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Project

Preliminary Sizing of Propeller Aircraft (Part 25)

Author: Marlis Krull

Supervisor: Prof. Dr.-Ing. Dieter Scholz, MSME

Submitted: 2022-04-29

Faculty of Engineering and Computer Science
Department of Automotive and Aeronautical Engineering

DOI:
https://doi.org/xxxxxxxx

URN:
https://nbn-resolving.org/urn:nbn:de:gbv:18302-aero2022-04-29.012
Associated URLs:
https://nbn-resolving.org/html/urn:nbn:de:gbv:18302-aero2022-04-29.012

Any further request may be directed to:
Prof. Dr.-Ing. Dieter Scholz, MSME
E-Mail see: http://www.ProfScholz.de

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Published by
Aircraft Design and Systems Group (AERO)
Department of Automotive and Aeronautical Engineering
Hamburg University of Applied Science

This report has associated published data in Harvard Dataverse:
https://doi.org/10.7910/DVN/ET4ZKV

Abstract

Purpose – This project incorporates methods for propeller efficiency estimation into a preliminary sizing tool for large aircraft certified for CS-25 respectively FAR Part 25.
Methodology – Variable pitch propellers are considered. For them, previously collected methods for propeller efficiency estimation are evaluated and used. The resulting preliminary aircraft sizing tool is evaluated with a redesign of the ATR 72-600.
Findings – Propeller efficiency estimation methods are based on experience or theory and are defined in diagrams or equations. The main parameters with an influence on propeller efficiency are cruise speed, air density and propeller disc diameter. Furthermore, friction and shock waves (occurring at high Mach numbers) have a large influence on the propeller efficiency. When aerodynamic effects at high Mach numbers are not considered, estimation methods yield maximum propeller efficiency at maximum speed.
Research Limitations – The influence of high Mach number on propeller efficiency needs to be evaluated further. Propeller efficiency methods are referenced and explained, but not derived.
Practical Implications – Aircraft preliminary sizing works with automatic calculation of propeller efficiencies. User look-up of efficiencies from diagrams is not required anymore.
Social Implications – The preliminary sizing tool for large propeller driven aircraft is openly available. Therefore, the potential of future propeller driven aircraft can be discussed by the public.
Originality – A didactically enhanced design, redesign, and optimization tool (on preliminary sizing level) for large propeller driven aircraft is made openly available. It is especially suited for students and fills a perceived gap.

DEPARTMENT OF AUTOMOTIVE AND AERONAUTICAL ENGINEERING

Preliminary Sizing of Propeller Aircraft (Part 25)

Task for a Project

Background

The Aircraft Design and Systems Group (AERO) developed a preliminary sizing tool for propeller driven aircraft (PreSTo-Classic-Prop). This is based on a preliminary sizing tool for Part 25 jets (PreSTo-Classic-Jet). All the tools are implemented with Excel. When adapting the tool from jets to propeller driven aircraft, an estimation of the propeller efficiency is needed. Methods were proposed in the group's previous research work and in the literature. Furthermore, AERO had developed an optimization tool for Simple Aircraft Sizing and Optimization (SAS) as a simplification of the PhD-level tool OPerA for jets (which is based on the PreSTo suit): SAS-Part25-Jet is openly available and used by students. The PhD-level tool PrOPerA was derived from OPerA and PreSTo-Classic-Prop and simplified to SAS-Part25-Prop, but it is so far not available Open Access.

Task

The first task of this project is to improve PreSTo-Classic-Prop such that the propeller efficiency calculation is automated. Further modification should make the tool more user-friendly. PreSTo-Classic-Prop should be evaluated by the redesign of a large propeller driven aircraft. The second task is to prepare SAS-Part25-Prop for Open Access. A layout similar to SAS-Part25-Jet should provide a user-friendly tool also for props.

The subtasks are:

- Implementation of propeller efficiency calculation methods to improve PreSTo-Classic-Prop
- Improvement of the usability of PreSTo-Classic-Prop
- Evaluation of the implementations by a redesign of the ATR 72-600
- Improvement of the user interface of SAS-Part25-Prop

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

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List of Symbols

A	Aspect ratio
a	Speed of sound / Slope
B_S	Breguet range factor
B_t	Breguet time factor
c	Constant
C_D	Drag Coefficient
C_L	Lift Coefficient
c_S	Grade of thrust load
d	Diameter
E	Lift-to-drag ratio
e	Oswald factor
f	Constant
g	Earth acceleration
j	Constant
k	Constant
L_D	Disc loading
M	Mach number
m	Mass
M_{ff}	Mission fuel fraction
n	Number / Rotational speed
P	Power
p	Pressure
R	Range
s	Distance
S	Surface
t	Time
u	Circumferential speed
V	Velocity
x	Variable
y	Variable

Greek Symbols

γ	Gradient of Climb / Ratio of specific heats
ζ	Quality grade
η_P	Propeller efficiency
λ	Advance ratio

ρ	Density
σ	Relative density
ς	Variable
φ	Sweep angle

Indices

0	Initial value / Clean / At sea level
25	25% of chord
2^{nd}	2^{nd} Segment
A	Available
APP	Approach
CARGO	Cargo
CLB	Climb
CR	Cruise
D	Disc
DES	Descent
E	Engine
eff	Effective
F	Fuel
flap	Flap
gear	Landing gear
L	Landing
LFL	Landing field length
LOI	Loiter
MA	Missed approach
max	Maximum
md	Minimum drag
ML	Maximum landing
MPL	Maximum payload
MTO	Maximum take-off
OE	Operating empty
P	Performance / Profile
PAX	Passengers
PL	Payload
RES	Reserves
res	Reserves (total)
S	Stall / Shaft
slat	Slat
std	Standard flight

T	Total
th	Theoretical
TO	Take-off
TOFL	Take-off field length
W	Wing
wet	Wettet

List of Abbreviations

AERO	Aircraft Design and Systems Group
ATR	Avions de Transport Régional
CS	Certification Specifications
DE	Differential Evolution
DOE	Design of Experiments
FAR	Federal Aviation Regulations
OPerA	Optimization in Preliminary Aircraft Design
PhD	Doctor of Philosophy
PreSTo	Preliminary Sizing Tool
PrOPerA	Turboprop Optimization in Preliminary Aircraft Design
PS	Preliminary Sizing
PW	Pratt & Whitney
SAS	Simple Aircraft Sizing and Optimization
SFC	Specific Fuel Consumption

List of Definitions

Algorithm

"a set of mathematical instructions that must be followed in a fixed order, and that, especially if given to a computer, will help to calculate an answer to a mathematical problem" (Cambridge Dictionary 2022)

Code

"a language used to program (= give instructions to) computers" (Cambridge Dictionary 2022)

Efficiency

"the difference between the amount of energy that is put into a machine in the form of fuel, effort, etc. and the amount that comes out of it in the form of movement" (Cambridge Dictionary 2022)

Fuel efficiency

"a measure of how much energy is produced by an engine in relation to the amount of fuel that it uses" (Cambridge Dictionary 2022)

Macro

"a single instruction given to a computer that produces a set of instructions for the computer to perform a particular piece of work" (Cambridge Dictionary 2022)

Propeller

"a device with two or more blades that spin around to produce a force for moving the ship or aircraft to which it is attached" (Cambridge Dictionary 2022)

1 Introduction

1.1 Motivation

More then 1000 students (Scholz 2020b) have already worked with the Preliminary Sizing Tool Classic (PreSTo-Classic-Jet). The spreadsheet is available for jets as well as for propeller driven aircraft (PreSTo-Classic-Prop). The aim of this project is to further improve PreSTo-Classic-Prop. A sophisticated calculation method with respect to the propeller efficiency leads to an easy understandable spreadsheet. As propeller driven aircraft have a higher fuel efficiency than jets, they might come back into the spotlight in the near future. Therefore, PreSTo-Classic-Prop can be used parallel to the lecture by students designing new propeller driven aircraft.

An optimization of the aircraft design is given in the follow-on spreadsheet Simple Aircraft Sizing and Optimization (SAS). This is openly available for jets only. As the transfer from jets to props has already been done, the second aim of this project is to further improve SAS-Part25-Prop for propeller driven aircraft. The goal is to prepare SAS-Part25-Prop for Open Access.

1.2 Title Terminology

Preliminary
The term *preliminary* means "*coming before a more important action or event, esp. introducing or preparing for it*" (Cambridge Dictionary 2022). In this case preliminary sizing an aircraft prepares for a detailed sizing of such.

Sizing
The term *sizing* means to determine "*the degree to which something or someone is large or small*" (Cambridge Dictionary 2022). In this case the size of various aircraft parameters is to be determined.

Propeller
A *propeller* is "*a device with two or more blades that spin around to produce a force for moving the ship or aircraft to which it is attached*" (Cambridge Dictionary 2022).

Aircraft
An *aircraft* is "*any vehicle, with or without an engine, that can fly, such as a plane or helicopter*" (Cambridge Dictionary 2022).

Part 25
This states that only large airplanes certified by CS25 (EASA 2021) are considered.

1.3 Objectives

The objective of this project is to study possible estimations of the propeller efficiency. Furthermore, proper estimation methods are to be implemented in PreSTo-Classic-Prop.

The second objective is to track down and then implement improvements of SAS-Part25-Prop.

1.4 Literature Review

This work is based on the initial versions of PreSTo-Classic-Prop and SAS-Part25-Prop developed by Nita (2008) and Garcia (2013).

The fundamentals of preliminary sizing of this work are mainly based on Scholz (2015) and Loftin (1980) with respect to the certification speficitations (CS25) stated in EASA (2021).

Estimation methods of the propeller efficiency are mainly based on Marckwardt (1998) (and therefore Wolf (2009)), Truckenbrodt (1996) and Truckenbrodt (1999).

1.5 Structure of the Work

The structure of this work is as follows:

Chapter 2 states previous work covering propeller efficiency estimation, PreSTo-Classic and SAS for jets and props.

Chapter 3 covers fundamentals of preliminary sizing, its optimization and discusses the main influence parameters on propeller efficiency.

Chapter 4 deals with methods to estimate propeller efficiency and discusses their quality based on Chapter 3.

Chapter 5 states further improvements made in PreSTo-Classic-Prop structured according to the worksheets.

Chapter 6 evaluates the implementations of propeller efficiency estimation methods in PreSTo-Classic-Prop by redesigning the ATR 72-600.

Chapter 7 states improvements made in SAS-Part25-Prop.

Chapter 8 gives a summary and a conclusion of the implementations made in PreSTo-Classic-Prop and SAS-Part25-Prop.

Chapter 9 covers recommendations for future work.

Appendix A shows the code for propeller efficiency calculation in cruise in PreSTo-Classic-Prop.

Appendix B shows the code for interpolating the speed of sound in PreSTo-Classic-Prop.

Appendix C shows the macro of DE Algorithm from SAS-Part25-Prop.

Appendix D shows the macro of DOE Diagonal Algorithm from SAS-Part25-Prop.

The associated Excel spreadsheets SAS-Part25-Prop and PreSTo-Classic-Prop are seperatly available at: https://doi.org/10.7910/DVN/ET4ZKV .

2 State of the Art

Marckwardt (1998) presents a diagram of propeller efficiency estimation. The propeller efficiency is dependent on velocity and disc loading in this diagram.

Nita (2008) developed PreSTo-Classic-Prop based on PreSTo-Classic-Jet in collaboration with Prof. Dr. Dieter Scholz, University of Applied Sciences Hamburg, Department of Automotive and Aeronautical Engineering. This work was based on the diagram of Marckwardt (1998) and theory stated in Scholz (2015). Improvements made in PreSTo-Classic-Prop stated in this work are based on this version.

Scholz (2015) states the theoretical background of preliminary sizing used for lecture based on Loftin (1980), Roskam (1989), Torenbeek (1982) and others.

Wolf (2009) studied the diagram of Marckwardt (1998). A development of an equation to depict the diagram has taken place.

Johanning (2013) pesents fundamentals of propeller efficiency calculation as well as the influence of the main parameters on propeller efficiency. Furthermore, he states various calculation methods from the diagram of Marckwardt (1998) to formulas stated in Truckenbrodt (1999) based on theory. In addition, he refers to Adkins (1994).

Adkins (1994) presents a calcualtion method of propeller efficiency based on theory. The work takes into account influences of friction as well as influences of a high Mach number resulting in shock waves.

Scholz (2020a) describes various propeller efficiency estimations. He refers to Marckwardt (1998) as well as to theory based formulas stated in Truckenbrodt (1996) and Truckenbrodt (1999).

Truckenbrodt (1996) states a propeller efficiency calculation method based on theory and explains its derivation.

Truckenbrodt (1999) states a propeller efficiency estimation method based on Betz (1959). This considers the influence of the advance ratio in addition to Truckenbrodt (1996).

Heinemann (2012) developed SAS-Part25-Jet for jets.

Garcia (2013) developed SAS-Part25-Prop. This is based on Heinemann (2012) as well as on PreSTo-Classic-Prop. This has been the starting point of SAS-Part25-Prop improvements stated in this work.

3 Fundamentals

This section covers the fundamentals of preliminary sizing and its optimization. Furthermore, fundamentals of the propeller efficiency and the main parameters to influence it are discussed.

3.1 Preliminary Sizing

The preliminary sizing of a propeller driven aircraft is defined by requirements from certifications, airworthiness and maneuverability. The presented method and equations refer to Loftin (1980). The method of preliminary sizing is therefore dived into the sizening flight phases: landing, take-off, 2nd segment, missed approach, and cruise. Finally, calcutions of fuel mass and maximum take-off mass are done.

Any values of constansts k that are not further explained in this work have been evaluated in a parameter statistic in Nita (2008).

A propeller efficiency becomes necessary in take-off, 2nd segment, missed approach and cruise. This is explained in Chapter 3.2.

3.1.1 Landing

For landing an aircraft it is necessary that the landing field length is equal to or longer than the landing distance divided by a safety factor of 0.7 as presented in Figure 3.1. The aircraft is set to a landing configuration in this flight phase.

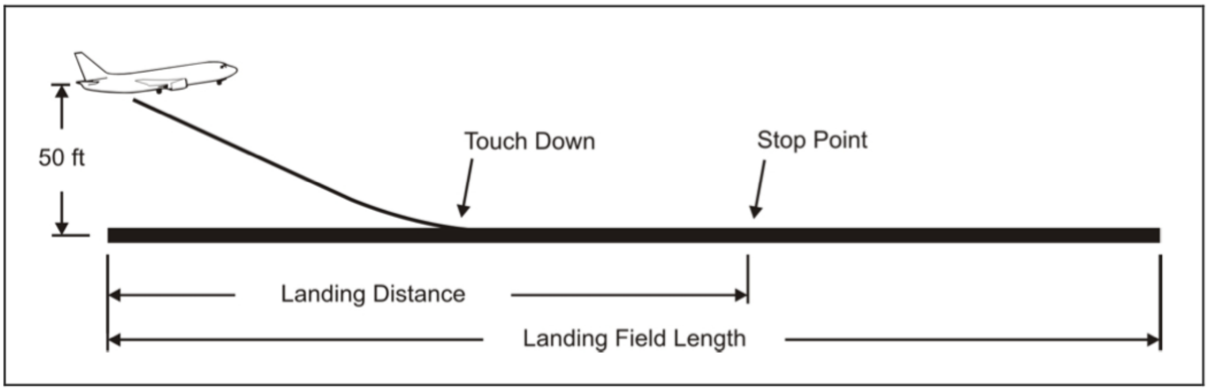

Figure 3.1 Definition of the landing field length according to CS and FAR (Scholz 2020a)

A relation of the approach speed and the landing field length is defined as

$$V_{APP} = k_{APP} \cdot \sqrt{s_{LFL}} \quad . \tag{3.1}$$

Therefore, either the approach speed or the landing field length has to be known for preliminary sizing. The landing field length is then used to calculate the wing loading at maximum landing mass as defined in (3.2).

$$m_{ML}/S_W = k_L \cdot \sigma \cdot C_{L,max,L} \cdot s_{LFL} \tag{3.2}$$

The maximum lift coefficient in landing can be estimated from statistics. In case of a redesign, it can also be estimated by (3.3). This eqation is based on the assumption that lift is equal to weight.

$$C_{L,max,L} = \frac{2 \cdot m_{ML} \cdot g}{\rho \cdot S_W \cdot V_{S,0}^2} \tag{3.3}$$

With the mass ratio of maximum landing mass over maximum take-off mass the wing loading at the maximum take-off mass is defined by

$$m_{MTO}/S_W = \frac{m_{ML}/S_W}{m_{ML}/m_{MTO}} \quad . \tag{3.4}$$

3.1.2 Take-off

The aircraft is set to a take-off configuration in this flight phase.

In the take-off phase a slope defines the minimum value of the power-to-weight ratio as a function of the wing loading at maximum take-off mass.

$$a = \frac{P_{S,TO}/m_{MTO}}{m_{MTO}/S_W} = \frac{k_{TO} \cdot 1{,}2 \cdot g \cdot V_{S,1}}{s_{TOFL} \cdot \sigma \cdot C_{L,max,TO} \cdot \eta_{P,TO} \cdot \sqrt{2}} \tag{3.5}$$

The slope is dependent on the take-off field length which must be known. With all engines working, the take-off field length is defined as 115% of the distance required to fly over an obstacle of 35 ft (EASA 2021). In case there is a failure of one engine after the decision speed is reached the pilot has to proceed the take-off. If the failure occurs before the decision speed is reached the pilot has to brake to stop the aircraft. The distance required for this is called balanced field length, as can be seen in Figure 3.2. The balanced field length defines the take-off field length if it is the larger one. In either case the required take-off field length has to be smaller than the available take-off field length.

