method. Because of a lack of time tools for Part 23 Jet and CS-VLA were not built, which means there is still room for another project on these domains.

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# Appendix A

In order to determine the statistical constants $k_{APP}$ and $k_{TO}$ described in **Section 6.3.2** and **Section 6.3.3**, some data had to be gathered and calculated. All non-calculated data is taken from **Jane's**.

**Table A.1** Data for statistics according to **Jane's**.

| Aircraft | MTOW (kg) | MLM | Cruise speed [kts] | Propeller diameter [m] | Wing area (m2) | Power |
|---|---|---|---|---|---|---|
| Piper PA-28-140 Cherokee Cruiser | 975 | 975 | 108 | 1,9 | 15,14 | 113 |
| Cessna 172 | 1111 | 1111 | 122 | 1,9 | 16,17 | 119 |
| Cirrus SR-22 | 1542 | 1542 | 180 | 1,98 | 13,46 | 231 |
| Beech King Air 350 | 6804 | 6804 | 281 | 2,67 | 28,8 | 1908 |
| Lancair Sentry | 1610 | 1451 | 291 | 1,93 | 9,1 | 261 |
| Luscombe 11E | 1034 | 1034 | 117 | 1,93 | 15,51 | 138 |
| Solaris Sigma 310 | 1587 | | 205 | 1,88 | 12,94 | 231 |
| AG-5B TIGER | 1089 | | 143 | 1,98 | 13,02 | 134 |
| LANCAIR COLUMBIA 350 | 1542 | 1465 | 190 | 1,96 | 13,12 | 231 |
| Cessna 208 Caravan | 3629 | 3538 | 186 | 2,69 | 25,96 | 503 |
| Gippsland GA8 Airvan | 1814 | 1814 | 135 | 2,4 | 19,32 | 224 |
| IBIS Ae270 | 3700 | 3700 | 121 | 2,13 | 21 | 224 |

**Table A.2** Stall speed with flaps up for different aircrafts according to **Jane's**

| Aircraft | $V_{S,flaps\ up}$ (kt) |
|---|---|
| Piper PA-28-140 Cherokee Cruiser | |
| Cessna 172 | 51 |
| Cirrus SR-22 | 70 |
| Beech King Air 350 | |
| Lancair Sentry | |
| Luscombe 11E | 47 |
| Solaris Sigma 310 | 71 |
| AG-5B TIGER | 56 |
| LANCAIR COLUMBIA 350 | 71 |
| Cessna 208 Caravan | 75 |
| Gippsland GA8 Airvan | 60 |
| IBIS Ae270 | 85 |

**Table A.3** Data needed for determining $k_{APP}$ according to **Jane's** (I)

| **Aircraft** | **$S_{LG}$(ft)** | **$V_{S,flaps\ up}^2$ (kt²)** |
|---|---|---|
| Piper PA-28-140 Cherokee Cruiser | 535 | 0 |
| Cessna 172 | 550 | 2601 |
| Cirrus SR-22 | 1140 | 4900 |
| Beech King Air 350 | 1450 | 0 |
| Lancair Sentry | 1700 | 0 |
| Luscombe 11E | 866 | 2209 |
| Solaris Sigma 310 | | 5041 |
| AG-5B TIGER | 410 | 3136 |
| LANCAIR COLUMBIA 350 | 1550 | 5041 |
| Cessna 208 Caravan | 745 | 5625 |
| Gippsland GA8 Airvan | | 3600 |
| IBIS Ae270 | | 7225 |

**Table A.4** Data needed for determining $k_{APP}$ according to **Jane's** (II)

| **Aircraft** | **$S_{LG}$(ft)** | **$S_{LFL}$ (ft)** |
|---|---|---|
| Piper PA-28-140 Cherokee Cruiser | 535 | 1080 |
| Cessna 172 | 550 | 1295 |
| Cirrus SR-22 | 1140 | 2325 |
| Beech King Air 350 | 1450 | 2695 |
| Lancair Sentry | 1700 | |
| Luscombe 11E | 866 | 1900 |
| Solaris Sigma 310 | | 1600 |
| AG-5B TIGER | 410 | 1120 |
| LANCAIR COLUMBIA 350 | 1550 | 2350 |
| Cessna 208 Caravan | 745 | 1655 |
| Gippsland GA8 Airvan | | 1200 |
| IBIS Ae270 | | 1640 |

**Table A.5** Calculated data for determining $k_{TO}$

| Aircraft | $\frac{1}{s_{TOFL} \cdot \sigma^{3/2} \cdot C_{L,MAX,TO}^{3/2} \cdot \eta_{TRUCKENBRODT}}$ (kg/m²) | $\frac{P_{TO}/m_{MTO}}{m_{MTO}/S_W}$ |
|---|---|---|
| Piper PA-28-140 Cherokee Cruiser | 0,00250 | 0,224 |
| Cessna 172 | 0,00271 | 0,188 |
| Cirrus SR-22 | 0,00195 | 0,122 |
| Beech King Air 350 | 0,00135 | 0,077 |
| Lancair Sentry | | 0,069 |
| Luscombe 11E | 0,00311 | 0,245 |
| Solaris Sigma 310 | | 0,107 |
| AG-5B TIGER | | 0,161 |
| LANCAIR COLUMBIA 350 | 0,00148 | 0,118 |
| Cessna 208 Caravan | | 0,084 |
| Gippsland GA8 Airvan | | 0,136 |
| IBIS Ae270 | | 0,026 |

