Model for the design and analysis of PMSM and ASM (MEAPA)

1 General

1.1 Modeling

MEAPA is composed of two metamodels, *Design* and *Analysis* (Fig. 1). Based on input parameters, the main dimensions are determined in the first step of the *design* metamodel. Once these are determined, the stator and rotor are designed in the second and third steps. The last step of the metamodel *design is* the recalculation of the machine. The design parameters are then passed to the *analysis* metamodel and the currents and voltages are calculated using a motor and generator model for operating points in the valid operating range. Finally, the losses are determined and the characteristic diagrams are created, which are the output parameters.

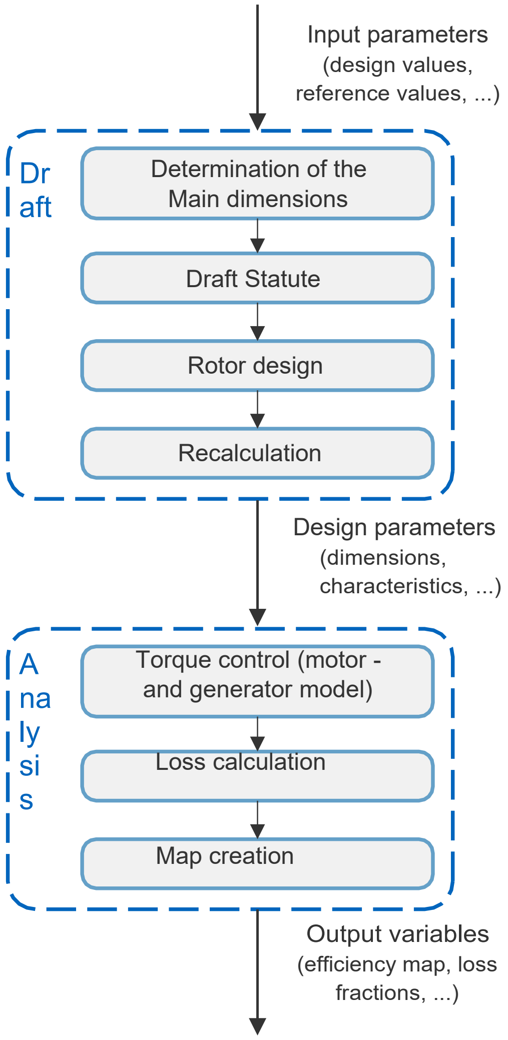

Figure 1: Model for the design and analysis of PMSM and ASM (MEAPA)

1.2 Program structure and functions

The program structure of the tool is based on MEAPA and implemented in MATLAB. Analogous to the two metamodels *design* and *analysis,* the MEAPA tool is also divided into a design and analysis component (Fig. 2). Both components contain two main functions each for the calculation process of the respective machine type. Both the design component and the analysis component have separate graphical user interfaces (GUI) that guide the user through the design and analysis process. The functions that are only required for the internal processes of the graphical user interface and data handling are not listed.