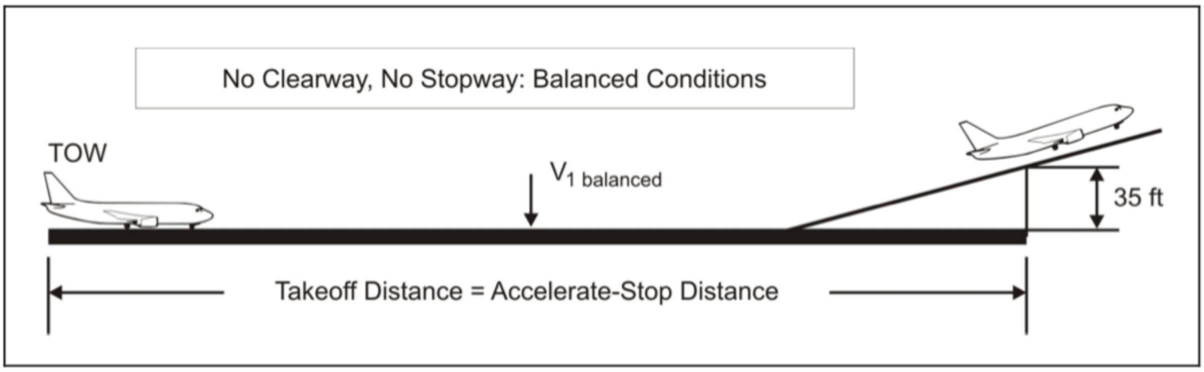

Figure 3.2 Definition of balanced field length (Scholz 2020a)

The maximum lift coefficient in take-off comes from statistics or is estimated by

$$C_{L,max,TO} = 0.8 \cdot C_{L,max,L} \quad . \tag{3.6}$$

With the stall speed in landing configuration defined by rules of cetifications as

$$V_{S,0} = \frac{V_{APP}}{1.3} \tag{3.7}$$

the stall speed in take-off configuration becomes

$$V_{S,1} = V_{S,0} \cdot \sqrt{\frac{C_{L,max,L}}{C_{L,max,TO}}} \quad . \tag{3.8}$$

The constant value of 1.3 has been changed to 1.23 in CS 25 (EASA 2021). As the original ATR 72 has been designed with a factor of 1.3 this value is considered here. The value can be changed in PreSTo-Classic-Prop if necessary.

The power-to-weight ratio at the wing loading at maximum take-off mass is calculated by multiplying the slope (3.5) by the wing loading at maximum take-off mass (3.4) defined in Subchapter 3.1.1.

3.1.3 Climb Rate during 2nd Segment

In 2nd segment the climb rate is sizing during this phase. With a failure of one engine the other engines are at maximum power. The aircraft is still set in take-off configuration, but the landing gear is retracted.

A generall relation between a lift coefficient and the maximum lift coefficient is given by

$$C_L = C_{L,max} \cdot \left(\frac{V_S}{V}\right)^2 \quad . \tag{3.9}$$

Therefore, the lift coefficient in take-off is

$$C_{L,TO} = \frac{C_{L,max,TO}}{1.2^2} \quad . \tag{3.10}$$

The lift-to-drag ratio is dependent on the lift coefficient and defined by

$$E_{TO} = \frac{C_{L,TO}}{C_{D,P} + \frac{C_{L,TO}^2}{\pi \cdot A \cdot e}} \tag{3.11}$$

with the Oswald factor equal to 0.7 due to extended slats and flaps. The profile drag can further be defined by

$$C_{D,P} = C_{D,0} + \Delta C_{D,flap} + \Delta C_{D,slat} + \Delta C_{D,gear} \tag{3.12}$$

with

$$\Delta C_{D,flap} = 0.05 \cdot C_{L,TO} - 0.055 \tag{3.13}$$

valid for a lift coefficient of at least 1.1. With the landing gear retracted $\Delta C_{D,gear}$ is equal to zero. $\Delta C_{D,slat}$ is neglectable. $C_{D,0}$ can be set to 0.02 for a passenger aircraft.

Then a lower boundary of the power-to-weight ratio is given as a function of the number of engines.

$$\frac{P_{S,TO}}{m_{MTO}} = \left(\frac{n_E}{n_E - 1}\right) \cdot \left(\frac{1}{E_{TO}} + \sin\gamma\right) \cdot \left(\frac{V_2 \cdot g}{\eta_{P,2nd}}\right) \tag{3.14}$$

The take-off speed is equal to the stall speed in take-off configuration multiplied by 1.2.

$$V_2 = 1.2 \cdot V_{S,1} \tag{3.15}$$

The still unknown gradient of climb is defined in EASA (2021) in dependency of the number of engines. This is shown in Table 3.1.

Table 3.1 Gradient of climb during 2nd segment according to EASA (2021)

Number of Engines	Gradient of Climb	$\sin\gamma$
2	2.4 %	0.024
3	2.7 %	0.027
4	3.0 %	0.03

3.1.4 Climb Rate during Missed Approach

The aircraft is set to landing configuration during missed approach. There is a failure of one engine with the remaining engines at maximum power according to CS 25. The landing gear is retracted according to CS 25 but still extended according to FAR 25.

In simililarity to (3.10) the lift coefficient in landing is dependent on the maximum lift coefficient in landing.

$$C_{L,L} = \frac{C_{L,max,L}}{1.3^2} \tag{3.16}$$

As the aircraft is in landing configuration, the lift-to-drag ratio in landing is of importance during missed approach. The Owald factor is still set to 0.7.

$$E_L = \frac{C_{L,L}}{C_{D,P} + \frac{C_{L,L}^2}{\pi \cdot A \cdot e}} \tag{3.17}$$

Again, the profile drag is estimated by (3.12) with

$$\Delta C_{D,flap} = 0.05 \cdot C_{L,L} - 0.055 \tag{3.18}$$

valid for a lift coefficient of at least 1.1. In similarity to the 2nd segment $C_{D,0} = 0.02$ and $\Delta C_{D,slat} = 0$ are set. $\Delta C_{D,gear}$ is equal to zero for CS 25 and equal to 0.015 for FAR 25.

The power-to-weight ratio is defined similar to (3.14). In like manner, it is a lower boundary of power-to-weight ratio as a function of the number of engines. The mass ratio of the maximum landing mass over the maximum take-off mass has been defined in Subchapter 3.1.1 and is considered known.

$$\frac{P_{S,TO}}{m_{MTO}} = \left(\frac{n_E}{n_E - 1}\right) \cdot \left(\frac{1}{E_L} + \sin\gamma\right) \cdot \left(\frac{V_2 \cdot g}{\eta_{P,MA}}\right) \cdot \frac{m_{ML}}{m_{MTO}} \tag{3.19}$$

The gradient of climb during missed approach differs from the one during 2nd segment. Table **3.2** shows the gradient of climb according to EASA 2021.

Table 3.2 Grandient of climb during missed approach according to EASA (2021)

Number of Engines	Gradient of Climb	$\sin\gamma$
2	2.1 %	0.021
3	2.4 %	0.024
4	2.7 %	0.027

3.1.5 Cruise

A stationary straight flight at cruise altitude is assumed for this section. In cruise, the power-to-weight ratio and the wing loading are calculated separately each as a function of height.

The power-to-weight-ratio is based on the equilibrium equation *drag=thrust*.

$$\frac{P_{S,TO}}{m_{MTO}} = \frac{V_{CR} \cdot g}{\frac{P_{CR}}{P_{S,TO}} \cdot E \cdot \eta_{P,CR}} \tag{3.20}$$

The lift-to-drag ratio for this equation needs to be further defined. The maximum lift-to-drag ratio can be defined as

$$E_{max} = k_E \cdot \sqrt{A/(S_{wet}/S_W)} \quad . \tag{3.21}$$

The relative wetted area is in a range from 6.0 to 6.2 for commercial aircraft. Furthermore, a realtion between the actual and the minimum drag lift coefficienct and speed is defined.

$$\frac{C_L}{C_{L,md}} = \frac{1}{\left(\frac{V}{V_{md}}\right)^2} \tag{3.22}$$

The ratio of speed over minimum drag speed is approximately 1 for propeller driven aircraft. Finally, the lift-to-drag ratio in cruise is calculatable by (3.23).

$$E = \frac{2 \cdot E_{max}}{\frac{1}{\left(\frac{C_L}{C_{L,md}}\right)} + \left(\frac{C_L}{C_{L,md}}\right)} \tag{3.23}$$

In (3.20) the ratio of the power in cruise over the take-off power is still unknown. A research of this power variation with height has been studied by Nita (2008). Therefore, the formula used in PreSTo-Classic-Prop is stated here only.

$$P_{CR}/P_{S,TO} = c \cdot M^j \cdot \sigma^f \tag{3.24}$$

The following values apply for the PW 120 family and therefore for the ATR 72.

$$c = 1.8829 \tag{3.25}$$

$$j = 0.7409 \tag{3.26}$$

$$f = 0.9287 \tag{3.27}$$

As the relative density differs with height, the power-to-weight ratio is dependent on height.

Secondly, the wing loading as a function of height is needed. Equation (3.28) is based on the equilibrium equation *lift=weight*.

$$\frac{m_{MTO}}{S_W} = \frac{C_L \cdot \gamma \cdot M_{CR}^2 \cdot p}{2 \cdot g} \tag{3.28}$$

This equation is dependent on the pressure and therefore dependent on height. The lift coefficient in cruise has not been defined, yet. With (3.21), (3.22) and

$$C_{L,md} = \frac{\pi \cdot A \cdot e}{2 \cdot E_{max}} \tag{3.29}$$

with an Oswald factor of 0.85 the lift coefficient can be caluated by

$$C_L = C_{L,md} \cdot \left(\frac{C_L}{C_{L,md}}\right) \ . \tag{3.30}$$

Finally, the wing loading and the power-to-weight ratio can be listed in a chart with a variation of height. A connection of the datapoints will result in the line seen in a matching chart.

3.1.6 Matching Chart

All sizening flight phases reprensent one line in the matching chart. A hypothetical matching chart is depicted in Figure 3.3. The line for landing represents an upper boundary of the wing loading whereas the lines for take-off, cruise, missed approach and 2nd segment represent a lower boundary of the power-to-weight ratio. The design point is set as the lowest possible power-to-weight ratio as first priority and as the highest wing loading as second priority.

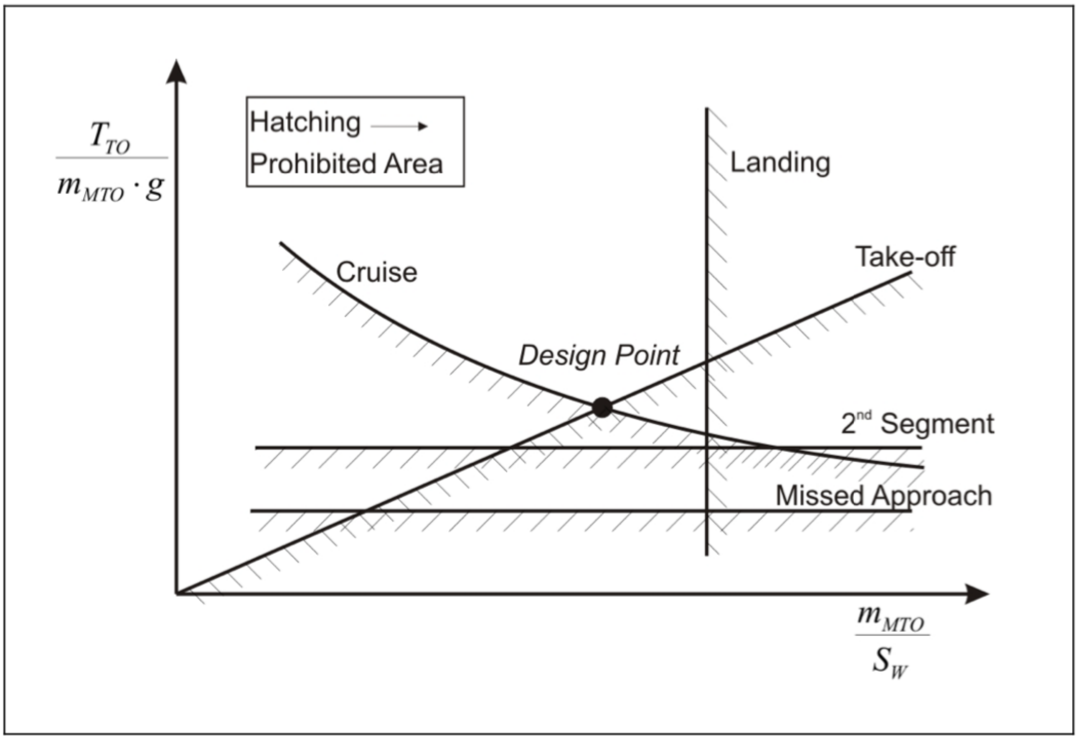

Figure 3.3 Hypothetical Matching Chart (Scholz 2015)

3.1.7 Maximum Take-off Mass

The maximum take-off mass consists of the operating empty mass, the fuell mass and the pay-load as defined in (3.31).

$$m_{MTO} = \frac{m_{PL}}{1 - \frac{m_F}{m_{MTO}} - \frac{m_{OE}}{m_{MTO}}} \tag{3.31}$$

The relative operating empty mass can be approximated from statistics. In case of a redesign the value can be calculated directly from the original data as it will be done in Chapter 6. The relative fuel mass can be calculated with the total mission fuel fraction.

$$m_F/m_{MTO} = 1 - M_{ff} \tag{3.32}$$

This consists of a mass ratio for each flight phase. Figure 3.4 shows these flight phases. The mission segment mass fractions of take-off, climb, descent, landing, start-up and taxi are stated in Table 3.3 based on Roskam (1989).

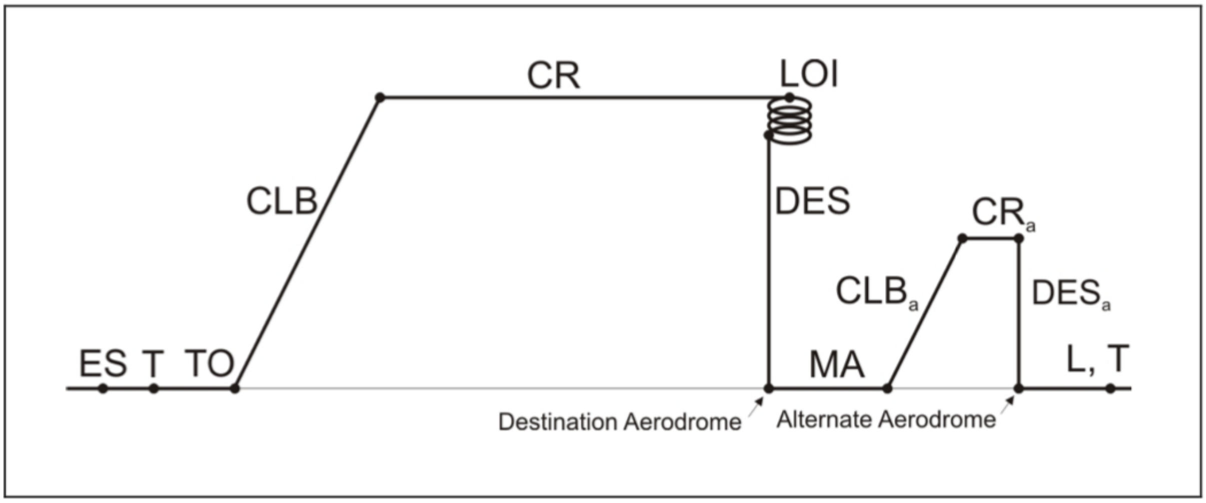

Figure 3.4 Typical flight phases of a civil transport flight mission (Scholz 2020a)

Table 3.3 Mission segment mass fractions (based on Roskam (1989))

Flight phase	take-off	climb	descent	landing	start-up	taxi
Mass fraction	0.995	0.985	0.985	0.995	0.990	0.995

The mass fractions for cruise and loiter need to be calculated with the help of the Breguet range factor.

$$B_s = \frac{E \cdot \eta_{P,CR}}{SFC_P \cdot g} \tag{3.33}$$

The performance specific fuel consumption can be estimated from statistics. Apart from that, the value can be taken from the manufacturer's factsheet of the engine in case of a redesign. The mission fuel fraction for cruise can then be defined as

$$M_{ff,CR} = e^{-\frac{R}{B_s}} \ . \tag{3.34}$$

In similar matter, the mission fuel fraction of the reserves is defined.

$$M_{ff,RES} = e^{-\frac{R_{RES}}{B_s}} \ . \tag{3.35}$$

The Breguet factor for time is necessary for the mass fraction for loiter.

$$B_t = B_s / V_{CR} \tag{3.36}$$

Then the mission fuel fraction for loiter is defined as

$$M_{ff,LOI} = e^{-\frac{t_{LOI}}{B_t}} \quad . \tag{3.37}$$

The mission fuel fraction of a standard flight is then

$$M_{ff,std} = M_{ff,TO} \cdot M_{ff,CLB} \cdot M_{ff,CR} \cdot M_{ff,DES} \cdot M_{ff,L} \tag{3.38}$$

and the mission fuel fraction for the reserves is

$$M_{ff,res} = M_{ff,CLB} \cdot M_{ff,RES} \cdot M_{ff,LOI} \cdot M_{ff,DES} \quad . \tag{3.39}$$

The total mission fuel fraction therefore becomes

$$M_{ff} = M_{ff,std} \cdot M_{ff,res} \quad . \tag{3.40}$$

Finally, the maximum take-off mass can be calculated. Next, all remaining aircraft parameters such as the maximum landing weight, operating empty mass, fuel mass, wing area and the take-off power are directly calculatable.