**Table A.6** Calculated values for $k_{TO}$

| Aircraft | $k_{TO}$ |
|---|---|
| Piper PA-28-140 Cherokee Cruiser | 89,65 |
| Cessna 172 | 69,33 |
| Cirrus SR-22 | 62,77 |
| Beech King Air 350 | 57,21 |
| Luscombe 11E | 78,91 |
| LANCAIR COLUMBIA 350 | 79,69 |
| **AVERAGE** | 72,92 |

# Appendix B

In this section the codes for the different macros are given. These codes are from SAS Optimization Part 25 Jet, those for Part 23 are almost identical and therefore not given.

## B.1 Diagonal macro

```
Option Explicit
Sub diagonal()
Dim i, j, k, v_row, f_row As Integer
Dim f_values(), title_values(1 To 100), V_nP(1 To 10) As Double
Dim Title(1 To 100) As String
Dim var, low, high, finss, finness, KFE, step_o, f_value As Double



Sheets("INPUT").Select
j = 0
For i = 2 To 16
  If Cells(i, 6) = "yes" Then
  j = j + 1
  v_row = i
  End If
  Next
Cells(2, 7) = j
If j <> 1 Then
  MsgBox "You have chosen more than one variable! Run algorithm for multiple inputs!"
  End
End If

j = 0
For i = 51 To 76
  If Cells(i, 6) = "yes" Then
  j = j + 1
  f_row = i
  End If
  Next
Cells(2, 7) = j
If j <> 1 Then
  MsgBox "You have more than one objective!"
  End
End If

high = Cells(v_row, 4)
low = Cells(v_row, 3)
finness = Cells(3, 10)


If v_row = 8 Then
```

```
    finness = 2
End If

KFE = 1000000000
If v_row = 9 Then
    finss = Cells(3, 10)
    V_nP(1) = 80 - finss
    V_nP(2) = 40 - finss
    V_nP(3) = 20 - finss
    V_nP(4) = 16 - finss
    V_nP(5) = 10 - finss
    V_nP(6) = 8 - finss
    V_nP(7) = 5 - finss
    V_nP(8) = 4 - finss
    V_nP(9) = 2 - finss
    V_nP(10) = 1 - finss
    For i = 1 To 10
        If Abs(V_nP(i)) < Abs(KFE) Then
            KFE = V_nP(i)
finness = V_nP(i) + finss
        End If
    Next
End If

If v_row = 17 Or v_row = 18 Then
    finness = 1
End If

If v_row = 19 Then
    finness = 5
End If

 Cells(3, 11) = finness

 step_o = (high - low) / finness

Sheets("Results DOE Diagonal").Select
ActiveSheet.Shapes.AddChart.Select
Sheets("Results DOE Diagonal").ChartObjects.Delete
Cells.Select
Selection.ClearContents
Range("A1").Select
Sheets("INPUT").Select

i = 1
Title(1) = Cells(1, 1)
For var = low To high + step_o Step step_o
   Cells(v_row, 2) = var
   Title(2) = Cells(v_row, 1)
   Call Makro1
```

```
    Call Makro2
    Call DP_Fast
    f_value = Cells(f_row, 2)
    Title(3) = Cells(f_row, 1)
    k = 5
    For j = 2 To 19
      If var = low Then Title(k) = Cells(j, 1)
      title_values(k) = Cells(j, 2)
      k = k + 1
      Next

     For j = 51 To 73
      If var = low Then Title(k) = Cells(j, 1)
      title_values(k) = Cells(j, 2)
      k = k + 1
     Next

    Sheets("Results DOE Diagonal").Select
    Cells(1, 1) = Title(1)
    Cells(1, 2) = Title(2)
    Cells(1, 3) = Title(3)
    Cells(i + 1, 1) = i
    Cells(i + 1, 2) = var
    Cells(i + 1, 3) = f_value
    k = 5
    For j = 2 To 19
      If var = low Then Cells(1, k) = Title(k)
      Cells(i + 1, k) = title_values(k)
      k = k + 1
      Next

    For j = 51 To 76
      If var = low Then Cells(1, k) = Title(k)
      Cells(i + 1, k) = title_values(k)
      k = k + 1
      Next

    i = i + 1
    Sheets("INPUT").Select
    Next

Sheets("INPUT").Select
If Cells(19, 2) = 1 Or Cells(19, 2) = 6 Then
     Sheets("Results DOE Diagonal").Select
     Range("AY28").Select
     ActiveSheet.Shapes.AddChart.Select
     ActiveChart.ChartType = xlXYScatter
     ActiveChart.Axes(xlValue).Select
     ActiveChart.Axes(xlValue).MinimumScale = 0
     ActiveChart.HasTitle = True
```

```
    ActiveChart.ChartTitle.Text = "Diagonal"
    For i = 1 To finness + 1
        If Cells(i + 1, 45) = 0 Or Cells(i + 1, 46) = 0 Or Cells(i + 1, 47) = 0 Or Cells(i + 1, 48) =
0 Then
            ActiveChart.SeriesCollection.NewSeries
            ActiveChart.SeriesCollection(i).XValues = Cells(i + 1, 2)
            ActiveChart.SeriesCollection(i).Values = Cells(i + 1, 24)
            ActiveChart.HasLegend = False
            ActiveChart.SeriesCollection(i).Select
            With Selection
                .MarkerStyle = 2
                .MarkerSize = 7
                .MarkerBackgroundColor = RGB(170, 42, 32)