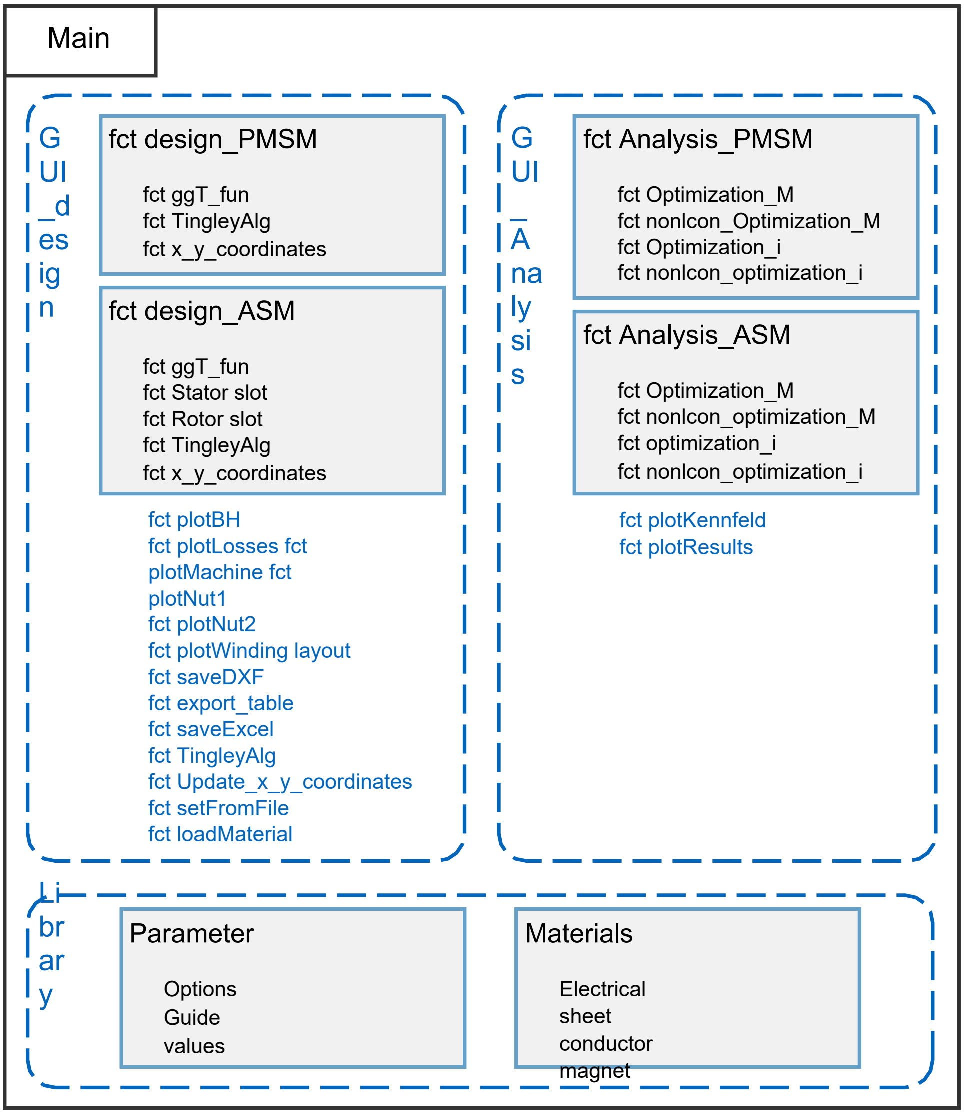

Figure 2: Functional structure MEAPA

In addition to the two main components, there are two libraries that can be used by the design and analysis components. In the library *Parameters,* among other things, the standard values taken from the literature are stored in a machine-dependent manner. The characteristic values of the materials are stored in the *Materials library.* For the electrical sheets, for example, material parameters such as the BH and iron loss curves are contained there.

Further components of the MEAPA tool are the data storage system and two interfaces. With the data storage system, the machine design can be temporarily stored at any time and continued later. In addition, it is possible to call up a machine that has already been designed and to recalculate it with changes. Another advantage is the possibility of easy archiving of the results. As interfaces, an export of geometry data into the CAD data format *dxf* as well as an export of the design results into an Excel file are implemented. The CAD data can then be imported into an FEM program, for example, where further calculations can be performed. This is particularly relevant for the IPMSM in order to be able to precisely calculate the transverse and longitudinal axis inductances.

1.3 Folder and file structure

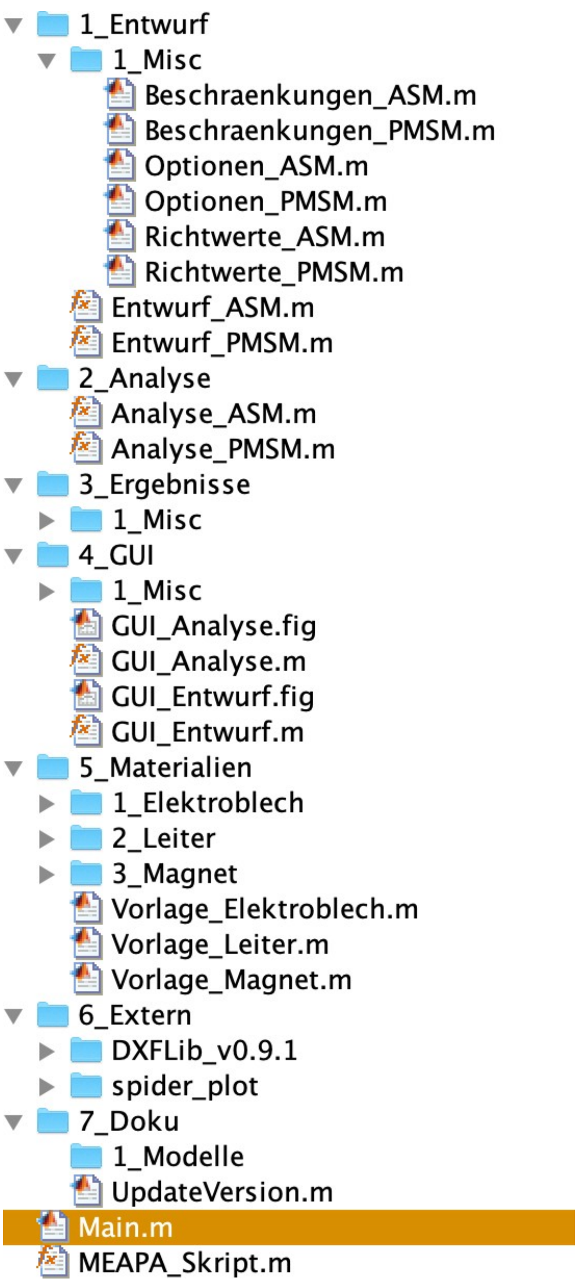

Figure 3: MEAPA folder structure

1_Draft

The main functions for the calculation process of the design are stored in the folder *1_Design* and are described in more detail in chapter 2. The parameter libraries are stored in the subfolder *1_Draft/1_Misc.* The guideline values in the respective script always consist of a max, min and standard value per line. If there are several lines, the different conditions for the lines are indicated. In the scripts *Options_xy* the implemented and in the GUI dynamically displayed options are stored. The options for material selection are loaded dynamically according to the available material library.

2_Analysis

The main functions of the calculation steps for the analysis are stored in the folder *2_Analysis.* The analysis is presented in detail in chapter 3.

3_Results

The results of the design and analysis process are saved in the folder *3_Results* according to the associated ID of the file. The template for the Excel export is located in the subfolder *3_Results/1_Misc of* the results.