A final check of assumptions is made. The preliminary sizing is done when (3.41) is true.

$$m_{ML} > m_{OE} + m_{MPL} + m_{F,res} \tag{3.41}$$

3.2 Propeller Efficiency

The propeller efficiency is needed for take-off, 2nd segment, missed approach and cruise as seen in Chapter 3.1. This section states the influence of main parameters on the propeller efficiency and general relations. Concrete methods to estimate a value of the propeller efficiency are presented and discussed in Chapter 4.

Based on Johanning (2013) the main parameters to influence the propeller efficiency are density, cruise speed and the propeller diameter. The efficiency of a propulsive devise is dependent on the mass flow, the cuise speed and the speed difference of income and outcome. As the mass flow is dependent on the three main parameters mentioned above, these could be considered best as high as possible.

On one hand a high aircraft speed leads to a high propeller efficiency. Moreover, a high aircraft speed will enable a higher number of trips and therefore lower the operating costs per seat-mile. On the other hand, the higher the cruise speed the higher is the speed at the propeller blade tip. If this speed reaches the speed of sound, shock waves will be produced. As the shock waves rapidly increase the wave drag and reduce the lift coefficient, both resulting in a reduction of thrust, the propeller efficiency will decrease. With decresing propeller efficiency, the fuel consumption increases leading to higher operating costs. Therefore, there must be a trade-off between the propeller efficiency and the cruise speed.

Also, an increase in density will increase the propeller efficiency. Therefore, propeller driven aircraft should fly as low as possible. But as commercial aircraft have a design altitude of 7000 m to 12000 m (Johanning 2013) the propeller efficiency is influenced negatively.

The third parameter is the propeller diameter. A larger diameter will lead to a larger propeller area and therefore increase propeller efficiency. This can also be reached by a higher number of engines when accepting the additional costs of maintenance and mass. A large propeller diameter has the same disadvantage as a high cruise speed. The larger the propeller diameter the higher is the speed at the propeller blade tip. If this speed reaches the speed of sound, the shock waves with the same consequences as stated above occur. Therefore, a trade-off between the propeller efficiency and the propeller diameter is necessary.

The general design of the propeller also influences its efficiency. To provide the maximum lift-to-drag ratio, the incidence angle of a propeller blade changes from root to tip to allow an optimum angle of attack at each blade section. Of course, different airfoils are therefore necessary along the blade sections. But as the cruise speed changes during flight the angle of attack also changes. Changing the rotational speed with changing cruise speeds solves this problem, but the engine could therefore not work at its maximum engine efficiency as this is linked with an optimum rotational speed. The better option is to change the incidence angle of the whole blade as it is done by a variable pitch propeller. Therefore, the rotational speed can stay constant at the optimum rotational speed for the maximum engine efficiency. In this case the variable pitch propeller is called constant speed propeller. The high efficiency of the engine is therefore combined with high efficiency of the propeller leading to a good fuel efficiency and performance, especially at high altitudes.

Figure 3.5 shows the influence of the blade angle on the propeller efficiency. The maximum value of the propeller efficiency stays nearly constant whereas the related advance ratio increases. If the circumferential speed is taken constant, that means that a higher speed requires a larger blade angle to achieve the same propeller efficiency. As mentioned above the propeller efficiency is kept nearly constant by changing the blade angle using a constant speed propeller.

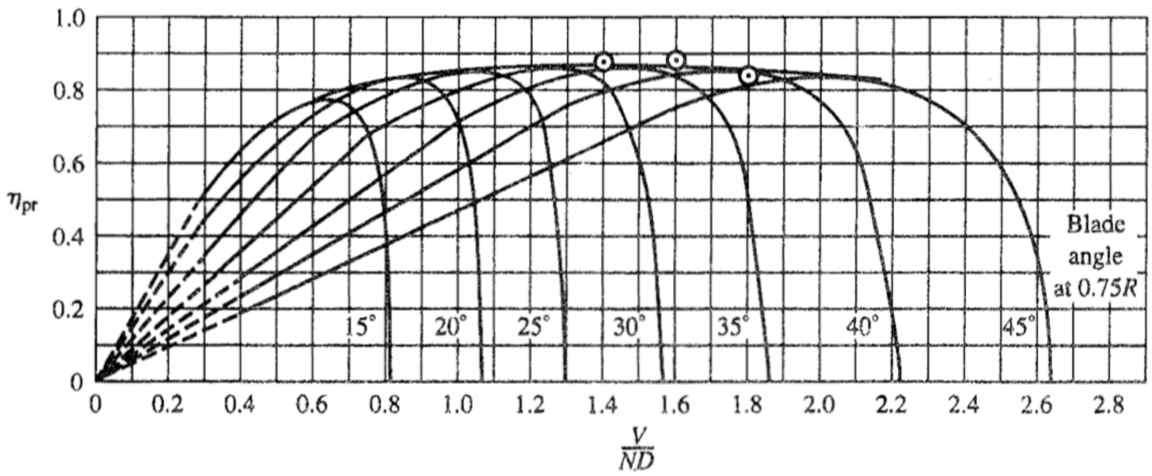

Figure 3.5 Propeller efficiency of various blade angles over advance ratio (Anderson 1999)

3.3 Optimization of Preliminary Sizing

The optimization of preliminary sizing is presented in SAS-Part25-Prop. The calculations are based on the equations used in PreSTo-Classic-Prop presented in Chapter 3.1. The optimization is that macros are used to automate the process. The design point is found by the tool automatically with help of the Excel Solver. Furthermore, the design point is variable on the design goal chosen. In addition, algorithms are used to vary the input data automatically to achieve the best value of a chosen output parameter. The algorithms are called Design of Experiments Diagonal Algorithm and Differential Evolution Algorithm. For more information of these lower- and upper-level evaluations refer to Garcia (2013) for SAS-Part25-Prop. The slightly adapted code (as described in Chapter 7) is also presented in Appendix C and Appendix D.

4 Propeller Efficiency Calculation

As described in Chapter 3 it is necessary to estimate the propeller efficiency for preliminary sizing. This chapter states different methods of propeller efficiency estimation and explains how they are implemented in PreSTo-Classic-Prop.

4.1 Methods Based on Diagrams

So far, in PreSTo-Classic-Prop the propeller efficiency was estimated with Figure 4.1. This diagram has been generated by and used in the lecture of Marckwardt (1998). The disadvantage of such diagrams is that its origin might be unknown.

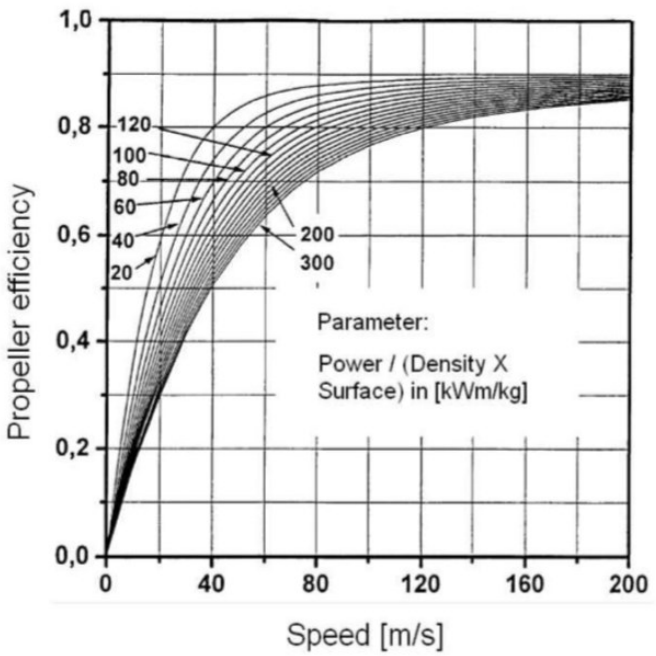

Figure 4.1 Propeller efficiency over speed (Johanning (2013) based on Marckwardt (1998))

According to Johanning (2013), Figure 4.1 might be based on (4.14) (see Chapter 4.2). The similarity of both functions can be seen in Figure 4.2. According to the small deviation, Marckwardt (1998) could have used a different circumferential speed to generate Figure 4.1 as Johanning (2013) has used in Figure 4.2 (see Chapter 4.2). It has to be mentioned that the disc loading defined by Marckwardt (1998) varies from the definition of the disc loading by Truckenbrodt (1999) by the factor 2. This is to be considered when comparing both functions.

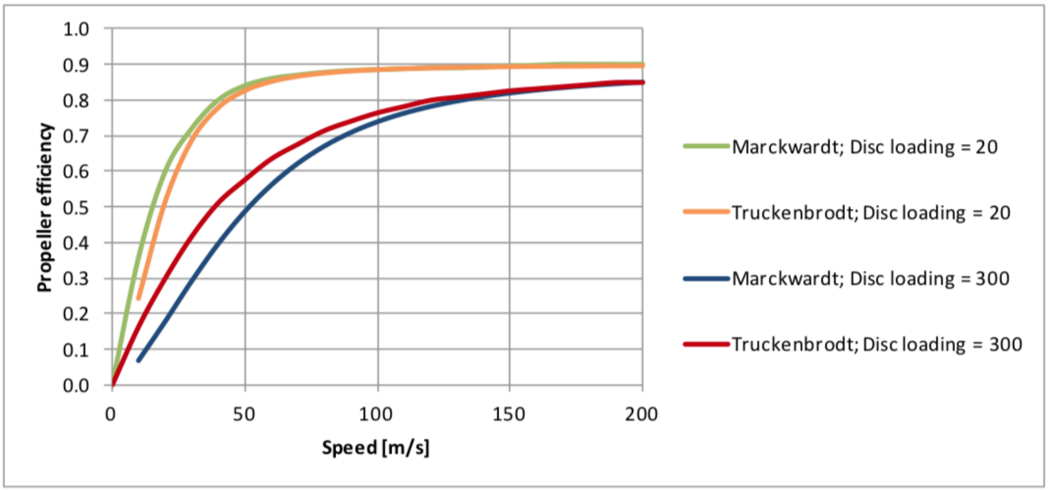

Figure 4.2 Comparison of Marckwardt (1998) and Truckenbrodt (1999) (Johanning 2013)

The diagram of Marckwardt (1998) shows a dependency of the propeller efficiency on the speed, density and propeller area. Therefore, all main parameters stated in Chapter 3.2 have been taken into account. But as the propeller efficiency reaches its maximum at maximum speed, the influence of the shock waves has not been considered. Hence, the diagram is to be used for low speeds only.

Diagrams are at a disadvantage with equations as it is not possible to evaluate an outcome automatically. Furthermore, if the outcome is evaluated by hand from a printed diagram the deviation might be high. For these reasons, the propeller efficiency calculation in PreSTo-Classic-Prop is automated with equations.

In like manner, Wolf (2009) studied the diagram in Figure 4.1. To be precise, he measured datapoints of the diagram by hand and used them to develop an equation. The equation that depicted the diagram best is

$$\eta_P = \varsigma - \varsigma \cdot e^{-k \cdot V} \tag{4.1}$$

with

$$\varsigma = -0.0002 \cdot L_D + 0.001 \tag{4.2}$$

and with

$$\mathrm{k} = 0.134 \cdot {L_D}^{-0.3008} \quad . \tag{4.3}$$

Figure 4.3 plots the original functions of Figure 4.1 as well as functions developed with (4.1). Moreover, Figure 4.3 illustrates that there is a small deviation only.

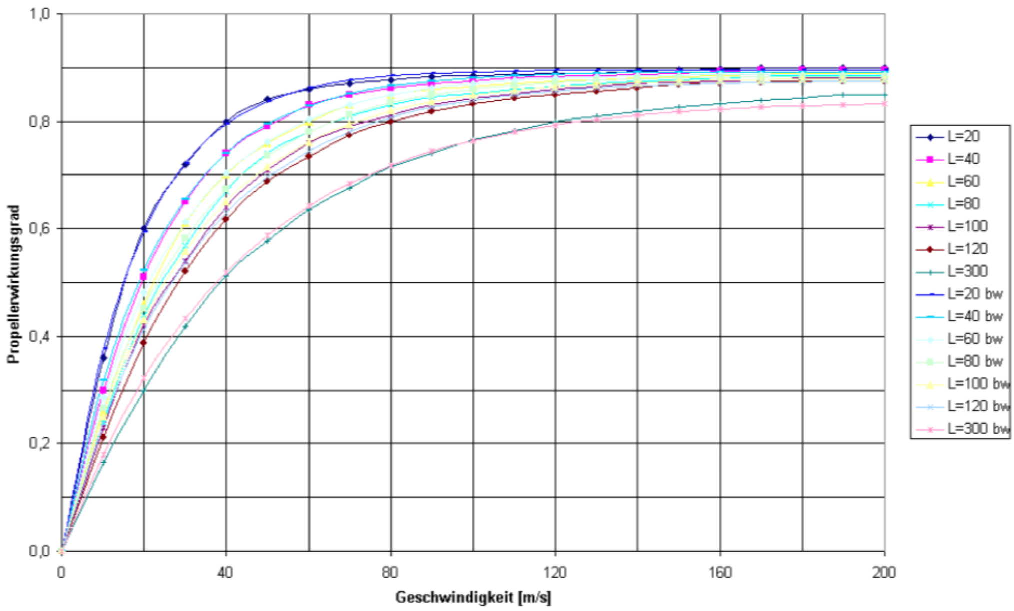

Figure 4.3 Propeller efficiency over Speed (Wolf 2009)

Stated in Chapter 3.2 is the loss of propeller efficiency at high Mach numbers due to the shock waves. As can be seen in Figure 4.3 the propeller effiency reaches its maximum at maximal speed. Again, this means that the influence of high Mach numbers is not considered in (4.1). The propeller efficiency calculation with (4.1) is therefore only valid for a first estimation at low cruise speeds.

4.2 Methods Based on Theory

The first method described is based on Truckenbrodt (1996). For a general estimation of a propeller efficiency the available power is divided by the total power.

$$\eta_{P,th} = P_A / P_T = V_1 / V_S \tag{4.4}$$

The speed V_S at which the propeller is passed is the arithmetic average of the speeds V_1 and V_4. These speeds are at the same pressure as can be seen in Figure 4.4.

$$V_S = 0.5 \cdot (V_1 + V_4) \tag{4.5}$$

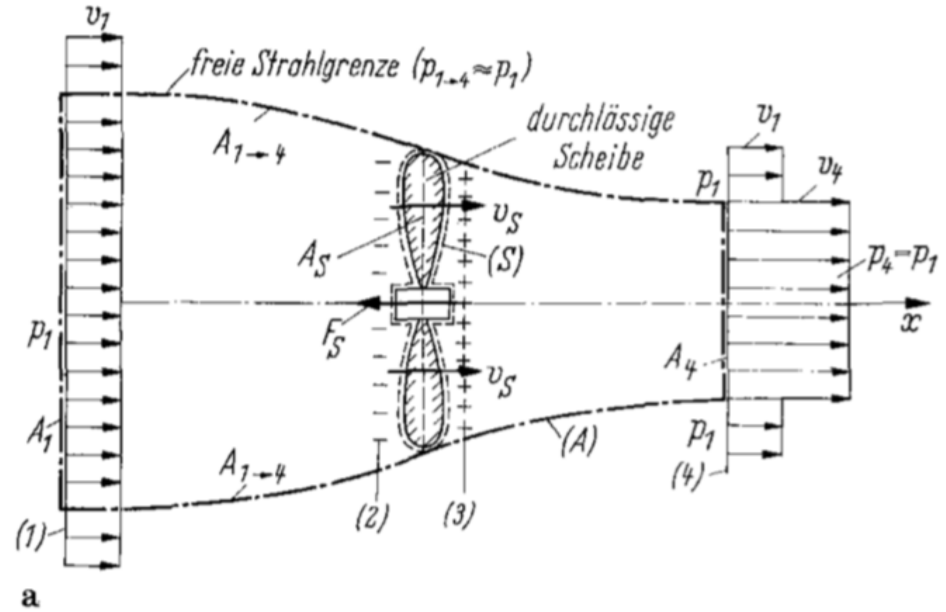

Figure 4.4 Flow thourgh a propeller (Truckenbrodt 1996)

Inserting (4.5) in (4.4) leads to (4.6).

$$\eta_{P,th} = \frac{2}{1 + V_4/V_1} \tag{4.6}$$

The ratio of V_4 over V_1 is defined by Truckenbrodt (1996) as

$$V_4/V_1 = \sqrt{1 + c_S} \quad . \tag{4.7}$$

Inserting (4.7) in (4.6) leads to the theoretical propeller efficiency

$$\eta_{P,th} = \frac{2}{1 + \sqrt{1 + c_S}} \tag{4.8}$$

with

$$c_S = \frac{2 \cdot L_D}{V^3} \quad . \tag{4.9}$$

The theoretical propeller efficiency is an upper boundary, which is not reachable in practice. Therefore, a quality grade based on experience leads to an estimation of the real propeller efficiency.

$$\eta_P = \zeta \cdot \eta_{P,th} \tag{4.10}$$

Inserting (4.8) and (4.9) in (4.10) leads to the final formula of the first method (4.11).

$$\eta_P = \zeta \cdot \frac{2}{1 + \sqrt{1 + \frac{2 \cdot L_D}{V^3}}} \tag{4.11}$$

This equation is used in PreSTo-Classic-Prop with the quality grade set to 0.9. Truckenbrodt (1996) suggests a value in the range of 0.85 to 0.9. In addition, Betz (1959) states a value of 0.9. The main influences on propeller efficiency have been stated in Chapter 3. Equation (4.11) takes into account the density and disc area within the disc loading. Also, the influences of friction are taken into account with the quality grade and the velocity is considered in general. On the other hand, there is no consideration of the loss of spin. Turning now to another matter, Figure 4.5 depicts (4.11) for various disc loadings exemplary. The quality grade is set to 0.9 in this figure.