                .MarkerForegroundColor = RGB(170, 42, 32)
            End With
        Else
            ActiveChart.SeriesCollection.NewSeries
            ActiveChart.SeriesCollection(i).XValues = Cells(i + 1, 2)
            ActiveChart.SeriesCollection(i).Values = Cells(i + 1, 24)
            ActiveChart.HasLegend = False
            ActiveChart.SeriesCollection(i).Select
            With Selection
                .MarkerStyle = 2
                .MarkerSize = 7
                .MarkerBackgroundColor = RGB(31, 73, 125)
                .MarkerForegroundColor = RGB(31, 73, 125)
            End With
        End If
    Next
    ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
    ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
    ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "m_MTO"
    ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "='Results DOE Diago-
nal'!$B$1"
End If

Sheets("INPUT").Select
If Cells(19, 2) = 2 Then
    Sheets("Results DOE Diagonal").Select
    Range("AY28").Select
    ActiveSheet.Shapes.AddChart.Select
    ActiveChart.ChartType = xlXYScatter
    ActiveChart.Axes(xlValue).Select
    ActiveChart.Axes(xlValue).MinimumScale = 0
    ActiveChart.HasTitle = True
    ActiveChart.ChartTitle.Text = "Diagonal"
    For i = 1 To finness + 1
        If Cells(i + 1, 45) = 0 Or Cells(i + 1, 46) = 0 Or Cells(i + 1, 47) = 0 Or Cells(i + 1, 48) =
0 Then
            ActiveChart.SeriesCollection.NewSeries
```

```
            ActiveChart.SeriesCollection(i).XValues = Cells(i + 1, 2)
            ActiveChart.SeriesCollection(i).Values = Cells(i + 1, 23)
            ActiveChart.HasLegend = False
            ActiveChart.SeriesCollection(i).Select
            With Selection
                .MarkerStyle = 2
                .MarkerSize = 7
                .MarkerBackgroundColor = RGB(170, 42, 32)
                .MarkerForegroundColor = RGB(170, 42, 32)
            End With
        Else
            ActiveChart.SeriesCollection.NewSeries
            ActiveChart.SeriesCollection(i).XValues = Cells(i + 1, 2)
            ActiveChart.SeriesCollection(i).Values = Cells(i + 1, 23)
            ActiveChart.HasLegend = False
            ActiveChart.SeriesCollection(i).Select
            With Selection
                .MarkerStyle = 2
                .MarkerSize = 7
                .MarkerBackgroundColor = RGB(31, 73, 125)
                .MarkerForegroundColor = RGB(31, 73, 125)
            End With
        End If
    Next
    ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
    ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
    ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "m_F"
    ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "='Results DOE Diago-
nal'!$B$1"
End If

Sheets("INPUT").Select
If Cells(19, 2) = 3 Then
    Sheets("Results DOE Diagonal").Select
    Range("AY28").Select
    ActiveSheet.Shapes.AddChart.Select
    ActiveChart.ChartType = xlXYScatter
    ActiveChart.Axes(xlValue).Select
    ActiveChart.Axes(xlValue).MinimumScale = 0
    ActiveChart.HasTitle = True
    ActiveChart.ChartTitle.Text = "Diagonal"
    For i = 1 To finness + 1
        If Cells(i + 1, 45) = 0 Or Cells(i + 1, 46) = 0 Or Cells(i + 1, 47) = 0 Or Cells(i + 1, 48) =
0 Then
            ActiveChart.SeriesCollection.NewSeries
            ActiveChart.SeriesCollection(i).XValues = Cells(i + 1, 2)
            ActiveChart.SeriesCollection(i).Values = Cells(i + 1, 26)
            ActiveChart.HasLegend = False
            ActiveChart.SeriesCollection(i).Select
            With Selection
```

```
            .MarkerStyle = 2
            .MarkerSize = 7
            .MarkerBackgroundColor = RGB(170, 42, 32)
            .MarkerForegroundColor = RGB(170, 42, 32)
         End With
      Else
         ActiveChart.SeriesCollection.NewSeries
         ActiveChart.SeriesCollection(i).XValues = Cells(i + 1, 2)
         ActiveChart.SeriesCollection(i).Values = Cells(i + 1, 26)
         ActiveChart.HasLegend = False
         ActiveChart.SeriesCollection(i).Select
         With Selection
            .MarkerStyle = 2