For an extension of the Excel file with regard to new calculation variables, these must be stored in the *Formula character directory* worksheet with formula character, designation and unit. The assignment to the data exported to the spreadsheets is then carried out dynamically.

4_GUI

The graphical user interfaces of the design and analysis components are stored in the folder *4_GUI.* The GUI have been created with GUIDE. Editing is therefore only recommended with GUIDE. The assignment and reading of the inputs is converted in the corresponding *m-files*. With the scripts in the parameter library a simple adjustment of the reference values and options in the GUI is possible without having to adjust the code of the GUI.

5_Materials

The material library contains *mat* files, which contain the corresponding material characteristics for each material. The template scripts are available for adding further materials. This can be used to conveniently generate the *mat* files for new materials. The required material parameters must be entered according to the template and the script then executed. Each script contains several examples for orientation.

6_External

The external functions required for the *dxf export* and the display of the property diagram are stored in the folder *6_External. The* license conditions for further use and distribution can be found in the respective subfolder.

7_Docu

The folder *7_Doku* contains the documentation of the MEAPA tool, as well as a script for updating the headers in all *m-files* (section 1.4).

1.4 Update version

To update the headers in all m-files, all *m-files of* the MEAPA tool must be closed. Then the new version number with editor code is entered in the *UpdateVersion script* under *newString*. Afterwards the *m-file UpdateVersion is* saved and also closed. Finally, the *UpdateVersion* command must be executed in the MATLAB *Command Window.*

1.5 Start of the program

The call of the tool and thus the start of the program is done with the *main file*. In this file the paths are automatically set and it can be selected whether the program is started with or without GUI. If the program is to be executed without GUI, the input parameters must be defined in the *m-file MEAPA_Skript* or transferred to it.

NOTES for the *MEAPA_Script* :

- The input parameters can be defined arbitrarily, e.g. the design values can be passed to the script, accordingly the design values part in the *MEAPA_Script* must be commented out. However, it is not mandatory to pass anything.
- If the script is used without the main file, care must be taken to set the paths correctly.
- Since no user interface is called to select the winding, only the classic design can be performed (no user interaction required).

2 Draft

The scripts *Design_PMSM* and *Design_ASM* are used to design a PMSM or ASM according to the rated values. The procedure for the electromagnetic design of an ASM is shown again graphically in Fig. 4. A similar procedure results for the PMSM.

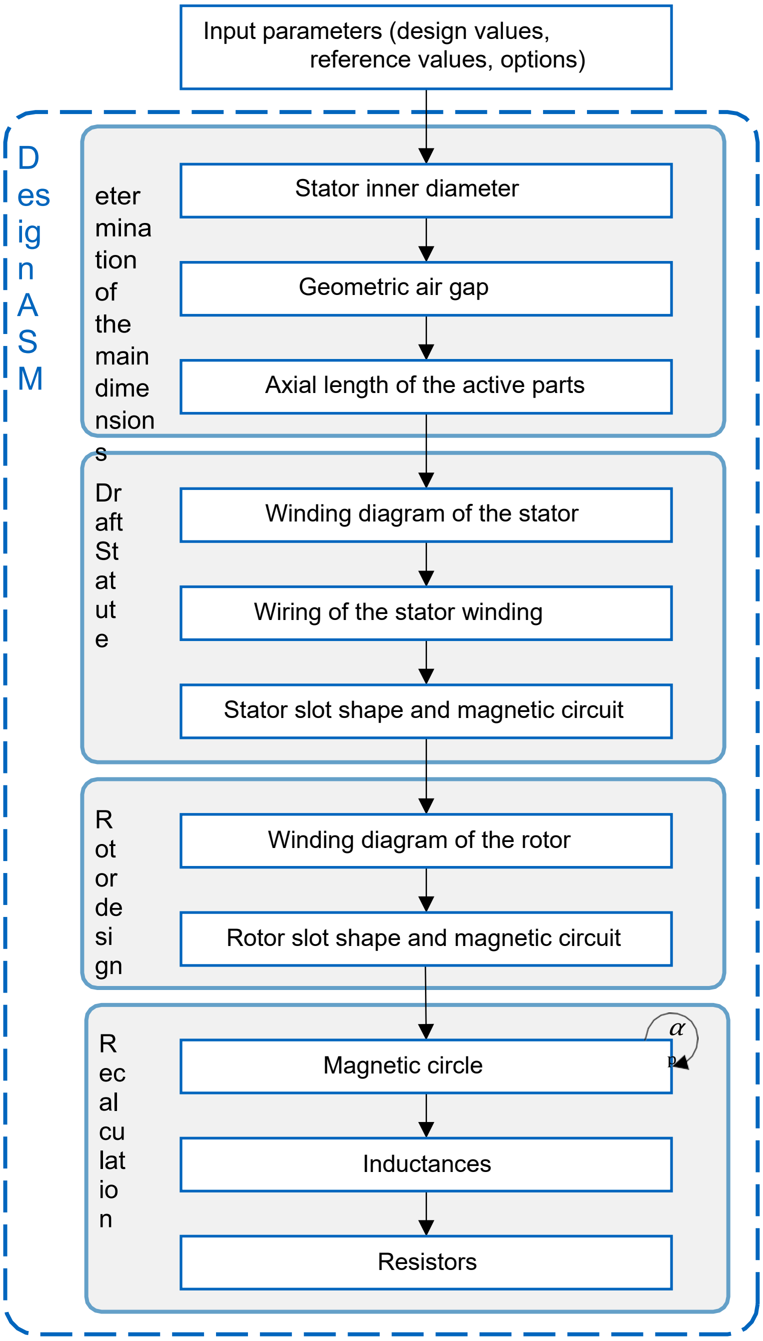

Figure 4: Design process for the ASM

2.1 Structure of the scripts

The structure of the scripts for the respective machine type is visibly subdivided analogously to the procedure in the code. In addition, the sources and the simplifications or assumptions made are listed for each formula used.