The propeller efficiency rises here continuously with higher speeds. Comparing this to the influence of the shock waves stated in Chapter 3.2, the influence of a high Mach number has clearly not been taken into account. For this reason, (4.11) is to use for a first estimation at low speeds only.

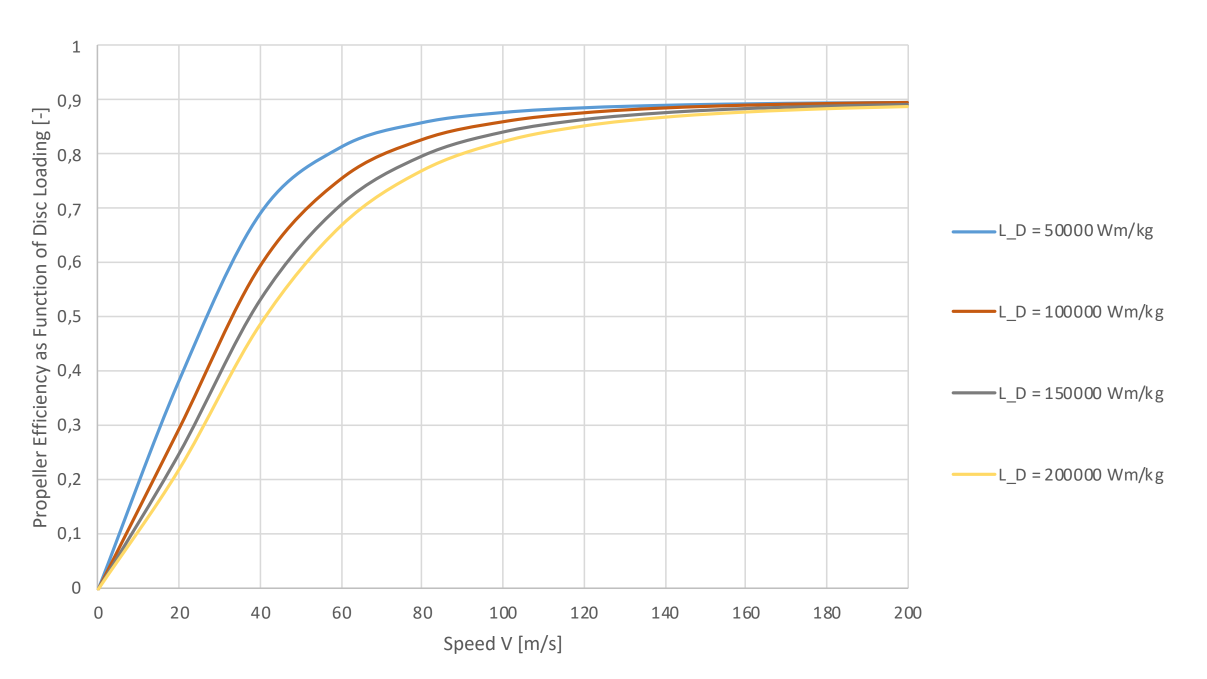

Figure 4.5 Propeller efficiency over speed genererated with (4.11)

The second calculation method presented here is defined in Truckenbrodt (1999) as well as in Betz (1959). The propeller efficiency is an approximate estimation as defined in (4.12).

$$\eta_P \approx \frac{2 - 2 \cdot \lambda^2 \cdot \ln\left(1 + \frac{1}{\lambda^2}\right)}{1 + \sqrt{1 + \frac{2 \cdot L_D}{V^3} - 2 \cdot \lambda^2 \cdot \ln\left(1 + \frac{1}{\lambda^2}\right)}} \tag{4.12}$$

This formula is based on the same theory in general. Hence, the density and disc area are considered again by the disc loading, and the velocity is considered in general. In contrast to (4.11), (4.12) is dependent on the advance ratio. Therefore, the loss of spin is considered here. An estimation of the advance ratio is presented in Chapter 4.3.

The influence of the advance ratio is depicted in Figure 4.6. This figure is generated with (4.13). Inserting (4.7) and (4.9) in (4.13) will lead back to (4.12).

$$\eta_P \approx \frac{2 - 2 \cdot \lambda^2 \cdot \ln\left(1 + \frac{1}{\lambda^2}\right)}{1 + \frac{V_4}{V_1} - 2 \cdot \lambda^2 \cdot \ln\left(1 + \frac{1}{\lambda^2}\right)} \tag{4.13}$$

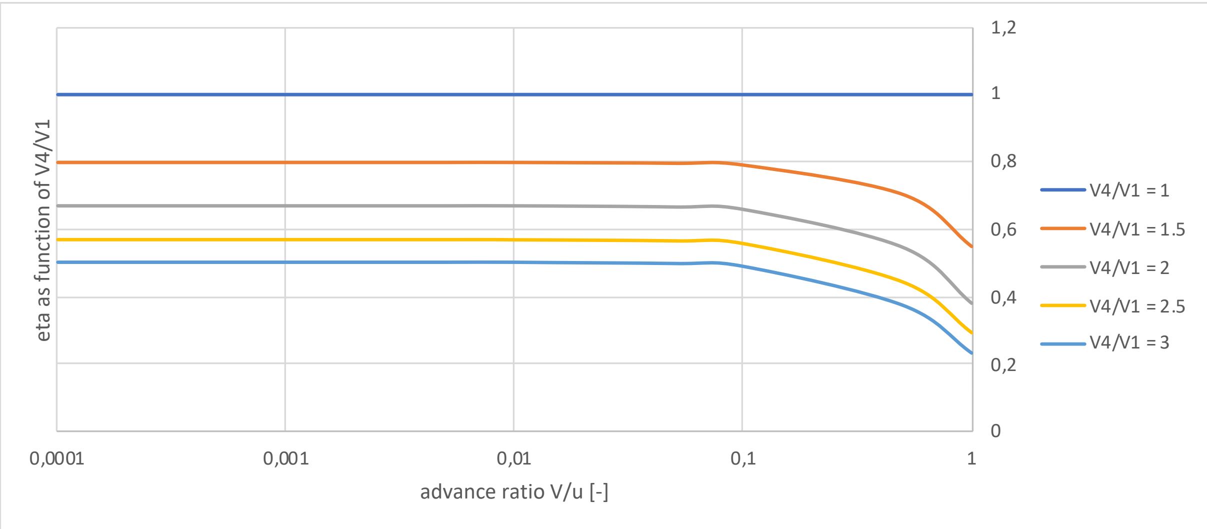

Figure 4.6 Propeller efficiency over advance ratio generated with (4.13)

In similar matters as described above a quality grade of 0.9 considers the influences of friction. The implementation of the quality grade leads from (4.12) to (4.14).

$$\eta_P \approx \zeta \cdot \frac{2 - 2 \cdot \lambda^2 \cdot \ln\left(1 + \frac{1}{\lambda^2}\right)}{1 + \sqrt{1 + \frac{2 \cdot L_D}{V^3} - 2 \cdot \lambda^2 \cdot \ln\left(1 + \frac{1}{\lambda^2}\right)}} \tag{4.14}$$

Figure 4.7 shows the propeller efficiency over speed for different disc loadings calculated with (4.14). In similarity to Figure 4.5 the efficiency rises with higher speeds. That means that the influence of a high Mach number is still not considered with this equation. For this reason, (4.14) is to be used for a first estimation at low speeds only.

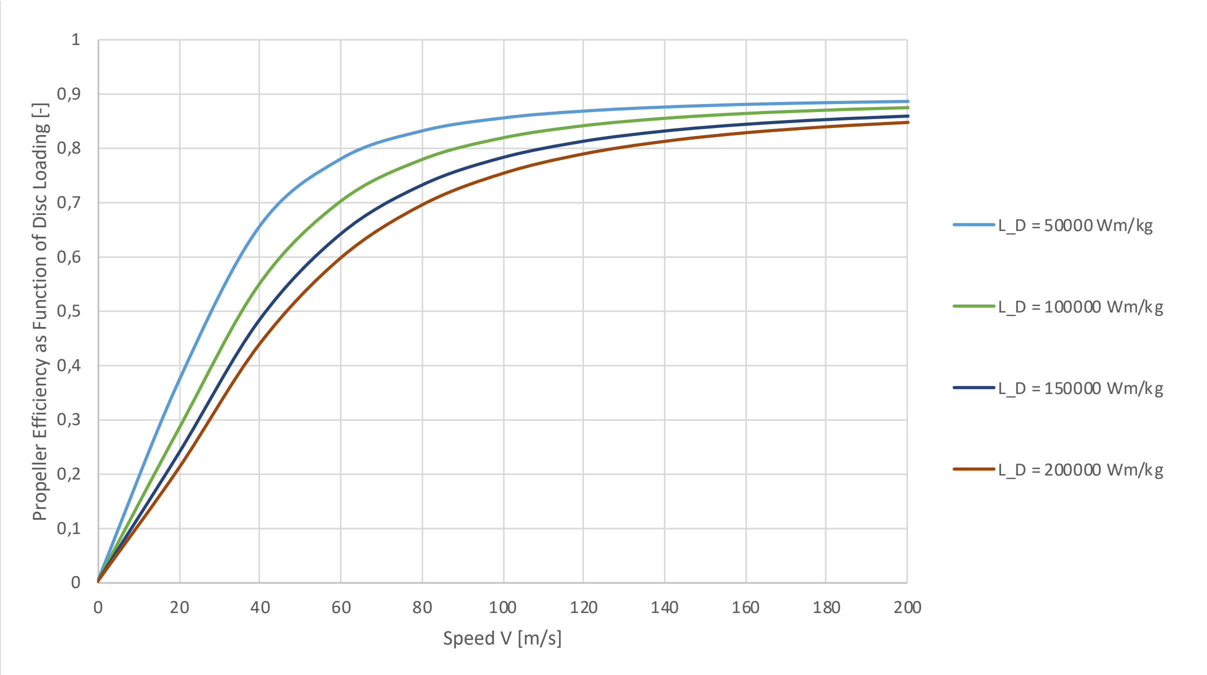

Figure 4.7 Propeller efficiency over speed genererated with (4.14)

4.3 Advance Ratio

This section covers an estimation of the advance ratio, which is needed for (4.14). The advance ratio is defined as forward speed divided by circumferential speed.

$$\lambda = V/u \tag{4.15}$$

Furthermore, the circumferential speed is defined by:

$$u = \pi \cdot d_D \cdot n \tag{4.16}$$

The forward speed as well as the disc diameter can be considered known. The reason is that these parameters are necessary also for the other propeller efficiency calculation methods shown above. Hence, the rotational speed is further looked at in detail. If there is no information of the rotational speed of the propeller available, there are two methods to estimate it from.

The first method comes from statistics and is used in SAS-Part25-Prop to estimate the rotational speed. It covers cruise speeds from 86 m/s to 185 m/s and a disc diameter from 2.6 m to 4.2 m. The average deviation of this equation is 5%.

$$n = 1986.8 - 1.3267 \cdot d_D \cdot V_{CR} \tag{4.17}$$

The second method is based on theory and described by Johanning (2013) (based on Adkins (1994)). According to him (based on Torenbeek (1982)) the maximum possible Mach number at the blade is

$$M_{max} = \frac{M_{eff}}{\sqrt{\cos \varphi_{25}}} \quad . \tag{4.18}$$

The effective Mach number is reduced due to the sweep angle of the blade φ_{25}. To exclude any influences of a high Mach number, the effective Mach number is set to 0.85 as suggested by Dubs (1979). If the sweep angle of the propeller tip is known, the maximum Mach number can be calculated. Based on this, the maximum Mach number is used to calculate the rotational speed by the following equation (Johanning 2013).

$$n = \frac{\sqrt{(M_{max} \cdot a^2) - V_{CR}^2}}{\pi \cdot d_D} \tag{4.19}$$

4.4 Implementation in PreSTo-Classic-Prop

The task of this work is to develop a more sophisticated PreSTo-Clasic-Prop. Therefore, the methods implemented in PreSTo-Classic-Prop must be equations. This ensures an automatic calculation of the propeller efficiency. As PreSTo-Classic-Prop was based on Figure 4.1 so far, (4.1) has been implemented. Furthermore (4.11) and (4.14) have been implemented as these equations are based on theory. The user can choose out of these three calculation methods in the worksheet "Propeller Efficiency". None of those equations considers the loss of propeller efficiency at high speeds. Preliminary sizing with PreSTo-Classic-Prop is therefore an estimation.

In addition, the user can choose the estimation method of the rotational speed. This is only required if (4.14) is selected. If the theoretical calculation is selected, the sweep angle of the blade tip is required. As this parameter is usually not given, there are three example values given to choose from (see Chapter 5.5).

Each flight phase (except landing) requires the calculation of the propeller efficiency. As defined in (4.1), (4.11) and (4.14) the propeller efficiency is mostly dependent on the disc loading and velocity. As each flight phase is defined by its individual sizening velocity and disc loading, each propeller efficiency calculation cell requires the three formulas individually. A variable "Prop_eff_formula" is implemented in PreSTo-Classic-Prop. "Prop_eff_formula" is equal to the calculation method that is selected by the user. That being so, the propeller efficiency calculation cells will select the correct formula by the value of “Prop_eff_formula”. This is realized by the Excel “IF” (german: “WENN”) function. Figure 4.8 shows this for missed approach exemplarily. The code can also be seen in Appendix A (English and German).

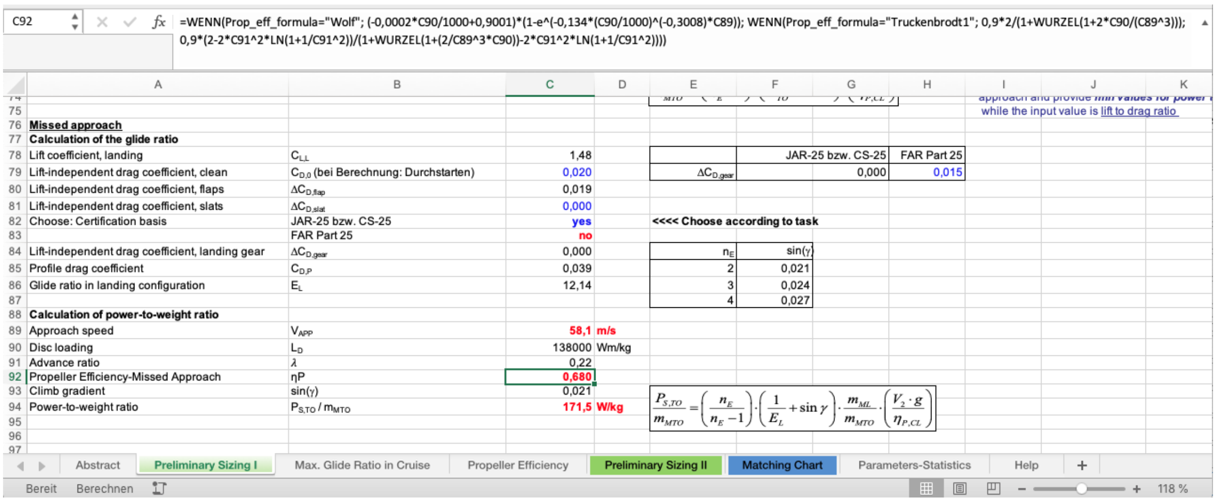

Figure 4.8 Propeller efficiency calculation cell code

In case (4.1) or (4.11) is selected as the calculation method the propeller efficiency estimation of take-off, missed approach and 2nd segment is stable, as there is no iteration needed. But, as the cruise speed depends on the propeller efficiency and the propeller efficiency estimation is dependent on the cruise speed, the propeller efficiency in cruise is implemented in a circular reference which might be unstable. Therefore, iterations need to be enabled in the spreadsheet. Moreover, if (4.14) is selected as the calculation method, all four flight phases are dependent on the advance ratio and therefore on the disc diameter. As the disc diameter is dependent on the propeller efficiency, all propeller efficiencies need to be in a circular reference in this case. This is the reason that if the spreadsheet crashes due to an unrealistic input, the easiest way to fix it is to select (4.11) as the calculation method (see Chapter 5.6).