            .MarkerSize = 7
            .MarkerBackgroundColor = RGB(31, 73, 125)
            .MarkerForegroundColor = RGB(31, 73, 125)
         End With
      End If
   Next
   ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
   ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
   ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "m_OE"
   ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "='Results DOE Diago-
nal'!$B$1"
End If
Sheets("INPUT").Select
If Cells(19, 2) = 4 Then
   Sheets("Results DOE Diagonal").Select
   Range("AY28").Select
   ActiveSheet.Shapes.AddChart.Select
   ActiveChart.ChartType = xlXYScatter
   ActiveChart.Axes(xlValue).Select
   ActiveChart.Axes(xlValue).MinimumScale = 0
   ActiveChart.HasTitle = True
   ActiveChart.ChartTitle.Text = "Diagonal"
   For i = 1 To finness + 1
      If Cells(i + 1, 45) = 0 Or Cells(i + 1, 46) = 0 Or Cells(i + 1, 47) = 0 Or Cells(i + 1, 48) =
0 Then
         ActiveChart.SeriesCollection.NewSeries
         ActiveChart.SeriesCollection(i).XValues = Cells(i + 1, 2)
         ActiveChart.SeriesCollection(i).Values = Cells(i + 1, 35)
         ActiveChart.HasLegend = False
         ActiveChart.SeriesCollection(i).Select
         With Selection
            .MarkerStyle = 2
            .MarkerSize = 7
            .MarkerBackgroundColor = RGB(170, 42, 32)
            .MarkerForegroundColor = RGB(170, 42, 32)
         End With
      Else
```

```
            ActiveChart.SeriesCollection.NewSeries
            ActiveChart.SeriesCollection(i).XValues = Cells(i + 1, 2)
            ActiveChart.SeriesCollection(i).Values = Cells(i + 1, 35)
            ActiveChart.HasLegend = False
            ActiveChart.SeriesCollection(i).Select
            With Selection
               .MarkerStyle = 2
               .MarkerSize = 7
               .MarkerBackgroundColor = RGB(31, 73, 125)
               .MarkerForegroundColor = RGB(31, 73, 125)
            End With
         End If
      Next
      ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
      ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
      ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "T_TO"
      ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "='Results DOE Diago-
nal'!$B$1"
End If

Sheets("INPUT").Select
If Cells(19, 2) = 5 Then
         Sheets("Results DOE Diagonal").Select
      Range("AY28").Select
      ActiveSheet.Shapes.AddChart.Select
      ActiveChart.ChartType = xlXYScatter
      ActiveChart.Axes(xlValue).Select
      ActiveChart.Axes(xlValue).MinimumScale = 0
      ActiveChart.HasTitle = True
      ActiveChart.ChartTitle.Text = "Diagonal"
      For i = 1 To finness + 1
         If Cells(i + 1, 45) = 0 Or Cells(i + 1, 46) = 0 Or Cells(i + 1, 47) = 0 Or Cells(i + 1, 48) =
0 Then
            ActiveChart.SeriesCollection.NewSeries
            ActiveChart.SeriesCollection(i).XValues = Cells(i + 1, 2)
            ActiveChart.SeriesCollection(i).Values = Cells(i + 1, 34)
            ActiveChart.HasLegend = False
            ActiveChart.SeriesCollection(i).Select
            With Selection
               .MarkerStyle = 2
               .MarkerSize = 7
               .MarkerBackgroundColor = RGB(170, 42, 32)
               .MarkerForegroundColor = RGB(170, 42, 32)
            End With
         Else
            ActiveChart.SeriesCollection.NewSeries
            ActiveChart.SeriesCollection(i).XValues = Cells(i + 1, 2)
            ActiveChart.SeriesCollection(i).Values = Cells(i + 1, 34)
            ActiveChart.HasLegend = False
            ActiveChart.SeriesCollection(i).Select
```

```
        With Selection
          .MarkerStyle = 2
          .MarkerSize = 7
          .MarkerBackgroundColor = RGB(31, 73, 125)
          .MarkerForegroundColor = RGB(31, 73, 125)
        End With
      End If
    Next
    ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
    ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
    ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "S_W"
    ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "='Results DOE Diago-
nal'!$B$1"
End If

End Sub
```