The tables of contents of the respective design scripts are listed below. The auxiliary functions contain functions that are required for the geometry of the machine, for example, or are used several times.

Table of contents Draft ASM

Table of contents Draft PMSM

2.2 Program structure - draft stator

The procedures for the three different options of the stator design are combined into a uniform program structure on a common code basis and integrated into the two main functions of the design. The program structure is based on the optimized procedure for stator design and is shown in Figs. 5 and 6.

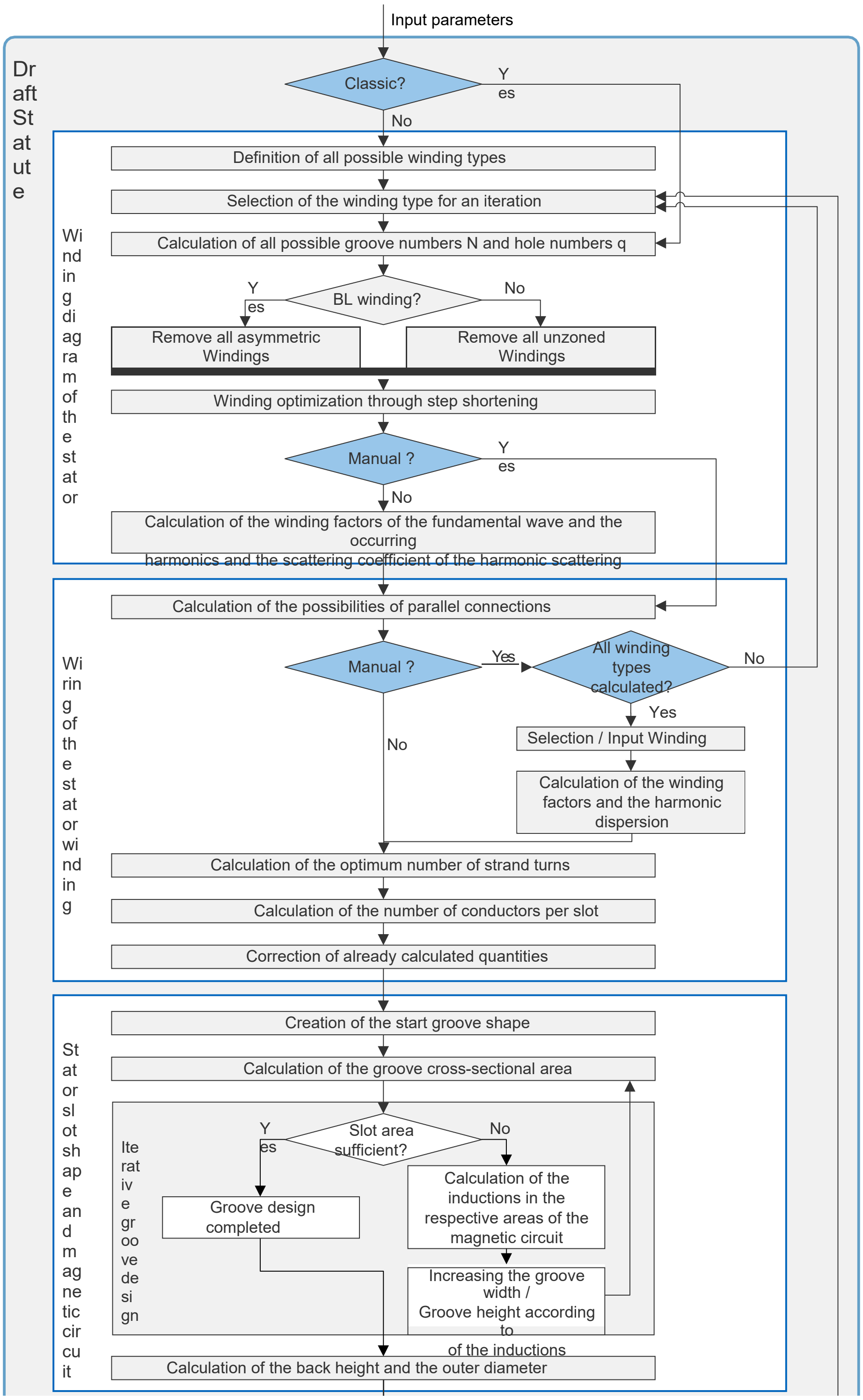

Figure 5: Program structure stator design (part 1)