To obtain clarity of the spreadsheet, each direct parameter of each propeller efficiency calculation is located in a cell close by. These are the disc loading, reference speed and the advance ratio for take-off, missed approach, 2nd segment and cruise.

5 PreSTo-Classic-Prop Improvements

This section introduces various changes in PreSTo-Classic-Prop. Improvements are implemented to ensure a sophisticated and user-friendly spreadsheet.

5.1 Abstract

When opening PreSTo-Classic-Prop the first time, the worksheet “Abstract” should be selected. This sheet provides the user with general information about the spreadsheed as it can be seen in Figure 5.1. Furthermore, the “Abstract” points out that iterations are necessary to calculate an outcome as described in Chapter 4.4. On that account, it is possible that the spreadsheet crashes in case there is an uncommon input entered. A worksheet “Help” tells information on how to rectify the situation (see Chapter 5.6). In addition, Figure 5.1 presents that some worksheet tabs have been coloured. This ensures a higher clarity and points out the most important worksheets to the user.

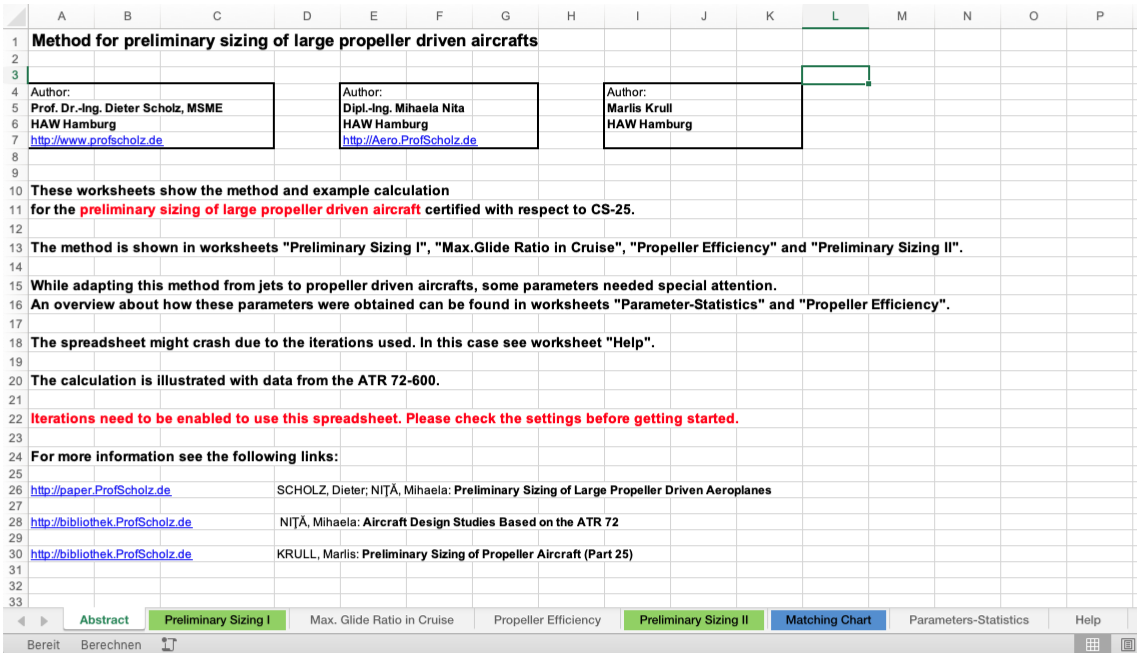

Figure 5.1 Worksheet “Abstract“ from PreSTo-Classic-Prop

5.2 Preliminary Sizing I and II

This section covers worksheets “Preliminary Sizing I” as well as “Preliminary Sizing II”. The reason is that both worksheets refer to each other by many equations.

PS I covers calculations for the flight phases landing, take-off, missed approach, and 2nd segment. As it is the first calculation sheet a small users guide states which cells represent input data and which cells might need the user's action. The main implementation in this worksheet is the calculation of the propeller efficiency, which is done automatically. Therefore, cells refering to propeller calculation are not coloured anymore. The precise implementation of the calculation of propeller efficiency is explained in Chapter 5.5 and Chapter 4.4. Moverover, there is another improvement made in PS I. As the propeller efficiency is dependent on the disc loading, which is defined as

$$L_D = \frac{P_{S,TO}}{\sigma \cdot \rho_0 \cdot S_D} \tag{5.1}$$

with

$$S_D = \frac{\pi}{4} \cdot d_D^2 \tag{5.2}$$

(Marckwardt 1998), the propeller disc diameter and the take-off power of one engine have been set as input parameters so far. However, the take-off power of one engine is considered to be a result of preliminary sizing. If this parameter is input and output at the same time, an iteration is needed. To avoid this iteration the disc loading itself has been set as input in PS I. In case of redesigning an aircraft, the disc loading can be estimated from (5.1). In this way, the propeller disc diameter and the take-off power of one engine are then calculated as output-parameters in PS II only.

The worksheet PS II covers the calculations for the flight phase cruise. In addition, calculations on the fuel mass and aircraft parameters are located in PS II. A table is included to provide the data of all flight phases for the matching chart. Finally, there is a statement in cell E152 if the aircraft sizing is finished. As mentioned for PS I, the automatic propeller efficiency is implemented in PS II, too, but not further described here.

In case of redesign PS II provides the option to enter original aircraft data. This allows the user to evaluate its design. As mentioned above the propeller disc diameter is also located here to allow a direct comparison to the original aircraft.

A main improvement of PS II is an automatic interpolation of the speed of sound in cell C61 based on the design point. This had to be done manually so far. The wing loading and the power-to-weight ratio of the design point are provided by the tool automatically. As PreSTo-Classic-Prop is a “simple” spreadsheet without the use of macros, the Excel Solver is not used to analyse the design point. For that reason, the value for the wing loading of the design point is taken from the calculation of the flight phase landing and the value for the power-to-weight ratio of the design point is taken from the calculation of the flight phase take-off. It is important to check on the matching chart, if the lines for cruise, take-off and landing meet in one point. A general equation of an interpolation is (5.3).

$$y = y_1 + (x - x_1) \cdot \frac{(y_2 - y_1)}{(x_2 - x_1)} \tag{5.3}$$

In this case with

$$y = a \tag{5.4}$$

and

$$x = P_{S,TO}/m_{MTO} \quad . \tag{5.5}$$

The speed of sound (y) is therefore interpolated with respect to the power-to-weight ratio of the design point based on take-off (x). The parameters x1 and x2 (/y1 and y2) represent the lower and upper boundary of the power-to-weight ratio (/speed of sound). These parameters are selected from the table with respect to height. As the design point changes, the tool must select different values and therefore different cells for these parameters. This is realized with the help of the Excel functions “MATCH” (German: “VERGLEICH”) and “INDEX”. The code for the cells of these parameters together with an explanation can be seen in Appendix B.

5.3 Matching Chart

The worksheet “Matching Chart” does only display the matching chart. Therefore, this worksheet has not been changed in regard to content. Nevertheless, the worksheet tab has been coloured blue to indicate the importance of this worksheet. As stated above, the user has to check manually if the lines for cruise, take-off and landing meet in one point. For this reason, this worksheet is the most important one. Additionally, units have been added to both axes.

5.4 Max. Glide Ratio in Cruise and Parameter Statistics

The worksheets “Max. Glide Ratio in Cruise” and “Parameter Statistics” have not been changed as they do not interfere with the propeller efficiency estimation. More information on this content can be read in Nita (2008).

5.5 Propeller Efficiency

The worksheet "Propeller Efficiency" is one of the main improvements of PreSTo-Classic-Prop. The tab has been located in between PSI and PSII, because it comprises necessary auxiliary calculations like "Max. Glide Ratio in Cruise" does, too. Please refer to Chapter 4 for additional information.

Figure 5.2 displays the upper part of this worksheet. The user has the option to choose out of three calculation methods of propeller efficiency. The formula and the main information are given for each method. Please refer to Chapter 4.1 and Chapter 4.2 for further information.

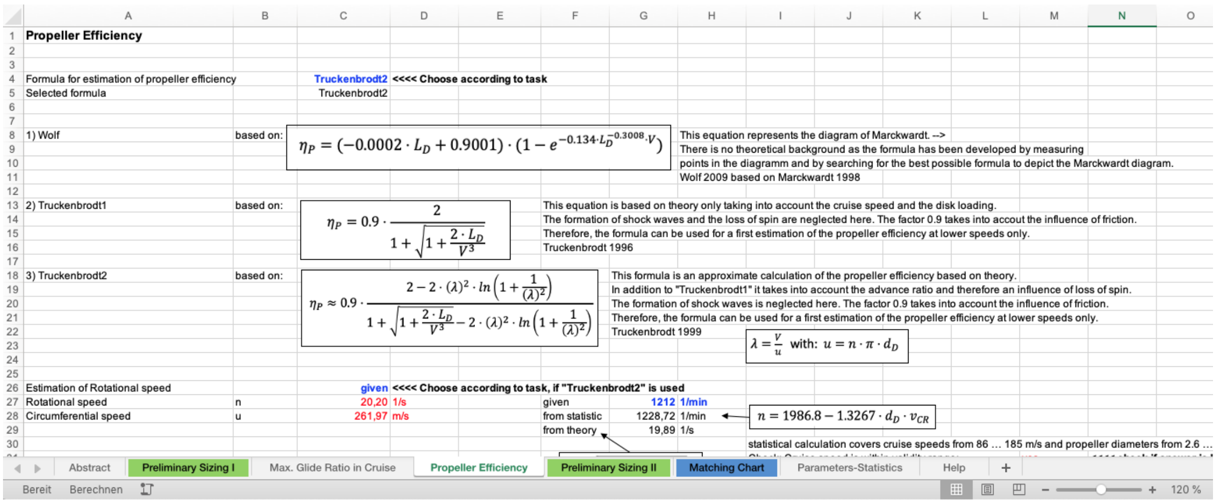

Figure 5.2 Worksheet "Propeller Efficiency" Part I

In case (4.14) is selected, the advance ratio is needed. It is dependent on the circumferential speed and therefore on the rotational speed as defined in (4.16). Both the rotational speed and the circumferential speed are considered constant for all flight phases using a constant speed propeller. For that reason, the calculation of these parameters is located in this worksheet. As the advance ratio changes for all flight phases due to the different speeds, the calculation of the advance ratio is located at each flight phase individually.

The second part of this worksheet refers to the estimation of the rotational speed. Hence, it is only of importance if (4.14) is selected. As can be seen in Figure 5.3 the user is able to enter a given rotational speed or choose out of (4.17) and (4.19). To check that the statistical equation is only used within its valid range there are two checks implemented. These cells display "yes" if the value of the parameter is within the valid range. Otherwise, they show "no". The code for these cells is based on the Excel function "IF" (german: "WENN"). To keep this spreadsheet simple without the use of macros the user itself has to check if both cells display "yes".

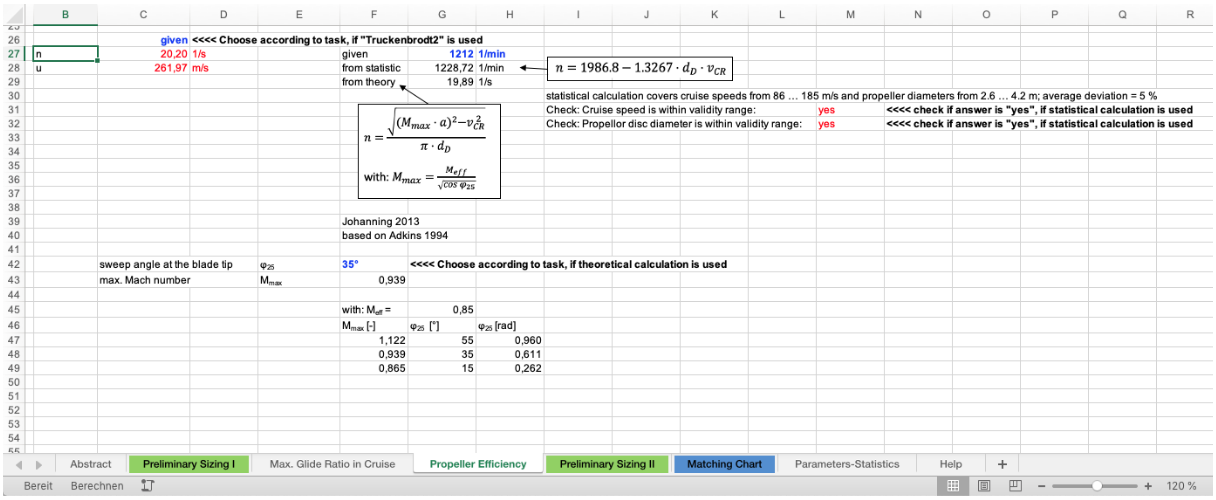

Figure 5.3 Worksheet "Propeller Efficiency" Part II

In case the theoretical calculation is selected, the maximum Mach number and the sweep angle at the blade tip are required. The sweep angle at the blade tip can be selected out of 15°, 35° and 55°. This parameter is usually not known and can therefore be estimated with one of these values. The effective Mach number is set to 0.85 as explained in Chapter 4.3. This value could be changed if necessary.

5.6 Help

The worksheet "Help" has been implemented to give additional information to the user. The worksheet "Help" is displayed in Figure 5.4. As already stated above the use of iterations is necessary to calculate the aircraft's design. Unfortunately, if an error occurs the error is stuck in the circular reference. An error might occur if unrealistic high or low or wrong input data are entered accidentaly or by means. In this case the user has two options to solve the problem. Option A is to close the spredsheet without saving the work and open it again. The restart will help as long as the last version saved has worked properly. Of course, this is unsatisfying if work is getting lost.

Option B fixes the situation without any loss of work. First the user has to undo the input that crashed the spreadsheet and replace it by a realistic value. This ensures that the spreadsheet will not run into the same error again. Secondly "Truckenbrodt1" (4.11) has to be selected in worksheet "Propeller Efficiency". This calculation scheme is only based on the disc loading (input data) and the speed as defined in (4.11). Therefore, the propeller efficiencies in take-off, missed approach and 2nd segment will be calculated properly, because their input speed is based on input data. The propeller efficiency in cruise depends on the cruise speed, which is included in the circular reference. Therefore, the propeller efficiency in cruise (PS II) needs to be set to 0.9 manually. At this point the spreadsheet should look fixed with all errors gone. To reset the calculation of the propeller efficiency in cruise to the automate calculation, the formula for this calculation can be copied from worksheet “Help” and pasted in PS II. It is important that only the formula will be copied not the whole cell as this will not work. This formula is attached in Appendix A also. Finally, the spreadsheet should be fixed. If that is not the case the easiest way to fix the problem is to proceed with Option A. Also, Option B does not help if any formulas in cells have been changed or deleted. In this case proceed with Option A.

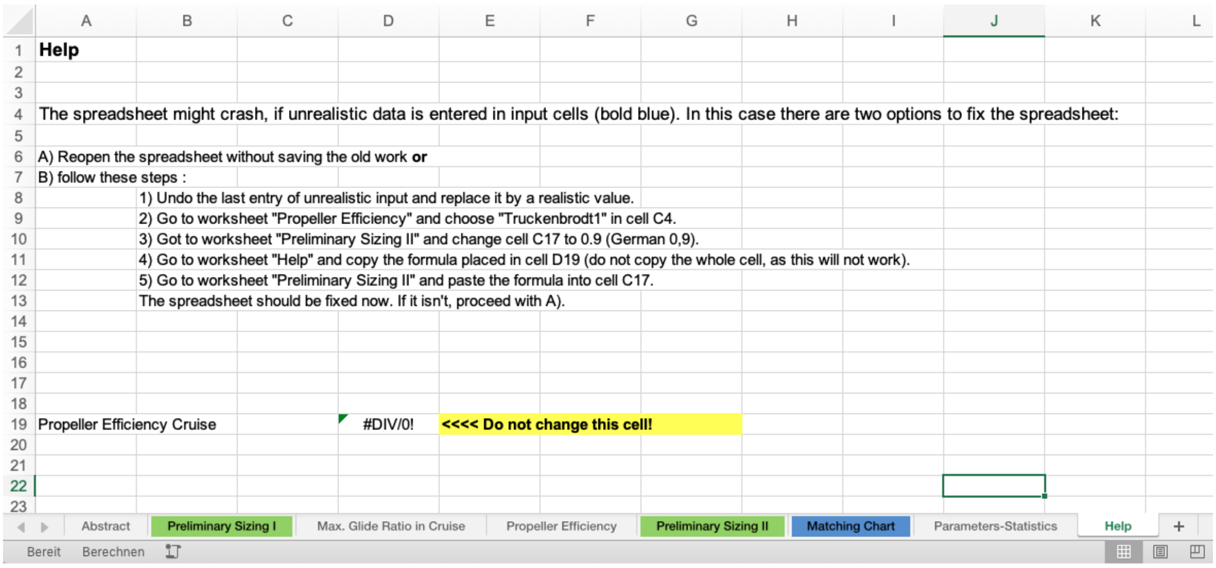

Figure 5.4 Worksheet “Help”

6 Redesign of ATR72-600

This section presents a redesign of the ATR 72-600 realised in PreSTo-Classic-Prop. This is done to evaluate the implementations.