## B.2 DP Fast macro

```
Sub DP_Fast()

Sheets("DP").Select
Cells(1, 1).Select

If Worksheets("INPUT").Cells(19, 2) = 1 Then
        SolverReset
        SolverOptions MaxTime:=3000, Iterations:=100, Precision:=0.0001, AssumeLine-
ar:= _
        False, StepThru:=False, Estimates:=2, Derivatives:=1, SearchOption:=2, _
        IntTolerance:=5, Scaling:=False, Convergence:=0.01, AssumeNonNeg:=False
        SolverOk SetCell:="$C$20", MaxMinVal:=3, Valueof:="0", ByChange:="$D$14"
        SolverAdd CellRef:="$D$14", Relation:=1, FormulaText:="$E$14"
        SolverAdd CellRef:="$D$14", Relation:=3, FormulaText:="$F$14"
        SolverSolve True

ElseIf Worksheets("Input").Cells(19, 2) = 2 Then
        SolverReset
        SolverOptions MaxTime:=3000, Iterations:=100, Precision:=0.0001, AssumeLine-
ar:= _
        False, StepThru:=False, Estimates:=2, Derivatives:=1, SearchOption:=2, _
        IntTolerance:=5, Scaling:=False, Convergence:=0.01, AssumeNonNeg:=False
        SolverOk SetCell:="$C$21", MaxMinVal:=3, Valueof:="0", ByChange:="$D$14"
        SolverAdd CellRef:="$D$14", Relation:=1, FormulaText:="$E$14"
```

```
            SolverAdd CellRef:="$D$14", Relation:=3, FormulaText:="$F$14"
            SolverSolve True

ElseIf Worksheets("Input").Cells(19, 2) = 3 Then
            SolverReset
            SolverOptions  MaxTime:=3000,  Iterations:=100,  Precision:=0.0001,  AssumeLine-
ar:= _
            False, StepThru:=False, Estimates:=2, Derivatives:=1, SearchOption:=2, _
            IntTolerance:=5, Scaling:=False, Convergence:=0.01, AssumeNonNeg:=False
            SolverOk SetCell:="$C$22", MaxMinVal:=3, Valueof:="0", ByChange:="$D$14"
            SolverAdd CellRef:="$D$14", Relation:=1, FormulaText:="$E$14"
            SolverAdd CellRef:="$D$14", Relation:=3, FormulaText:="$F$14"
            SolverSolve True

ElseIf Worksheets("Input").Cells(19, 2) = 4 Then
            SolverReset
            SolverOptions  MaxTime:=3000,  Iterations:=100,  Precision:=0.0001,  AssumeLine-
ar:= _
            False, StepThru:=False, Estimates:=2, Derivatives:=1, SearchOption:=2, _
            IntTolerance:=5, Scaling:=False, Convergence:=0.01, AssumeNonNeg:=False
            SolverOk SetCell:="$C$23", MaxMinVal:=3, Valueof:="0", ByChange:="$D$14"
            SolverAdd CellRef:="$D$14", Relation:=1, FormulaText:="$E$14"
            SolverAdd CellRef:="$D$14", Relation:=3, FormulaText:="$F$14"
            SolverSolve True

ElseIf Worksheets("Input").Cells(19, 2) = 5 Then
            SolverReset
            SolverOptions  MaxTime:=3000,  Iterations:=100,  Precision:=0.0001,  AssumeLine-
ar:= _
            False, StepThru:=False, Estimates:=2, Derivatives:=1, SearchOption:=2, _
            IntTolerance:=5, Scaling:=False, Convergence:=0.01, AssumeNonNeg:=False
            SolverOk SetCell:="$C$24", MaxMinVal:=3, Valueof:="0", ByChange:="$D$14"
            SolverAdd CellRef:="$D$14", Relation:=1, FormulaText:="$E$14"
            SolverAdd CellRef:="$D$14", Relation:=3, FormulaText:="$F$14"
            SolverSolve True

ElseIf Worksheets("Input").Cells(19, 2) = 6 Then

          If (Cells(2, 3) > Cells(3, 3)) And (Cells(2, 3) > Cells(4, 3)) Then
            SolverReset
            SolverOptions  MaxTime:=3000,  Iterations:=100,  Precision:=0.0001,  AssumeLine-
ar:= _
```

```
        False, StepThru:=False, Estimates:=2, Derivatives:=1, SearchOption:=2, _
        IntTolerance:=5, Scaling:=False, Convergence:=0.01, AssumeNonNeg:=False
        SolverOk SetCell:="$C$14", MaxMinVal:=3, Valueof:="0", ByChange:="$D$14"
        SolverAdd CellRef:="$D$14", Relation:=1, FormulaText:="$E$14"
        SolverAdd CellRef:="$D$14", Relation:=3, FormulaText:="$F$14"
        SolverSolve True
      ElseIf (Cells(3, 3) > Cells(2, 3)) And (Cells(3, 3) > Cells(4, 3)) Then
        SolverReset
        SolverOptions  MaxTime:=3000,  Iterations:=100,  Precision:=0.0001,  AssumeLine-
ar:= _
        False, StepThru:=False, Estimates:=2, Derivatives:=1, SearchOption:=2, _
        IntTolerance:=5, Scaling:=False, Convergence:=0.01, AssumeNonNeg:=False
        SolverOk SetCell:="$C$15", MaxMinVal:=3, Valueof:="0", ByChange:="$D$14"
        SolverAdd CellRef:="$D$14", Relation:=1, FormulaText:="$E$14"
        SolverAdd CellRef:="$D$14", Relation:=3, FormulaText:="$F$14"
        SolverSolve True
      ElseIf (Cells(4, 3) > Cells(2, 3)) And (Cells(4, 3) > Cells(3, 3)) Then
        SolverReset
        SolverOptions  MaxTime:=3000,  Iterations:=100,  Precision:=0.0001,  AssumeLine-
ar:= _
        False, StepThru:=False, Estimates:=2, Derivatives:=1, SearchOption:=2, _
        IntTolerance:=5, Scaling:=False, Convergence:=0.01, AssumeNonNeg:=False
        SolverOk SetCell:="$C$16", MaxMinVal:=3, Valueof:="0", ByChange:="$D$14"
        SolverAdd CellRef:="$D$14", Relation:=1, FormulaText:="$E$14"
        SolverAdd CellRef:="$D$14", Relation:=3, FormulaText:="$F$14"
        SolverSolve True
      End If

End If

Sheets("Input").Select

End Sub
```