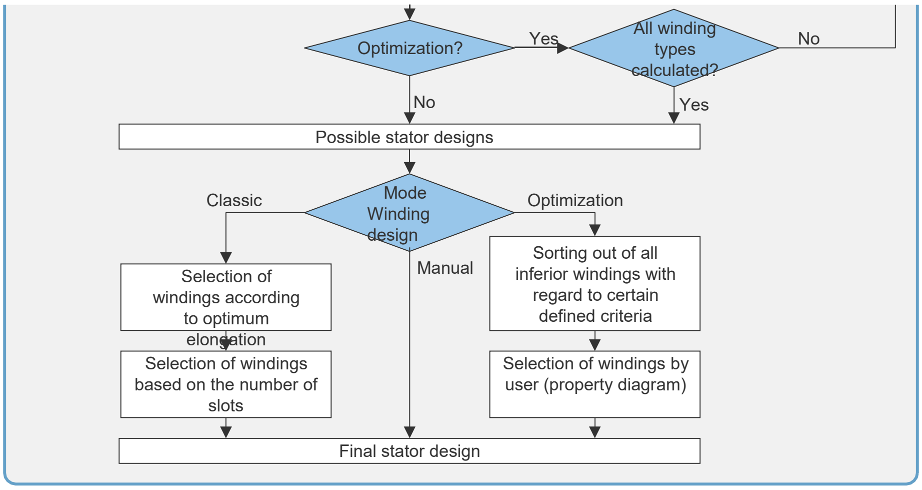

Figure 6: Program structure stator design (part 2)

2.3 Program structure - Iterative groove design

In iterative groove space generation by means of groove space balance, the groove shape is iteratively enlarged under consideration of optimum tooth and back inductions until the required groove cross-section is achieved. The condition for iterative groove generation is the definition of parameters that uniquely describe the groove shape. No overdetermination of the geometric shape may occur. In the MEAPA tool, a trapezoidal basic slot shape is implemented, which is uniquely described by the parameters in Fig. 7.

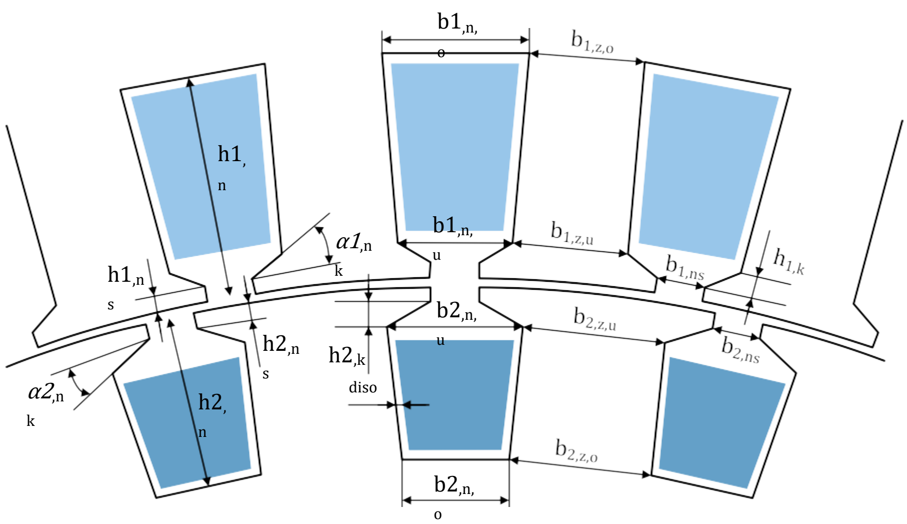

Figure 7: Groove dimensions

The procedure for iterative slot generation is shown in Fig. 8. Due to the structure of the selected algorithm, the slot is always enlarged at the point of lowest induction. The slot first grows in width until the permissible tooth inductions are reached. After that, the groove grows in height.