6.1 Input Data

To redesign the ATR 72-600 with as little deviation as possible is it important to select as much original input data as possible. Therefore, different sources have been used. This section explains which values have been selected.

The factsheet of ATR 72-600 (ATR 2020) has been selected as the primary source. The approach speed, take-off field length, the number of engines and the design range have directly been taken from ATR (2020). Moreover, the aspect ratio and the specific fuel consumption are calculatable from the data provided in the factsheet.

The landing field length given in ATR (2020) is equal to 915 m, whereas ATR (2011) states 1067 m and ATR (2014) states 1000 m for a wet runway at ISA conditions. To provide a conservative calculation the largest value has been chosen.

The Mach number in cruise can be calculated as defined in (6.1). The design cruise speed is given in ATR (2020) as 510 km/h. At an optimum height of 17000 ft as mentioned in ATR (2011) the speed of sound equals 319.8 m/s (ISA). Hence, a Mach number of 0.444 in cruise is chosen.

$$M = V_{CR}/a \quad . \tag{6.1}$$

The number of passengers varies according to different sources. ATR (2020) states 72 passengers for a standard configuration, whereas ATR (2014) speaks of 70 seats for a typical seating configuration. As ATR (2011) presents three different seating configurations with 68, 70 and 72 seats, the midway of 70 passengers has been selected.

The max. payload has been set to 7300 kg. This value is given in ATR (2014) for a standard configuration. The 7500 kg mentioned in ATR (2020) are reachable in an optional configuration as stated in ATR (2014).

According to ATR (2020) the engine used is called PW 127M/N with a propeller from Propellers Hamilton Standard type 568F. EASA (2018) covers this engine model and stated a maximum of rotational speed of 1212 RPM. No information about the sweep angle at the blade tip is found. The value is set to 35° as this represents the given 1212 RPM best.

Furthermore, the disc loading has been calculated with (5.1). The power and wing area needed for this are given in Chapter 6.2. The relative density is set to 1.

The value of the mass ratio lies between 0.9 and 1.0 for domestic aircraft. 0.97 has been selected to allow a change to a higher value if needed with (3.41) checked. A higher value of the mass ratio is needed if the final check is not true as defined in (3.41).

The maximum lift coefficient in landing can be estimated by (3.3) in case of a redesign. The values for the maximum landing weight and wing area are presented in Chapter 6.2. With a stall speed in landing configuration of about 45 m/s the maximum lift coefficient in landing becomes equal to 2.898. According to Scholz (2015) based on Roskam (1989) the maximum lift coefficient in landing for a twin propeller driven aircraft is in a range from 1.6 to 2.5. As the ATR 72 uses a double slotted flap, the value 2.5 is selected as an estimation.

Scholz (2015) based on Roskam (1989) also suggests a maximum lift coefficient in take-off configuration in the range from 1.4 to 2.0. In addition, the maximum lift coefficient calculated by (3.6) leads to a value of 2.0. To achieve a reference speed for take-off equal to 116 kt given in ATR (2020) the maximum lift coefficient for take-off is estimated with 2.05.

Finally, the speed ratio needs to be selected, so that the lines for cruise, take-off and landing meet in one point. If "Truckenbrodt1" (4.11) or "Truckenbrodt2" (4.14) is chosen for propeller efficiency calculation, the speed ratio of 1.2 ensures a valid design point. If "Wolf" (4.1) is selected, the speed ratio is set a little higher. 1.3 is a good value in this case.

Table 6.1 provides all required input data immediately.

Table 6.1 Summarzied input data of ATR 72-600

Category	Parameter	Symbol	Value	Unit
Approach	Landing field length	s_{LFL}	1067	m
	Approach speed	V_{APP}	113	kt
Landing	Max. lift coefficient, landing	$C_{L,max,L}$	2.5	-
	Mass ratio	m_{ML}/m_{TO}	0.97	-
Take-off	Take-off field length	s_{TOFL}	1279	m
	Max. lift coefficient, take-off	$C_{L,max,TO}$	2.05	-
	Disc loading	L_D	138000	Wm/kg
2nd Segment	Aspect ratio	A	12	-
	Number of engines	n_E	2	-
Max. Glide Ratio in Cruise	Factor	k_E chosen	12,14	-
	Relative wetted area	S_{WET}/S_W	6	-
Propeller efficiency	Rotational speed	n	1212	1/min
	Sweep angle of the blade	φ_{25}	35	°
Cruise	Mach number, cruise	M_{CR}	0.444	-
	Speed ratio, Truckenbrodt	V/V_{md}	1.2	-
	Speed ratio, Wolf	V/V_{md}	1.3	-
Fuel mass	Design range	R	758	Nm
	Specific fuel consumption	SFC_P	5.5 E-08	kg/W/s
	Specific fuel consumption, loiter	SFC_{loiter}	5.5 E-08	kg/W/s
Aircraft parameters	Number of passengers	n_{PAX}	70	-
	Cargo mass	m_{CARGO}	0	kg
	Max. payload	m_{MPL}	7300	kg

6.2 Results

As the Excel tool calculates immediately when entering input data, the influence of parameters as well as the resulting aircraft parameters are shown directly. To ensure that the results are based on correct calculations, the user has to check on the matching chart if the lines for take-off, landing and cruise meet in one point. This is shown in Figure 6.1 exemplarily.

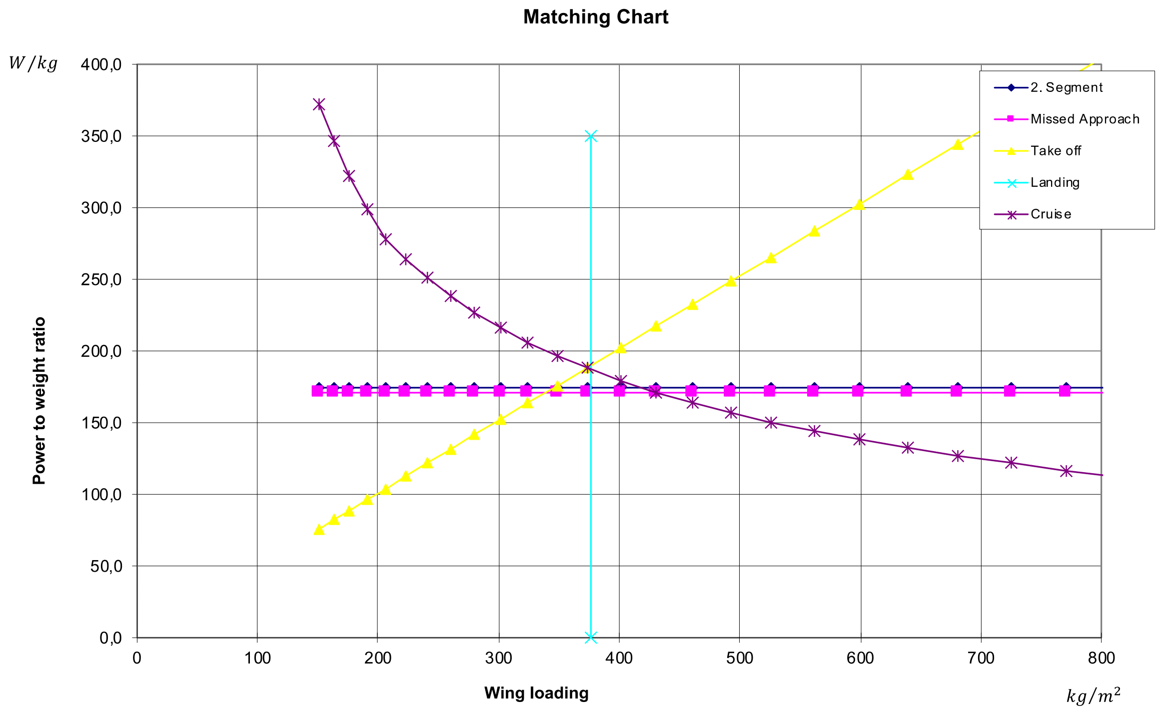

Figure 6.1 Matching chart in PreSTo-Classic-Prop

As already mentioned in Chapter 5.2 the worksheet PSII offers the opportunity to enter original aircraft data for direct comparison. The original data as well as the results of the redesigns are presented in Table 6.2. The sources of the original data are to be mentioned. Similarly, to the input data, ATR (2020) has been set as the primary source. The maximum take-off mass, the maximum landing mass, the operating empty mass, the maximum fuel load, the wing area, the take-off power of one engine and the propeller disc diameter refer to this source directly. The wing loading and the power-to-weight ratio of the design point are calculated values of the given parameters.

It can be seen in Table 6.2 that the values of the redesigns themselves are close to one another. Also, the values of the redesigns differ from the original values only a little. By reducing the number of passengers to 68 the values of the redesigns meet the original values even closer as can be seen in Table 6.3.

Table 6.2 Summarized results of redesigning ATR 72-600 (n_{PAX} = 70)

Parameter	Symbol	Unit	Original ATR 72-600	Redesign of ATR 72-600		
				Wolf	Trucken-brodt1	Trucken-brodt2 (n is given)
Wing loading	m_{MTO}/S_W	kg/m²	373.8	376.8	376.8	376.8
Power-to-weight ratio	$P_{S,TO}/m_{MTO}$	W/kg	179.9	182.4	186.5	190.5
Max. take-off mass	m_{MTO}	kg	22800	24182	23644	23754
Max. landing mass	m_{ML}	kg	22350	23457	22935	23042
Operating empty mass	m_{OE}	kg	13450	14265	13948	14013
Mission fuel fraction, stand-ard flight	m_F	kg	5000 (max.)	3407	3186	3231
Wing area	S_W	m²	61	64.2	62.8	63.1
Take-off power of one engine	$P_{S,TO}/n_E$	kW	2051	2205	2204	2262
Propeller disc diameter	d_D	m	3.93	4.08	4.07	4.13

Table 6.3 Summarized results of redesigning ATR 72-600 (n_{PAX} = 68)

Parameter	Symbol	Unit	Original ATR 72-600	Redesign of ATR 72-600		
				Wolf	Trucken-brodt1	Trucken-brodt2 (n is given)
Wing loading	m_{MTO}/S_W	kg/m²	373.8	376.8	376.8	376.8
Power-to-weight ratio	$P_{S,TO}/m_{MTO}$	W/kg	179.9	182.4	186.5	190.6
Max. take-off mass	m_{MTO}	kg	22800	23491	22969	23078
Max. landing mass	m_{ML}	kg	22350	22786	22280	22386
Operating empty mass	m_{OE}	kg	13450	13858	13550	13614
Mission fuel fraction, stand-ard flight	m_F	kg	5000 (max.)	3309	3095	3140
Wing area	S_W	m²	61	62.4	61.0	61.3
Take-off power of one engine	$P_{S,TO}/n_E$	kW	2051	2142	2141	2199
Propeller disc diameter	d_D	m	3.93	4.02	4.02	4.07

6.3 Evaluation

Table 6.4 is implemented to sum up the deviations of the redesigns compared to the original data. As preliminary sizing is a first estimation of an aircraft the amount of the deviations is acceptable. The methods of propeller efficiency calculation implemented in PreSTo-Classic-

Prop can therefore be further used. It is still to notice, that all propeller efficiency calculation methods do not consider the effect of a high Mach number. Therefore, these methods can be used for a first estimation at small cruise speeds. But the higher the cruise speed (at same density) the higher is the risk of a high deviation to practical propeller efficiencies.

Table 6.4 Summarized deviation (n_{PAX} =70)

Parameter	Symbol	Deviation to Original ATR 72-600 [%]		
		Wolf	Truckenbrodt1	Truckenbrodt2 (n is given)
Wing loading	m_{MTO}/S_W	0.8026	0.8026	0.8026
Power-to-weight ratio	$P_{S,TO}/m_{MTO}$	1.3897	3.6687	5.8922
Max. take-off mass	m_{MTO}	6.0614	3.7018	4.1842
Max. landing mass	m_{ML}	4.9530	2.6174	3.0962
Operating empty mass	m_{OE}	6.0595	3.7026	4.1859
Wing area	S_W	5.2459	2.9508	3.4436
Take-off power of one engine	$P_{S,TO}/n_E$	7.5085	7.4598	10.2877
Propeller disc diameter	d_D	3.8168	3.5623	5.0891

7 Improvements of SAS-Part25-Prop

This section states implementations made in SAS-Part25-Prop for propeller driven aircraft certified with respect to CS25. The implementations made mostly refer to the layout. For further information on the content of this spreadsheet please refer to Garcia (2013). Additional information can also be found in Heinemann (2012) on SAS-Part25-Jet. The initial layout of the worksheet “Input” is shown in Figure 7.1.

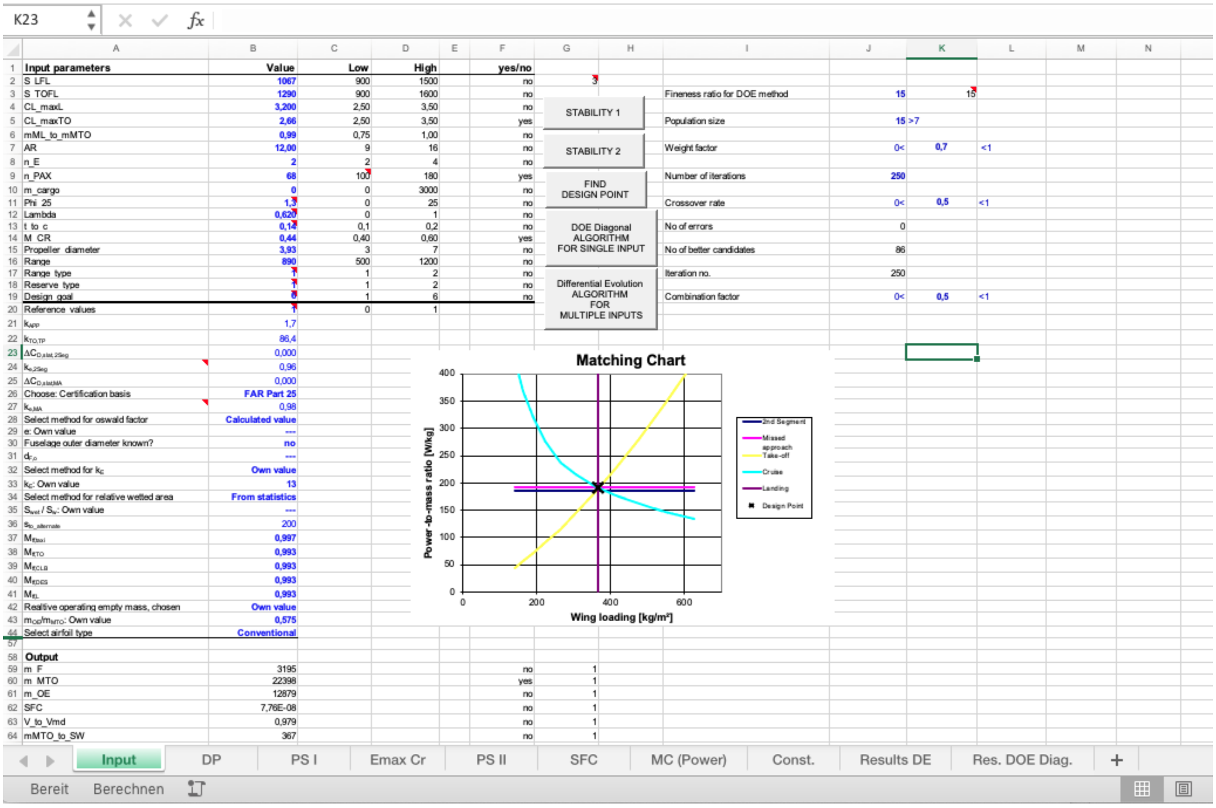

Figure 7.1 Initial layout of worksheet “Input” in SAS-Part25-Prop

To improve the usability and to enable an easy start in working with SAS-Part25-Prop some sections have been highlighted and the backgound has been coloured. This can be seen in Figure 7.2. The input section in the top left corner is now visually separated from the output section at the bottom left and the DOE/DE section at the upper right. The surface layout has been further developed in a way to look alike to SAS-Part25-Jet. Users that have worked with SAS-Part25-Jet will therefore adapt to SAS-Part25-Prop easily.