## B.3 Differential Evolution macro

```
Sub differential_evolution()
'
' differential_evolution Makro

Dim population_size, j, i, parameter_position(1 To 30), no_of_parameters, position, no_of_iterations, k, better_candidates, output_position, no_of_errors, position_best As Integer
Dim population_zero(1 To 1000, 1 To 1000), population(1 To 1000, 1 To 1000), rand, rand_D, F, KF, parent_1, parent_2, parent_3, parent_4, trial(1 To 30), candidate(1 To 30), CR, output_candidate, output_parent, output_best As Double
Dim inside_limits As Boolean
Dim value_test, value_test2, value_test3, value_test4


Sheets("INPUT").Select

'Definition of the population size
population_size = Cells(5, 10)

If population_size <= 7 Then
  MsgBox "Population size must be higher than 7!!"
  End
End If

population_size = population_size * 1
output_best = 10000000


j = 0
For i = 2 To 16
  If Cells(i, 6) = "yes" Then
    j = j + 1
    parameter_position(j) = i
  End If
Next

If j < 1 Then
  MsgBox "Vary at least one parameter!"
  End
End If
```

```
If Cells(19, 6) = "yes" Then
    MsgBox "You cannot choose  Design_goal as input in Differential Evolution."
    End
End If

Cells(2, 7) = j

no_of_parameters = j

j = 0
For i = 51 To 76
   If Cells(i, 6) = "yes" Then
      j = j + 1
      output_position = i
   End If
Next

If j <> 1 Then
   MsgBox "There must be only one objective!"
   End
End If

'Definition of the weight factor
F = Cells(7, 11)

If F > 1 Or F < 0 Then
   MsgBox "The weight factor should be between 0 and 1! Recommended low limit is 0.5"
   End
End If



KF = Cells(19, 11)

If KF > 1 Or KF < 0 Then
   MsgBox "The combination factor should be between 0 and 1! Recommended value is 0.5"
   End
End If



CR = Cells(11, 11)
If CR > 1 Or CR < 0 Then
```

```
  MsgBox "The crossover rate should be between 0 and 1! Recommended values are from 0.7
to 0.85"
  End
End If

'Generation of population
For i = 1 To population_size
  For j = 1 To no_of_parameters
    Randomize
    rand = Rnd
    population(i, j) = Cells(parameter_position(j), 3) + rand * (Cells(parameter_position(j), 4)
- Cells(parameter_position(j), 3))

    If parameter_position(j) = 8 Or parameter_position(j) = 9 Or parameter_position(j) = 10
Then population(i, j) = Round(population(i, j))
  Next
Next

no_of_iterations = Cells(9, 10)

'Copy parameter names and if it's varied or not
Sheets("Results DE").Select
ActiveSheet.Shapes.AddChart.Select
Sheets("Results DE").ChartObjects.Delete
Cells.Select
Selection.ClearContents
Range("A1").Select
Sheets("Input").Select

Range("A2:A19").Select
Selection.Copy
Sheets("Results DE").Select
Range("B1").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=True

Sheets("INPUT").Select

Range("A51:A76").Select
Selection.Copy
Sheets("Results DE").Select
Range("T1").Select
```

```
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=True

Sheets("Input").Select
Range("F2:F19").Select
Selection.Copy
Sheets("Results DE").Select
Range("B2").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=True

Sheets("Input").Select
Range("F51:F76").Select
Selection.Copy
Sheets("Results DE").Select
Range("T2").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=True

Cells(1, 1) = "Iteration"



no_of_errors = 0
Sheets("INPUT").Select

'Test population
For i = 1 To population_size
  For j = 1 To no_of_parameters
    Cells(parameter_position(j), 2) = population(i, j)
  Next

  value_test = Cells(output_position, 2)
  Call Makro1
  Call Makro2

value_test = Cells(output_position, 2)
  If TypeName(value_test) <> "Error" Then
  'If Cells(output_position, 7) = 1 Then
    Call DP_Fast
    value_test = Cells(output_position, 2)
    If TypeName(value_test) <> "Error" Then
    'If Cells(output_position, 7) = 1 Then
```

```
            Sheets("INPUT").Select
            If Cells(output_position, 2) < output_best And Cells(74, 2) <> 0 And Cells(75, 2) <> 0
And Cells(76, 2) <> 0 Then
                output_best = Cells(output_position, 2)
                position_best = i
            End If
            Range("B2:B19").Select
            Selection.Copy
            Sheets("Results DE").Select
            Cells(i + 2, 2).Select
            Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
                :=False, Transpose:=True
            Sheets("Input").Select
            Range("B51:B76").Select
            Selection.Copy
            Sheets("Results DE").Select
            Cells(i + 2, 20).Select
            Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
                :=False, Transpose:=True

            Cells(i + 2, 1) = 0
      Else: no_of_errors = no_of_errors + 1
      End If
   Else: no_of_errors = no_of_errors + 1
   End If
   Sheets("INPUT").Select
Next

better_candidates = 0

For i = 1 To no_of_iterations
      k = 1
      Cells(17, 10) = i
      Cells(13, 10) = no_of_errors
      inside_limits = True
      Randomize
      rand = Rnd
      parent_1 = 1 + Round(rand * (population_size - 1))
      'Do
            Randomize
            rand = Rnd
            parent_2 = 1 + Round(rand * (population_size - 1))
```

```
'Loop Until parent_1 <> parent_2

'Do
    Randomize