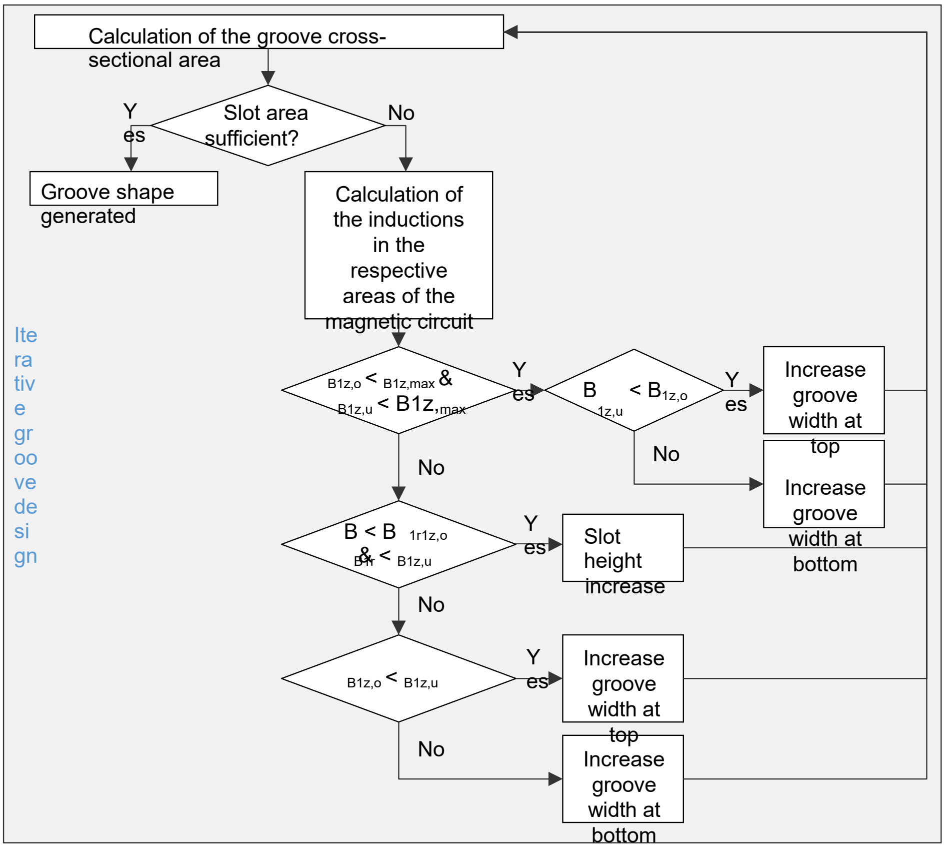

Figure 8: Iterative Nutgestaltung

2.4 Program structure - recalculation of the magnetic circuit

For the recalculation of the magnetic circuit, a program structure with a multi-stage iteration process is used, which is shown in Fig. 9. The nesting of the two iteration loops serves to feed back the effects of the corrections and to initiate a new correction loop.

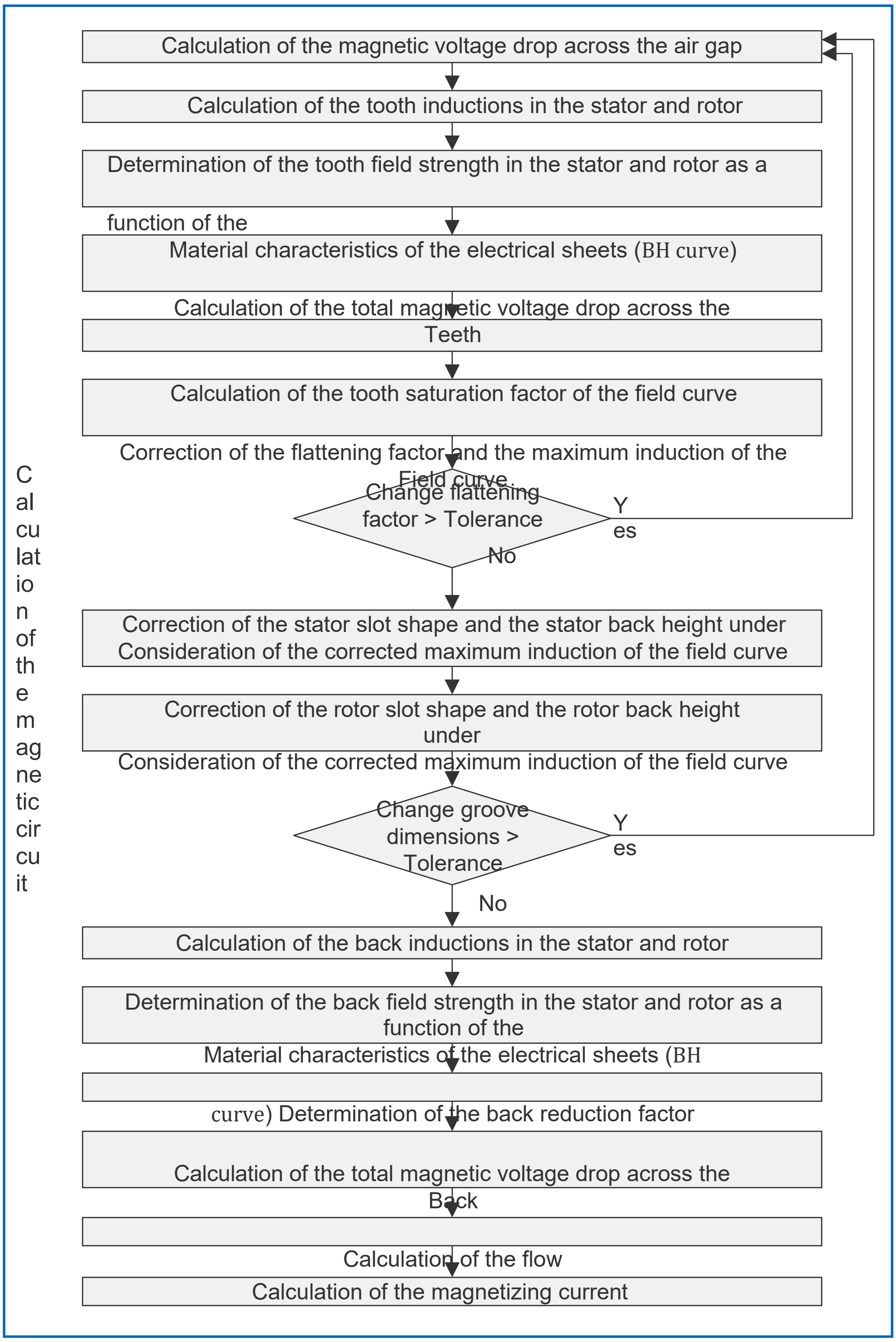

Figure 9: Program structure for the recalculation of the magnetic circuit

2.5 User interface

The user interface of the design is divided into two main areas. The *Input* tab is where the input parameters for the design are set. The *Results* tab is variable. Once the design has been successfully completed, selected design parameters and the machine's geometry are displayed there. However, depending on the selected mode of the winding design, intermediate steps requiring input or selection by the user are also displayed in the *Results tab.*

Enter

In the *Input* tab of the design user interface, the user specifies the input parameters for the design. The user interface of the input is shown in 10.