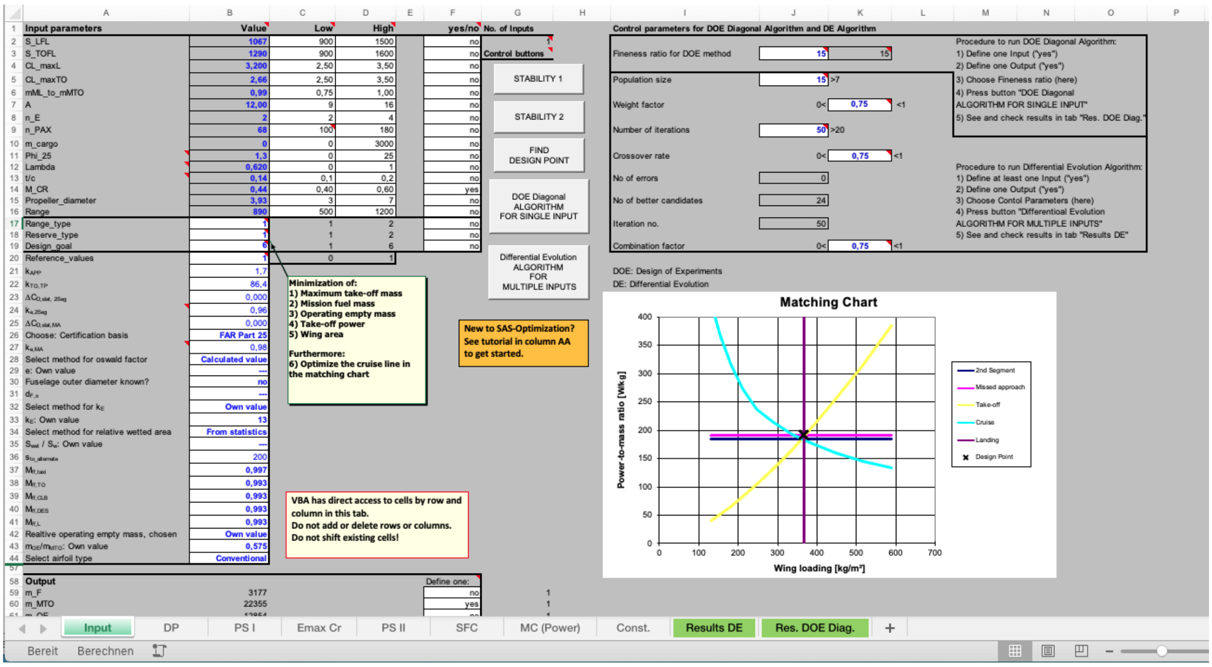

Figure 7.2 New layout of worksheet "Input" in SAS-Part25-Prop

In addition, the worksheet tabs "Input", "Results DE" and "Res. DOE Diag." have been highlighted. This is to help a new user orientate and to get started.

Figure 7.2 also shows a note edged in red stating: *VBA has direct access to cells by row and column in this tab. Do not add or delete rows or columns. Do not shift existing cells!* Due to the reason that a change of cells will lead to incorrect calculations, or even crash the spreadsheet, this information is of great importance. Therefore, this is stated again in the tutorial in Figure 7.3.

As mentioned, a tutorial to get started has been implemented. As this is located in column AA and therefore not visible on first sight, there is an orange highlighted note on the worksheet "Input" seen in Figure 7.2 to point that out. For uniformity the tutorial is highlighted in the same colour as the note. The tutorial shortly states an overview, hints and the main functions of SAS-Part25-Prop. The purpose and use of the different control buttons is explained here. The tutorial is depicted in Figure 7.3. In similarity to the layout, it is based on SAS-Part25-Jet.

AA	AB	AC	AD	AE	AF	AG

Tutorial to get started:

Please ensure the Excel Solver to be installed, iterations to be enabled and macros to be allowed before getting started.

0) **Input tab overwiew**: In SAS-Prop (almost) all input data is entered in the tab "Input". Blue values represent input data. Input parameters of the aircraft can be entered in cells B2 to B44. To get started use the provided data of the ATR 72 in column X. Output values will be available in cells B58 to B84. A matching chart shows the sizening flight phases and the design point. In case of redesign see column R. There are five control buttons in comlumn G that start macros. Additional control parameters can be found in columns J and K.

1) If you wish to use SAS-Prop in the same way as **PreSTo-Classic-Prop** you can do so by entering all your input parameters in the "Input"-tab. After that go to worksheet "DP" and change the value of v/vm in cell D14 manually until the lines for Take-Off, Landing and Cruise meet in one point.

2) **General procedure:** Enter and choose input data and parameters in the "Input"-tab. Press the control buttons. See the design in the tabs "DP" to "Res. DOE Diagonal".

3) **Control buttons**: It is possible that a single calculation runs into a numerically undefined situation and that the table gets into an unserviceable state. In this case press "**Stability 1**" and "**Stability 2**" to rectify the situation.
By pressing "**FIND DESIGN POINT**" the Matching Chart will be optimized by the Excel Solver autmatically. You can choose out of 6 Design goals. Therefore, see B19 with comment.
"**DOE Diagonal ALGORITHM FOR SINGLE INPUT**" can be used to show the influence of a single parameter on the design performance. The macro sweeps an input parameter from Low to High (columns C and D) by as many parts as the fineness ratio in cell J3 is chosen. The results and a plot can be seen in the tab "Res. DOE Diag.". The plot is autmatically generated for the design goal chosen in B19. Red points of the plot mark a violation in at least of of the four checks (columns AS to AV). Blue points represent permissible designs. See M2 ("Input"-tab) for the procedure to run DOE. Please be aware that the tab "Res. DOE Diag." will be overwritten after each run. Copy and rename the tab to preserve the results.
"**Differential Evolution ALGORITHM FOR MULTIPLE INPUTS**" allows optimizing many input parameters at the same time. This provides the most optimization of your aircraft as it is possible with SAS. Allow a large number of iterations (a few 1000) when optimizing many parameters at the same time. Be aware of long calculation times, so run in breaks or overnight. The results can be seen in the tab "Results DE". See M12 ("Input"-tab) for the procedure to run DE. Please be aware that the tab "Results DE" will be overwritten after each run. Copy and rename the tab to preserve the results.

4) Cells that are marked with a red corner are provided with **additional information**. By placing the curser onto a red corner, the linked comment will display automatically.

5) **Do not add or delete any columns or rows or shift exsting cells in the" Input"-tab as VBA has direct access to these cells.**

Figure 7.3 Tutorial to get started in SAS-Part25-Prop

To further improve the user's experience with SAS-Part25-Prop additional information is given for some cells. This is mentioned in the tutorial as can be seen in Figure 7.3. The additional information is given for cells that are marked with a red corner as can be seen in Figure 7.2. The information provided differs from good values over hints to explanations. For instance, the comment in cell G3 gives a short explanation of the control buttons whereas the comment in cell A13 states some example values of the relative wing thickness for different airplanes. The comment in cell B19 is shown permenantly as can be seen in Figure 7.4. It is of major importance as the design goal chosen influences the matching chart and the design point.

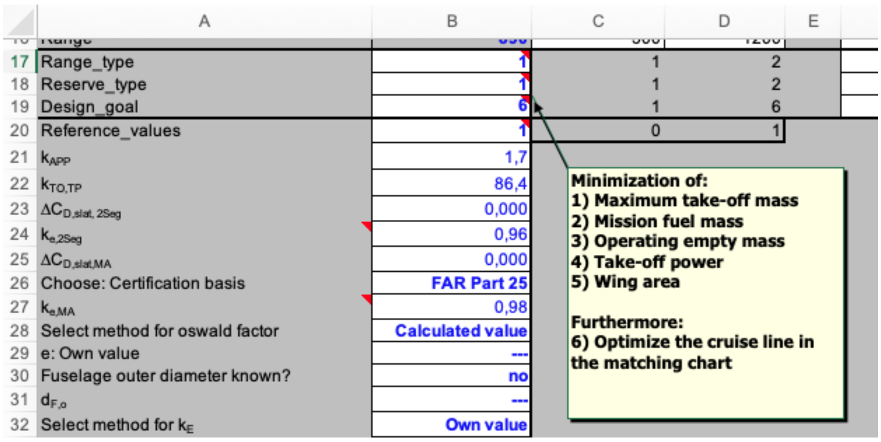

Figure 7.4 Options of the design goal

The section of control parameters for DOE Diagonal Algorithm and DE Algorithm has been coloured as mentioned above. Figure 7.5 shows the section of the control parameters for DOE Diaonal Algorithm and DE Algorithm. As these algorithms are of most importance each input cell (blue inc and white background) has been encircled and provided with additional information. Furthermore, a procedure to run each algorithm has been added.

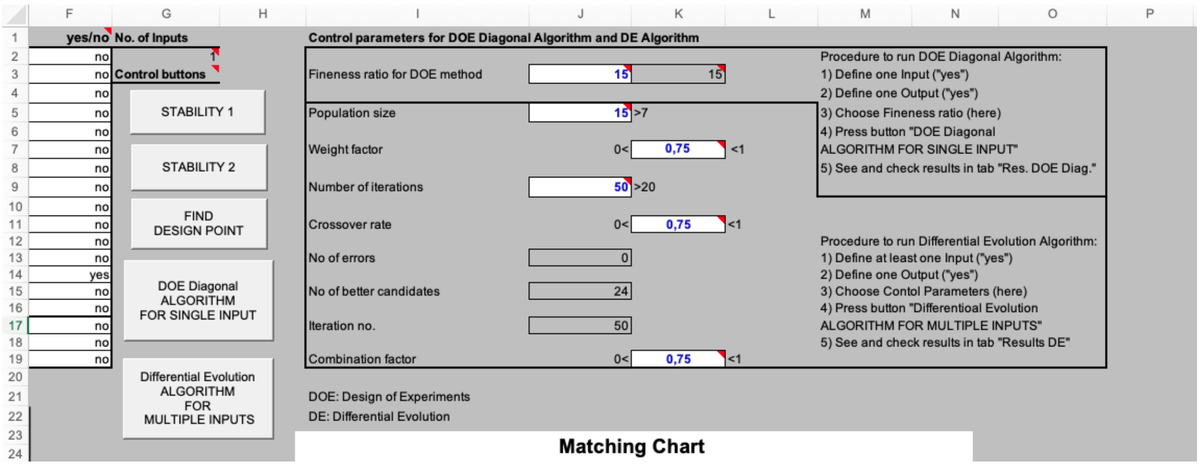

Figure 7.5 Control parameters for DOE Diagonal Algorithm and DE Algorithm

Finally the codes of the macros “Sub diagonal()” and “Sub differential_evolution()” have been adapted slightly. After a run of the DE Algorithm in the initial spreadsheet the spreadsheet crashed. The reason for this has been found after analizing the code. The macro copied values of the worksheet “Input” and pasted them in the “Results DE” worksheet correctly. But as the macro didn’t exit the copy-mode automatically the spreadsheet still waited for a definition of a range to paste it to. To stop the copy-mode, the command “Application.CutCopyMode = False” has been implemented.

Furthermore, the codes for implementing the diagrams of the results in “Results DE” and “Res. DOE Diag.” automatically, have slightly been adapted. The diagram in “Results DE” has been quite satisfying. Therefore only the commands “ActiveChart.Axes(xlValue).Select” and “ActiveChart.Axes(xlValue).MinimumScale = 0” have been deleted. This is to enable the automatic scaling of the value axis. Hence, a prevention of unused spaces in the diagram is guaranteed. The whole code of "Sub differential_evolution()" is added in Appendix C.

The diagram in worksheet "Res. DOE Diag." has not been as satisfying. To enable an adequate scaling of the category axis the commands "ActiveChart.Axes(xlCategory, xlPrimary).MinimumScale = low" and "ActiveChart.Axes(xlCategory, xlPrimary).MaximumScale = high" have been implemented. These commands set the minimum scale to the lowest possible input value defined in column C and the maximum scale to the highest possible input value defined in column D of the worksheet "Input". To allow the value axis to scale automatic, too, again the commands "ActiveChart.Axes(xlValue).Select" and "ActiveChart.Axes(xlValue).MinimumScale = 0" have been deleted. Furthermore, the diagrams size has been extended. The commands used are "ActiveSheet.ChartObjects(1).Width = 500" as well as "ActiveSheet.ChartObjects(1).Height = 360". These changes needed to be implemented in five loops to cover all options of the design goal. The whole code "Sub diagonal()" is added in Appendix D.

8 Summary and Conclusions

To sum up, PreSTo-Classic-Prop as well as SAS-Part25-Prop is based on theoretical equations of preliminary sizing stated in Chapter 3. When propeller driven aircraft are subject to preliminary sizing the propeller efficiency needs special attention. The main parameters to influence the propeller efficiency are the aircraft speed, propeller diameter and density as stated in Chapter 3.2. Trying to consider all influences especially the influence of the shock waves turns out as a complex method. Further improvements have been made in PreSTo-Classic-Prop to improve the overall usability as stated in Chapter 5. A redesign of large propeller driven aircraft as presented in Chapter 6 has been necessary to evaluate these implementations. The ATR 72-600 has been chosen as evaluations of previous versions of PreSTo-Classic-Prop have also been evaluated with ATR 72.

Working on the improvements in PreSTo-Classic-Prop produced some difficulties. Implementing the circular reference with enabled iterations has been tricky. Due to the working progress on input cells as well as result cells, errors occurred from time to time. These were stuck in the circular reference as already stated in Chapter 5.6. The spreadsheet therefore crashed several times. The procedure stated in worksheet “Help” had then still to be invented.

Also working on the improvements in SAS-Part25-Prop had some difficulties. First the usage of such a large spreadsheet without a tutorial had to be found out. Of course, SAS-Part25-Jet was helpful here. Second the spreadsheet crashed several times when trying to start working with it. The reason was that the copy-mode hasn’t been stopped as mentioned in Chapter 7, but that first had to be found out. Third, even the little changes made in the macro code have taken lots of time and nerves as the calculation time of DE Algorithm and DOE Diagonal Algorithm has been longer than a few seconds like used from usual Excel calculations.

To conclude, this project was aiming at developing a more sophisticated PreSTo-Classic-Prop. This has been realized with the automated estimation of propeller efficiency and general improvements as stated in Chapter 4.4 and Chapter 5. The evaluation done in Chapter 6 shows that the calculated results only differ a little from original data. The aim has therefore been sufficiently achieved.

The second aim was to prepare SAS-Part25-Prop for Open Access by improving the user-surface. The improvements made ensure a higher usability and additionally allow to acquaint users with the tool easily as stated in Chapter 7. SAS-Part25-Prop has therefore been improved in comparison to the initial tool, but there might still be further improvements needed for an Open Access tool.

9 Recommendations

This project manages to accomplish a number of things as stated in Chapter 8. Still some unsatisfying facts remain. These are stated in the following.

The major fact that is unsatisfying refers to (4.14). This formula is stated in Truckenbrodt (1999) as mentioned in Chapter 4.2. Unfortunately, Truckenbrodt (1999) does not provide a derivation of this equation. The similarity to (4.11) stated in Truckenbrodt (1996) can directly be seen, but for the extension with the advance ratio there is no derivation provided. Truckenbrodt (1999) states to be refering to Betz (1959). Truly, (4.14) is stated in Betz (1959) as well. But as Betz (1959) also refers to further literature for the background of this equation the derivation has not been provided here due to time restrictions. A research and study of such derivation might be a subject of a future work.

Another unsatisfactory situation has already been mentioned in Chapter 4 and Chapter 6.3. All equations to estimate the propeller efficiency stated in this work do not consider the effect of shock waves in case of a high velocity respectively a high Mach number. Nevertheless, this influence is not to be neglected as explained in Chapter 3.2. Equation (4.19) is a start trying to consider this, but further study of this subject is necessary to consider the influence of shock waves completely. As stated above PreSTo-Classic-Prop is therefore to use for a first estimation of preliminary sizing at low speeds only.

Finally, the user still has to supervise PreSTo-Classic-Prop to achieve correct results. As mentioned in Chapter 5.2 the design point is not generated directly from the intersection of the sizening flight phases lines but is taken from values calculated in the take-off and landing phase. Therefore, it is of major importance that the user checks the Matching Chart before having a look at the results. If the lines for cruise, take-off and landing do not all meet in one point, the design point might have not been chosen with respect to the first priority.

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All online resources have been accessed on 2022-04-12 or later.

Appendix A - Code of the Propeller Efficiency Calculation in Cruise

This section presents the code of the cell C17 in worksheet “Preliminary Sizing II” in PreSTo-Classic-Prop for the propeller efficiency calculation in cruise as stated in Chapter 4.4 and Chapter 5.6.This is a backup in case cell D19 in worksheet “Help” gets modified.