    rand = Rnd
    parent_3 = 1 + rand * Round((population_size - 1))
'Loop Until parent_1 <> parent_3 And parent_2 <> parent_3


For j = 1 To no_of_parameters
  trial(j) = population(parent_1, j) + F * (population(parent_2, j) - population(parent_3, j))
+ KF * (population(position_best, j) - population(parent_1, j))
  If parameter_position(j) = 8 Or parameter_position(j) = 9 Or parameter_position(j) = 17
Or parameter_position(j) = 18 Then trial(j) = Round(trial(j))
Next

Do
    Randomize
    rand = Rnd
    parent_4 = 1 + Round(rand * (population_size - 1))
Loop Until parent_4 <> parent_1 And parent_4 <> parent_2 And parent_4 <> parent_3

  For j = 1 To no_of_parameters
  Randomize
  rand = Rnd
  Randomize
  rand_D = Round(1 + Rnd * (no_of_parameters - 1))
  If rand < CR Or j = rand_D Then
    candidate(j) = trial(j)
                Else: candidate(j) = population(parent_4, j)
  End If
Next

For j = 1 To no_of_parameters
  If candidate(j) < Cells(parameter_position(j), 3) Or candidate(j) >
Cells(parameter_position(j), 4) Then inside_limits = False
Next

If inside_limits = True Then

  For j = 1 To no_of_parameters
    Cells(parameter_position(j), 2) = population(parent_4, j)
```

```
Next

'For j = 1 To 1000
'   rand = Rnd
'Next
value_test = Cells(output_position, 2)
Call Makro1
Call Makro2


value_test = Cells(output_position, 2)

If TypeName(value_test) = "Error" Then
'If Cells(output_position, 7) <> 1 Then
  output_parent = 10000000
  no_of_errors = no_of_errors + 1
  Else: Call DP_Fast
      value_test = Cells(output_position, 2)
      value_test2 = Cells(74, 2)
      value_test3 = Cells(75, 2)
      value_test4 = Cells(76, 2)
        If TypeName(value_test) = "Error" Or TypeName(value_test2) = "Error" Or
TypeName(value_test3) = "Error" Or TypeName(value_test4) = "Error" Then
        'If Cells(output_position, 7) <> 1 Then
          output_parent = 10000000
          no_of_errors = no_of_errors + 1
        Else:
          If Cells(74, 2) = 1 And Cells(75, 2) And Cells(76, 2) = 1 Then
             output_parent = Cells(output_position, 2)
          Else
             output_parent = 10000000
          End If
        End If
End If
      ''''''''''''''''''''''''''''''''


For j = 1 To no_of_parameters
  Cells(parameter_position(j), 2) = candidate(j)
Next
```

```
    value_test = Cells(output_position, 2)
    Call Makro1
    Call Makro2

    value_test = Cells(output_position, 2)

    If TypeName(value_test) = "Error" Then
    'If Cells(output_position, 7) <> 1 Then
      output_candidate = 10000000
      no_of_errors = no_of_errors + 1
      Else: Call DP_Fast
            value_test = Cells(output_position, 2)
            value_test2 = Cells(74, 2)
            value_test3 = Cells(75, 2)
            value_test4 = Cells(76, 2)
            If TypeName(value_test) = "Error" Or TypeName(value_test2) = "Error" Or
TypeName(value_test3) = "Error" Or TypeName(value_test4) = "Error" Then
            'If Cells(output_position, 7) <> 1 Then
              output_candidate = 10000000
              no_of_errors = no_of_errors + 1
            Else:
              If Cells(74, 2) = 1 And Cells(75, 2) = 1 And Cells(76, 2) = 1 Then
                output_candidate = Cells(output_position, 2)
              Else
                output_candidate = 10000000
              End If
            End If
    End If

If output_parent > output_candidate Then

      Sheets("INPUT").Select
      Range("B2:B19").Select
      Selection.Copy
      Sheets("Results DE").Select
      Cells(i + 4 + population_size, 2).Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=True

      Sheets("Input").Select
      Range("B51:B76").Select
      Selection.Copy
```

```
          Sheets("Results DE").Select
          Cells(i + 4 + population_size, 20).Select
          Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
            :=False, Transpose:=True

          Cells(i + 4 + population_size, 1) = i

          Sheets("INPUT").Select

          For j = 1 To no_of_parameters
            population(parent_4, j) = candidate(j)
          Next

          If output_candidate < output_best Then
             output_best = output_candidate
             position_best = parent_4
          End If

          better_candidates = better_candidates + 1
        End If
      End If

      Cells(15, 10) = better_candidates
  Next
Cells(13, 10) = no_of_errors

Sheets("INPUT").Select
Application.CutCopyMode = False
Range("A1").Select

If Cells(19, 2) = 1 Or Cells(19, 2) = 6 Then
      Sheets("Results DE").Select
      Range("AZ28").Select
      ActiveSheet.Shapes.AddChart.Select
      ActiveChart.SeriesCollection.NewSeries
      ActiveChart.SeriesCollection(1).Name = "m_MTO"
      ActiveChart.SeriesCollection(1).XValues = "='Results DE'!$A$3:$A$6000"
      ActiveChart.SeriesCollection(1).Values = "='Results DE'!$U$3:$U$6000"
      ActiveChart.ChartType = xlXYScatter
      ActiveChart.Axes(xlValue).Select
      ActiveChart.Axes(xlValue).MinimumScale = 0
      ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
```

```
        ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
        ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "m_MTO"
        ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "Number of iterations"
        ActiveChart.ChartTitle.Text = "Differential Evolution"
        ActiveChart.Axes(xlCategory).MinorUnit = 1
End If

Sheets("Input").Select
If Cells(19, 2) = 2 Then
        Sheets("Results DE").Select
        Range("AZ28").Select
        ActiveSheet.Shapes.AddChart.Select
        ActiveChart.SeriesCollection.NewSeries
        ActiveChart.SeriesCollection(1).Name = "m_F"
        ActiveChart.SeriesCollection(1).XValues = "='Results DE'!$A$3:$A$6000"
        ActiveChart.SeriesCollection(1).Values = "='Results DE'!$T$3:$T$6000"
        ActiveChart.ChartType = xlXYScatter
        ActiveChart.Axes(xlValue).Select
        ActiveChart.Axes(xlValue).MinimumScale = 0
        ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
        ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
        ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "m_F"
        ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "Number of iterations"
        ActiveChart.ChartTitle.Text = "Differential Evolution"
        ActiveChart.Axes(xlCategory).MinorUnit = 1
End If

Sheets("Input").Select
If Cells(19, 2) = 3 Then
        Sheets("Results DE").Select
        Range("AZ28").Select
        ActiveSheet.Shapes.AddChart.Select
        ActiveChart.SeriesCollection.NewSeries
        ActiveChart.SeriesCollection(1).Name = "m_OE"
        ActiveChart.SeriesCollection(1).XValues = "='Results DE'!$A$3:$A$6000"
        ActiveChart.SeriesCollection(1).Values = "='Results DE'!$V$3:$V$6000"
        ActiveChart.ChartType = xlXYScatter
        ActiveChart.Axes(xlValue).Select
        ActiveChart.Axes(xlValue).MinimumScale = 0
        ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
        ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
        ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "m_OE"
```

```
        ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "Number of iterations"
        ActiveChart.ChartTitle.Text = "Differential Evolution"
        ActiveChart.Axes(xlCategory).MinorUnit = 1
End If

Sheets("Input").Select
If Cells(19, 2) = 4 Then
        Sheets("Results DE").Select
        Range("AZ28").Select
        ActiveSheet.Shapes.AddChart.Select
        ActiveChart.SeriesCollection.NewSeries
        ActiveChart.SeriesCollection(1).Name = "P_TO"
        ActiveChart.SeriesCollection(1).XValues = "='Results DE'!$A$3:$A$6000"
        ActiveChart.SeriesCollection(1).Values = "='Results DE'!$AE$3:$AE$6000"
        ActiveChart.ChartType = xlXYScatter
        ActiveChart.Axes(xlValue).Select
        ActiveChart.Axes(xlValue).MinimumScale = 0
        ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
        ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
        ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "P_TO"
        ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "Number of iterations"
        ActiveChart.ChartTitle.Text = "Differential Evolution"
        ActiveChart.Axes(xlCategory).MinorUnit = 1
End If

Sheets("Input").Select
If Cells(19, 2) = 5 Then
        Sheets("Results DE").Select
        Range("AZ28").Select
        ActiveSheet.Shapes.AddChart.Select
        ActiveChart.SeriesCollection.NewSeries
        ActiveChart.SeriesCollection(1).Name = "S_W"
        ActiveChart.SeriesCollection(1).XValues = "='Results DE'!$A$3:$A$6000"
        ActiveChart.SeriesCollection(1).Values = "='Results DE'!$AD$3:$AD$6000"
        ActiveChart.ChartType = xlXYScatter
        ActiveChart.Axes(xlValue).Select
        ActiveChart.Axes(xlValue).MinimumScale = 0
        ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
        ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
        ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "S_W"
        ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "Number of iterations"
        ActiveChart.ChartTitle.Text = "Differential Evolution"
```

```
    ActiveChart.Axes(xlCategory).MinorUnit = 1
End If

Sheets("Input").Select
result_name = Cells(output_position, 1)
Sheets("Results DE").Select
Cells(2, 52) = "Output"
Cells(2, 53) = "Result"
Cells(3, 52) = result_name
Cells(3, 53) = output_best

End Sub
```

## B.4 Stability 1 macro

```
Sub Makro1()

    Sheets("PS II").Select
    Range("C121").Select
    ActiveCell.FormulaR1C1 = "60500"
    Range("C111").Select
    ActiveCell.FormulaR1C1 = "222400"
    Range("C105").Select
    ActiveCell.FormulaR1C1 = "73500"

    Sheets("DP").Select
    Cells(20, 7) = 1.3

    Sheets("INPUT").Select

End Sub
```

## B.5 Stability 2 macro

```
Sub Makro2()

    Sheets("PS II").Select
    Application.Calculation = xlManual
    Range("G8").Select
    ActiveCell.FormulaR1C1 = "=R[-1]C*CL_m"
    Range("C105").Select
    ActiveCell.FormulaR1C1 = "=R[-2]C/(1-R[-18]C-R[-12]C)"
    Range("C111").Select
    ActiveCell.FormulaR1C1 = "=R[-6]C*g*R[-66]C"
    Range("C121").Select
    ActiveCell.FormulaR1C1 = "=R[-25]C+R[-1]C"
'    Application.Calculation = xlManual
    Application.Calculation = xlAutomatic
    Sheets("INPUT").Select

End Sub
```