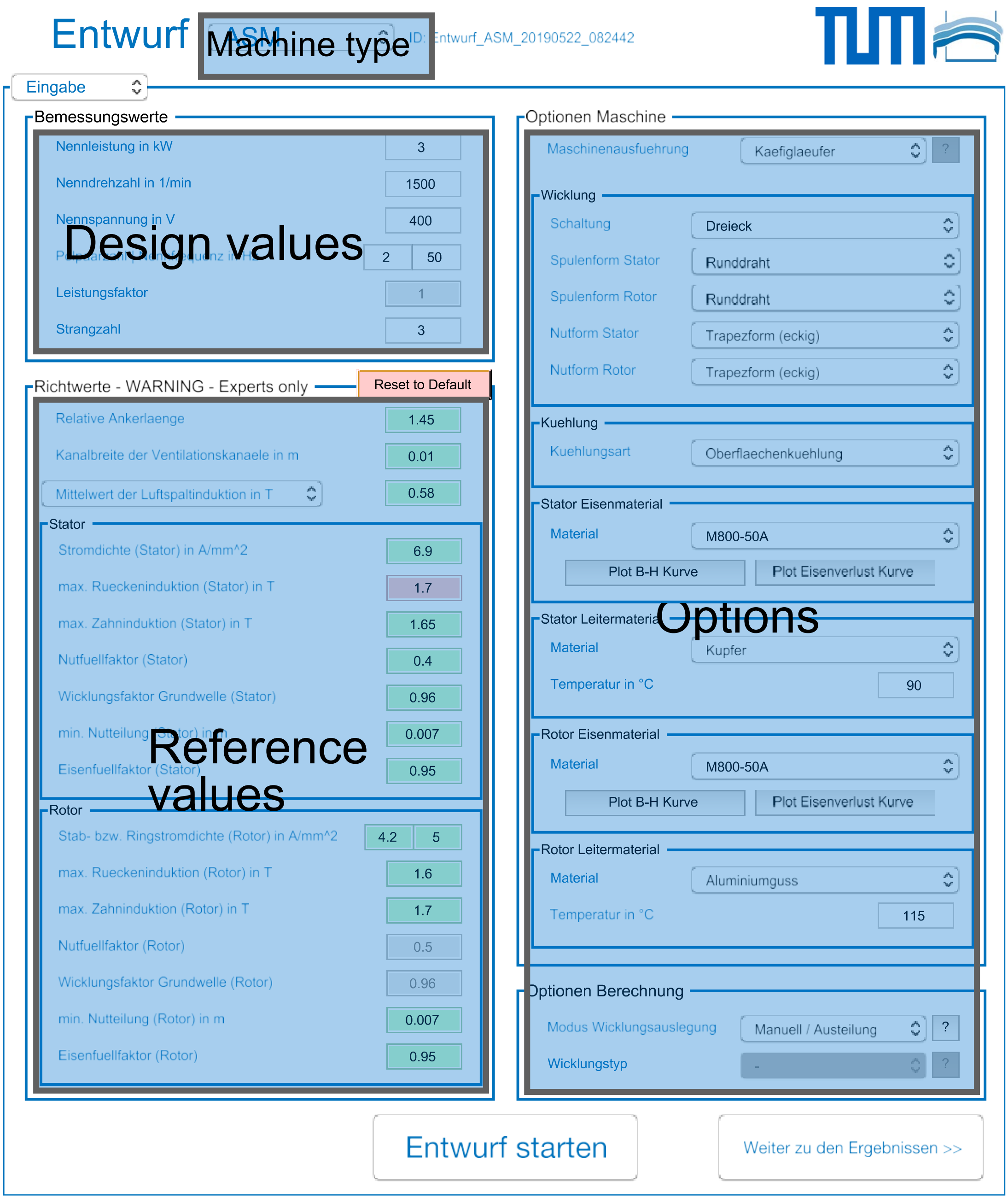

Figure 10: Entering input parameters for the design

In a first step, the desired machine type is selected. Depending on the selected machine type, the corresponding input fields required for the design are then enabled in the user interface and the reference values and the available options are loaded from the libraries.

After selecting the machine type, the design values must be entered and the machine options selected. With selection of the material-specific options the respective material properties are loaded from the *Materials* library. The material properties of the electrical sheet can then be displayed via the "Plot *BH curve*" button and the "Plot iron loss curve" button.

If necessary, the reference values can also be adapted to the requirements. The user interface supports the user in this by comparing the entries with the validity range for the respective reference value stored in the parameter library *Reference values.* If the entered value exceeds or falls below the limits for minimum and maximum permissible values, the background color of the input field changes from green to red (Fig. 10). The validity range can be viewed by moving the mouse pointer to the respective input field of the guide value. The initially entered reference values represent an average default value for each parameter, so that an initial valid dimensioning is possible without further input.

The "Start design" button starts the main function *fct design_xy* of the out-
selected machine type and the design process begins.

Mode optimization

If the *Optimization* option is selected in the winding design mode, an intermediate step is necessary in the design process. In this intermediate step, the user selects the parameter combination that best meets the requirements via a selection menu. In order to visualize the different parameter combinations, these are illustrated in the form of a property diagram in which the criteria are listed comparatively. After selecting a parameter combination, the design is then continued.