English:

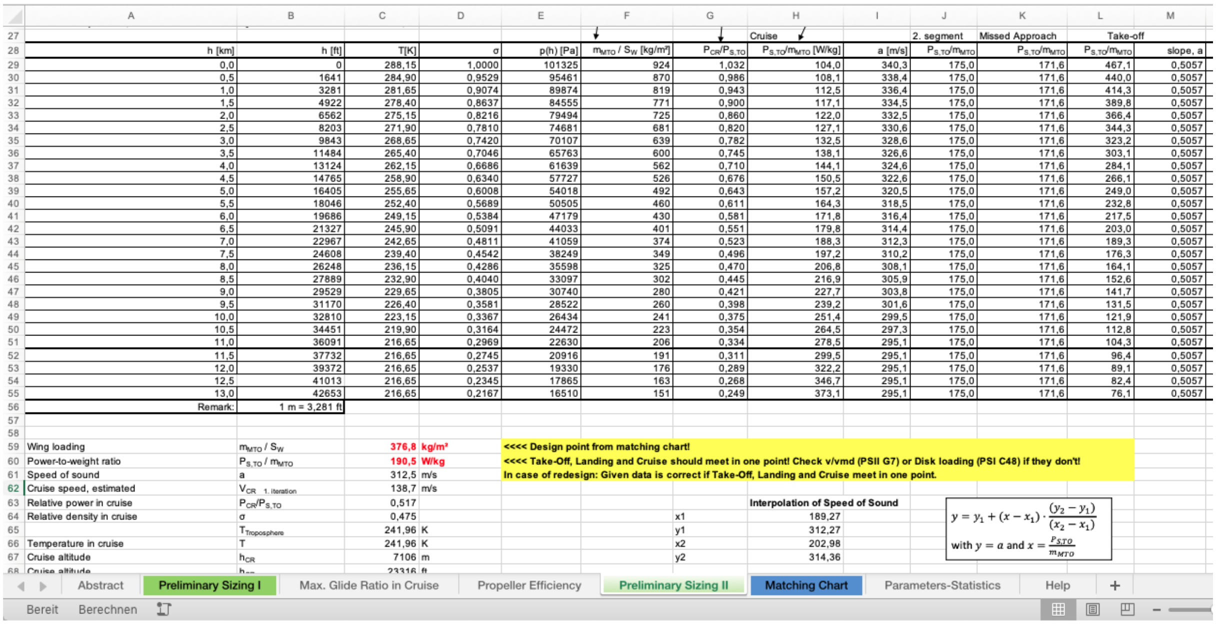
```
=IF(Prop_eff_formula="Wolf"; (-0,0002*C14/1000+0,9001)*(1-e^(-0,134*(C14/1000)^(-0,3008)*C16)); IF(Prop_eff_formula="Truckenbrodt1"; 0,9*2/(1+WURZEL(1+2*C14/(C16^3))); 0,9*(2-2*C15^2*LN(1+1/C15^2))/(1+WURZEL(1+2*C14/(C16^3))-2*C15^2*LN(1+1/C15^2))))
```

German:

```
=WENN(Prop_eff_formula="Wolf"; (-0,0002*C14/1000+0,9001)*(1-e^(-0,134*(C14/1000)^(-0,3008)*C16)); WENN(Prop_eff_formula="Truckenbrodt1"; 0,9*2/(1+WURZEL(1+2*C14/(C16^3))); 0,9*(2-2*C15^2*LN(1+1/C15^2))/(1+WURZEL(1+2*C14/(C16^3))-2*C15^2*LN(1+1/C15^2))))
```

Appendix B - Code of Interpolation of Speed of Sound

This section presents the code for the interpolation parameters x1, x2, y1 and y2 as stated in Chapter 5.2. To provide a better understanding, Figure B.1 shows the relevant range of worksheet “Preliminary Sizing II” in PreSTo-Classic-Prop.



	A	B	C	D	E	F	G	H	I	J	K	L	M
27								Cruise		2. segment	Missed Approach	Take-off	
28	h [km]	h [ft]	T[K]	σ	p(h) [Pa]	m_{MTO} / S_W [kg/m²]	$P_{CR}/P_{S,TO}$	$P_{S,TO}/m_{MTO}$ [W/kg]	a [m/s]	$P_{S,TO}/m_{MTO}$	$P_{S,TO}/m_{MTO}$	$P_{S,TO}/m_{MTO}$	slope, a
29	0,0	0	288,15	1,0000	101325	924	1,032	104,0	340,3	175,0	171,6	467,1	0,5057
30	0,5	1641	284,90	0,9529	95461	870	0,986	108,1	338,4	175,0	171,6	440,0	0,5057
31	1,0	3281	281,65	0,9074	89874	819	0,943	112,5	336,4	175,0	171,6	414,3	0,5057
32	1,5	4922	278,40	0,8637	84555	771	0,900	117,1	334,5	175,0	171,6	389,8	0,5057
33	2,0	6562	275,15	0,8216	79494	725	0,860	122,0	332,5	175,0	171,6	366,4	0,5057
34	2,5	8203	271,90	0,7810	74681	681	0,820	127,1	330,6	175,0	171,6	344,3	0,5057
35	3,0	9843	268,65	0,7420	70107	639	0,782	132,5	328,6	175,0	171,6	323,2	0,5057
36	3,5	11484	265,40	0,7046	65763	600	0,745	138,1	326,6	175,0	171,6	303,1	0,5057
37	4,0	13124	262,15	0,6686	61639	562	0,710	144,1	324,6	175,0	171,6	284,1	0,5057
38	4,5	14765	258,90	0,6340	57727	526	0,676	150,5	322,6	175,0	171,6	266,1	0,5057
39	5,0	16405	255,65	0,6008	54018	492	0,643	157,2	320,5	175,0	171,6	249,0	0,5057
40	5,5	18046	252,40	0,5689	50505	460	0,611	164,3	318,5	175,0	171,6	232,8	0,5057
41	6,0	19686	249,15	0,5384	47179	430	0,581	171,8	316,4	175,0	171,6	217,5	0,5057
42	6,5	21327	245,90	0,5091	44033	401	0,551	179,8	314,4	175,0	171,6	203,0	0,5057
43	7,0	22967	242,65	0,4811	41059	374	0,523	188,3	312,3	175,0	171,6	189,3	0,5057
44	7,5	24608	239,40	0,4542	38249	349	0,496	197,2	310,2	175,0	171,6	176,3	0,5057
45	8,0	26248	236,15	0,4286	35598	325	0,470	206,8	308,1	175,0	171,6	164,1	0,5057
46	8,5	27889	232,90	0,4040	33097	302	0,445	216,9	305,9	175,0	171,6	152,6	0,5057
47	9,0	29529	229,65	0,3805	30740	280	0,421	227,7	303,8	175,0	171,6	141,7	0,5057
48	9,5	31170	226,40	0,3581	28522	260	0,398	239,2	301,6	175,0	171,6	131,5	0,5057
49	10,0	32810	223,15	0,3367	26434	241	0,375	251,4	299,5	175,0	171,6	121,9	0,5057
50	10,5	34451	219,90	0,3164	24472	223	0,354	264,5	297,3	175,0	171,6	112,8	0,5057
51	11,0	36091	216,65	0,2969	22630	206	0,334	278,5	295,1	175,0	171,6	104,3	0,5057
52	11,5	37732	216,65	0,2745	20916	191	0,311	299,5	295,1	175,0	171,6	96,4	0,5057
53	12,0	39372	216,65	0,2537	19330	176	0,289	322,2	295,1	175,0	171,6	89,1	0,5057
54	12,5	41013	216,65	0,2345	17865	163	0,268	346,7	295,1	175,0	171,6	82,4	0,5057
55	13,0	42653	216,65	0,2167	16510	151	0,249	373,1	295,1	175,0	171,6	76,1	0,5057
56	Remark:	1 m = 3,281 ft											

	A	B	C	D	E–L
59	Wing loading	m_{MTO} / S_W	376,8	kg/m²	<<<< Design point from matching chart!
60	Power-to-weight ratio	$P_{S,TO}$ / m_{MTO}	190,5	W/kg	<<<< Take-Off, Landing and Cruise should meet in one point! Check v/vmd (PSII G7) or Disk loading (PSI C48) if they don't!
61	Speed of sound	a	312,5	m/s	In case of redesign: Given data is correct if Take-Off, Landing and Cruise meet in one point.
62	Cruise speed, estimated	V_{CR} 1. iteration	138,7	m/s	
63	Relative power in cruise	$P_{CR}/P_{S,TO}$	0,517		Interpolation of Speed of Sound (H)
64	Relative density in cruise	σ	0,475		x1 (G) 189,27 (H)
65		$T_{Troposphere}$	241,96	K	y1 (G) 312,27 (H)
66	Temperature in cruise	T	241,96	K	x2 (G) 202,98 (H)
67	Cruise altitude	h_{CR}	7106	m	y2 (G) 314,36 (H)
68	Cruise altitude	h_{CR}	23316	ft	

$$y = y_1 + (x - x_1) \cdot \frac{(y_2 - y_1)}{(x_2 - x_1)}$$

with $y = a$ and $x = \frac{P_{S,TO}}{m_{MTO}}$

Abstract | Preliminary Sizing I | Max. Glide Ratio in Cruise | Propeller Efficiency | Preliminary Sizing II | Matching Chart | Parameters-Statistics | Help

Bereit Berechnen

Figure B.1 PS II in PreSTo-Classic-Prop

Code in cell H64 (for x1):

```
=INDEX(L29:L51; MATCH(C60; L29:L51;-1)+1)
```

Code in cell H65 (for y1):

```
=INDEX(I29:I51; MATCH(C60; L29:L51;-1)+1)
```

Code in cell H66 (for x2):

```
=INDEX(L29:L51; MATCH(C60; L29:L51;-1))
```

Code in cell H67 (for y2):

```
=INDEX(I29:I51; MATCH(C60; L29:L51;-1))
```

In this code “MATCH” compares the values of cells L29:L51 to the value in C60 which is the power-to-weight ratio of the design point. The “-1” defines that “MATCH” selects the cell that is the smallest but larger than C60. “MATCH” gives back the number of the chosen cell with respect to the range L29:L51. “INDEX” then uses this number to select a cell of the range defined here. “INDEX” gives back the value of the selected cell. In the code for x1 and y1 one is added to the number given back by “MATCH”. This allows to give back the cell that is located one row below x2 respectively y2.

Appendix C - Code of DE Algorithm

```
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, parent_1, parent_2, parent_3, parent_4, trial(1 To 30), candidate(1 To 30), CR, output_candidate, KF, output_parent, output_best As Double
Dim inside_limits As Boolean
Dim result_name As String
Dim value_test, value_test2, value_test3, value_test4, value_test5

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 = 1000000000

'Position (and number) of the input parameters that are going to be varied
j = 0
For i = 2 To 18
  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

'Position of the output parameters and number of objectives (only supports 1)
j = 0
For i = 59 To 84
  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

'Definition of the crossover rate
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) = 17 Or parameter_position(j) = 18 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("A59:A84").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("F59:F84").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 STABILITY_1
  Call STABILITY_2

'If the results are good (no crash), copy them in the "results" sheet
  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(81, 2) <> 0 And Cells(82, 2) <> 0 And Cells(83, 2) <> 0 And
Cells(84, 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("B59:B84").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

'Differential Evolution:
'Randomly pick three (different) members of the population (parent 1, 2, 3) and generate trial member (trial)
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))

        Randomize
        rand = Rnd
        parent_2 = 1 + Round(rand * (population_size - 1))

        Randomize
        rand = Rnd
        parent_3 = 1 + Round(rand * (population_size - 1))

    For j = 1 To no_of_parameters
      trial(j) = population(parent_1, j) + F * (population(parent_2, j) - population(parent_3, j)) + KF * (popula-
tion(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

    'The new candidate is trial if it delivers a better value and parent 4 if not
    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

    'Check that the candidate is within low and high limits
    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 the limit is ok, produce result with the new population and copy them into "results" sheet
    If inside_limits = True Then

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

      value_test = Cells(output_position, 2)
      Call STABILITY_1
      Call STABILITY_2

      'If an error appears, than do not pick it as a candidate
      value_test = Cells(output_position, 2)

      If TypeName(value_test) = "Error" Then
      'If Cells(output_position, 7) <> 1 Then
        output_parent = 1000000
        no_of_errors = no_of_errors + 1
        Else: Call DP_Fast
            value_test = Cells(output_position, 2)
            value_test2 = Cells(81, 2)
            value_test3 = Cells(82, 2)
            value_test4 = Cells(83, 2)
            value_test5 = Cells(84, 2)
              If TypeName(value_test) = "Error" Or TypeName(value_test2) = "Error" Or TypeName(value_test3) = "Error"
Or TypeName(value_test4) = "Error" Or TypeName(value_test5) = "Error" Then
              'If Cells(output_position, 7) <> 1 Then
                output_parent = 1000000
                no_of_errors = no_of_errors + 1
              Else:
                If Cells(81, 2) = 1 And Cells(82, 2) = 1 And Cells(83, 2) = 1 And Cells(84, 2) = 1 Then
                  output_parent = Cells(output_position, 2)
```

```
                Else
                    output_parent = 1000000
                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 STABILITY_1
        Call STABILITY_2

        value_test = Cells(output_position, 2)

        If TypeName(value_test) = "Error" Then
        'If Cells(output_position, 7) <> 1 Then
          output_candidate = 1000000
          no_of_errors = no_of_errors + 1
          Else: Call DP_Fast
                value_test = Cells(output_position, 2)
                value_test2 = Cells(81, 2)
                value_test3 = Cells(82, 2)
                value_test4 = Cells(83, 2)
                value_test5 = Cells(84, 2)
                If TypeName(value_test) = "Error" Or TypeName(value_test2) = "Error" Or TypeName(value_test3) = "Error"
Or TypeName(value_test4) = "Error" Or TypeName(value_test5) = "Error" Then
                'If Cells(output_position, 7) <> 1 Then
                  output_candidate = 1000000
                  no_of_errors = no_of_errors + 1
                Else:
                  If Cells(81, 2) = 1 And Cells(82, 2) = 1 And Cells(83, 2) = 1 And Cells(84, 2) = 1 Then
                    output_candidate = Cells(output_position, 2)
                  Else
                    output_candidate = 1000000
                  End If
                End If
        End If

        'Copy only the better candidates in the "results" sheet
        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("B59:B84").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.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.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.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.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.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
For j = 1 To no_of_parameters
Sheets("Input").Select
Cells(parameter_position(j), 1).Copy
Sheets("Results DE").Select
Cells(j + 4, 52).Select
ActiveSheet.Paste
Cells(j + 4, 53) = population(parent_4, j)
Application.CutCopyMode = False
Next

End Sub
```

Appendix D - Code of DOE Diagonal Algorithm

```
Sub diagonal()
Dim i, j, k, v_row, f_row As Integer
Dim f_values(), title_values(1 To 53), V_nP(1 To 10) As Double
Dim Title(1 To 53) As String
Dim var, low, high, finss, KFE, finness, step_o, f_value As Double

Sheets("Input").Select
j = 0
For i = 2 To 19
  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 = 59 To 84
  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("Res. DOE Diag.").Select
ActiveSheet.Shapes.AddChart.Select
Sheets("Res. DOE Diag.").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 step_o
   Cells(v_row, 2) = var
   Title(2) = Cells(v_row, 1)
   Call STABILITY_1
   Call STABILITY_2
   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 = 59 To 84
      If var = low Then Title(k) = Cells(j, 1)
      title_values(k) = Cells(j, 2)
      k = k + 1
    Next

   Sheets("Res. DOE Diag.").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 = 59 To 84
          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("Res. DOE Diag.").Select
         Range("AY28").Select
         ActiveSheet.Shapes.AddChart.Select
         ActiveChart.ChartType = xlXYScatter
         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.Axes(xlCategory, xlPrimary).MinimumScale = low
    ActiveChart.Axes(xlCategory, xlPrimary).MaximumScale = high
    ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
    ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
    ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "m_MTO"
    ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "='Res. DOE Diag.'!$B$1"
    ActiveSheet.ChartObjects(1).Width = 500
    ActiveSheet.ChartObjects(1).Height = 360

End If

Sheets("Input").Select
If Cells(19, 2) = 2 Then
    Sheets("Res. DOE Diag.").Select
    Range("AY28").Select
    ActiveSheet.Shapes.AddChart.Select
    ActiveChart.ChartType = xlXYScatter
    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.Axes(xlCategory, xlPrimary).MinimumScale = low
    ActiveChart.Axes(xlCategory, xlPrimary).MaximumScale = high
    ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
    ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
    ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "m_F"
    ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "='Res. DOE Diag.'!$B$1"
    ActiveSheet.ChartObjects(1).Width = 500
    ActiveSheet.ChartObjects(1).Height = 360
```

```
End If

Sheets("Input").Select
If Cells(19, 2) = 3 Then
    Sheets("Res. DOE Diag.").Select
    Range("AY28").Select
    ActiveSheet.Shapes.AddChart.Select
    ActiveChart.ChartType = xlXYScatter
    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, 25)
            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, 25)
            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.Axes(xlCategory, xlPrimary).MinimumScale = low
    ActiveChart.Axes(xlCategory, xlPrimary).MaximumScale = high
    ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
    ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
    ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "m_OE"
    ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "='Res. DOE Diag.'!$B$1"
    ActiveSheet.ChartObjects(1).Width = 500
    ActiveSheet.ChartObjects(1).Height = 360
End If
Sheets("Input").Select
If Cells(19, 2) = 4 Then
    Sheets("Res. DOE Diag.").Select
    Range("AY28").Select
    ActiveSheet.Shapes.AddChart.Select
    ActiveChart.ChartType = xlXYScatter
    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.Axes(xlCategory, xlPrimary).MinimumScale = low
    ActiveChart.Axes(xlCategory, xlPrimary).MaximumScale = high
    ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
    ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
    ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "P_TO"
    ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "='Res. DOE Diag.'!$B$1"
    ActiveSheet.ChartObjects(1).Width = 500
    ActiveSheet.ChartObjects(1).Height = 360
End If

Sheets("Input").Select
If Cells(19, 2) = 5 Then
        Sheets("Res. DOE Diag.").Select
    Range("AY28").Select
    ActiveSheet.Shapes.AddChart.Select
    ActiveChart.ChartType = xlXYScatter
    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, 33)
            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, 33)
            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.Axes(xlCategory, xlPrimary).MinimumScale = low
    ActiveChart.Axes(xlCategory, xlPrimary).MaximumScale = high
    ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
    ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
    ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "S_W"
    ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "='Res. DOE Diag.'!$B$1"
    ActiveSheet.ChartObjects(1).Width = 500
    ActiveSheet.ChartObjects(1).Height = 360
End If

End Sub
```