The user interface for the *Optimization* option is shown in Fig. 11.

Manual mode

Analogous to the *Optimization option, the Manual* option also requires an intermediate step in the design process. In this step, the user can select from one of the possible winding combinations or enter his own winding layout in the form of a zone plan. The winding layout is then visualized using a generic machine. This is shown in the user interface in Fig. 12.

When entering the coil layout, a predefined notation must be followed. Positive coil sides are marked with an upper case letter and negative coil sides with a lower case letter. The letters A, B and C must be selected for the three strands. The next slot must be delimited with the separator "|". The input is designed compatible to the online winding calculation tool "Emetor", so that a simple transfer is possible. For manual input, the winding step shortening or lengthening of the winding must also be specified so that the winding factors can be calculated.

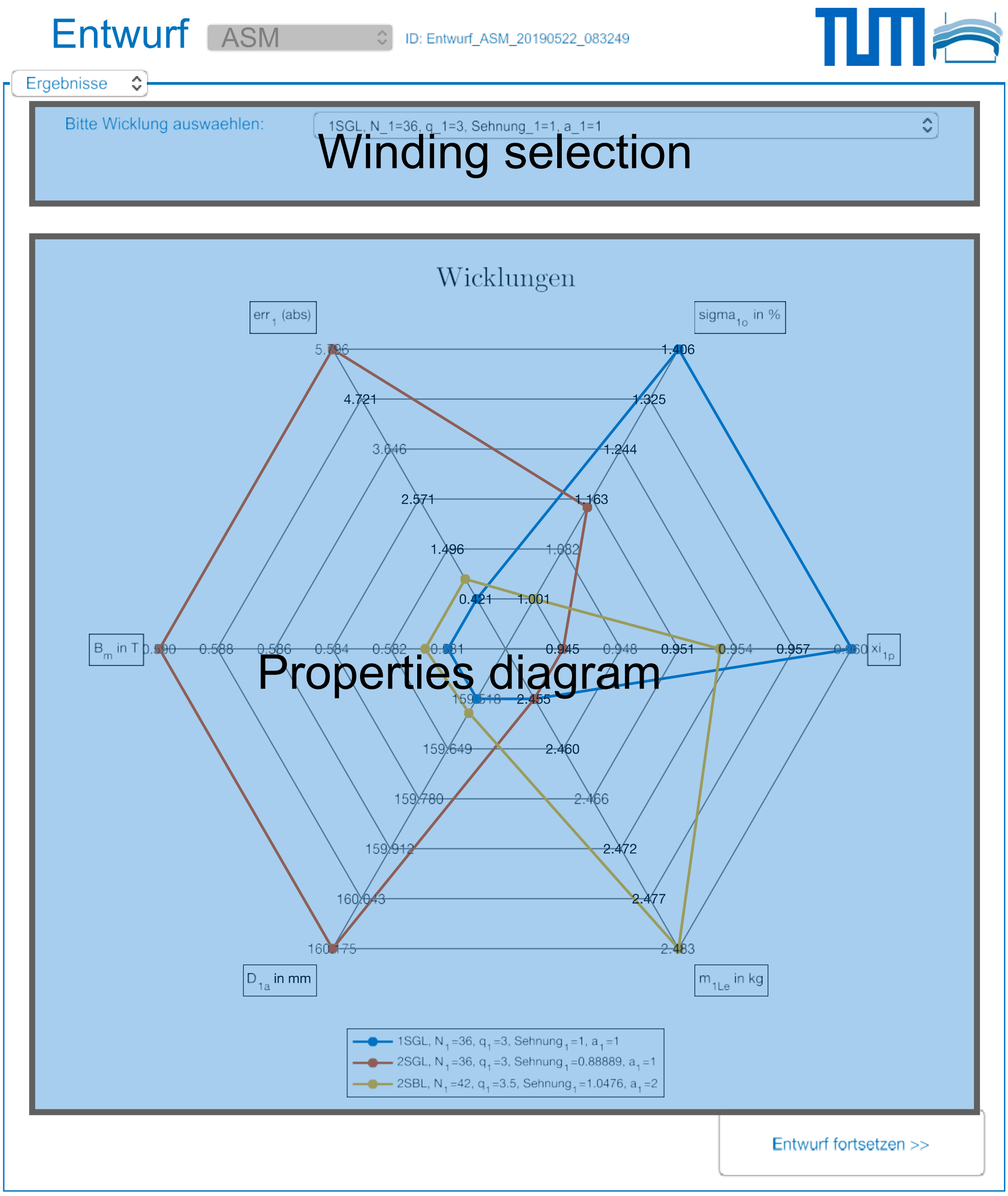

Figure 11: Optimization Option - Comparison of Windings by Specific Criteria in a Properties Diagram

Results

Once the design process is completed, the *Results* tab of the design user interface displays selected results and the geometry of the machine. Besides the most relevant main dimensions, such as stator inner diameter or ideal length, some machine characteristics are also displayed. When visualizing the geometry, it is possible to choose between the overall view of the machine, the geometry of the stator slot and, if available, the geometry of the rotor slot. The display of the winding layout is analogous to the procedure described in the previous section.

With PMSM, further functions are enabled. For example, the values

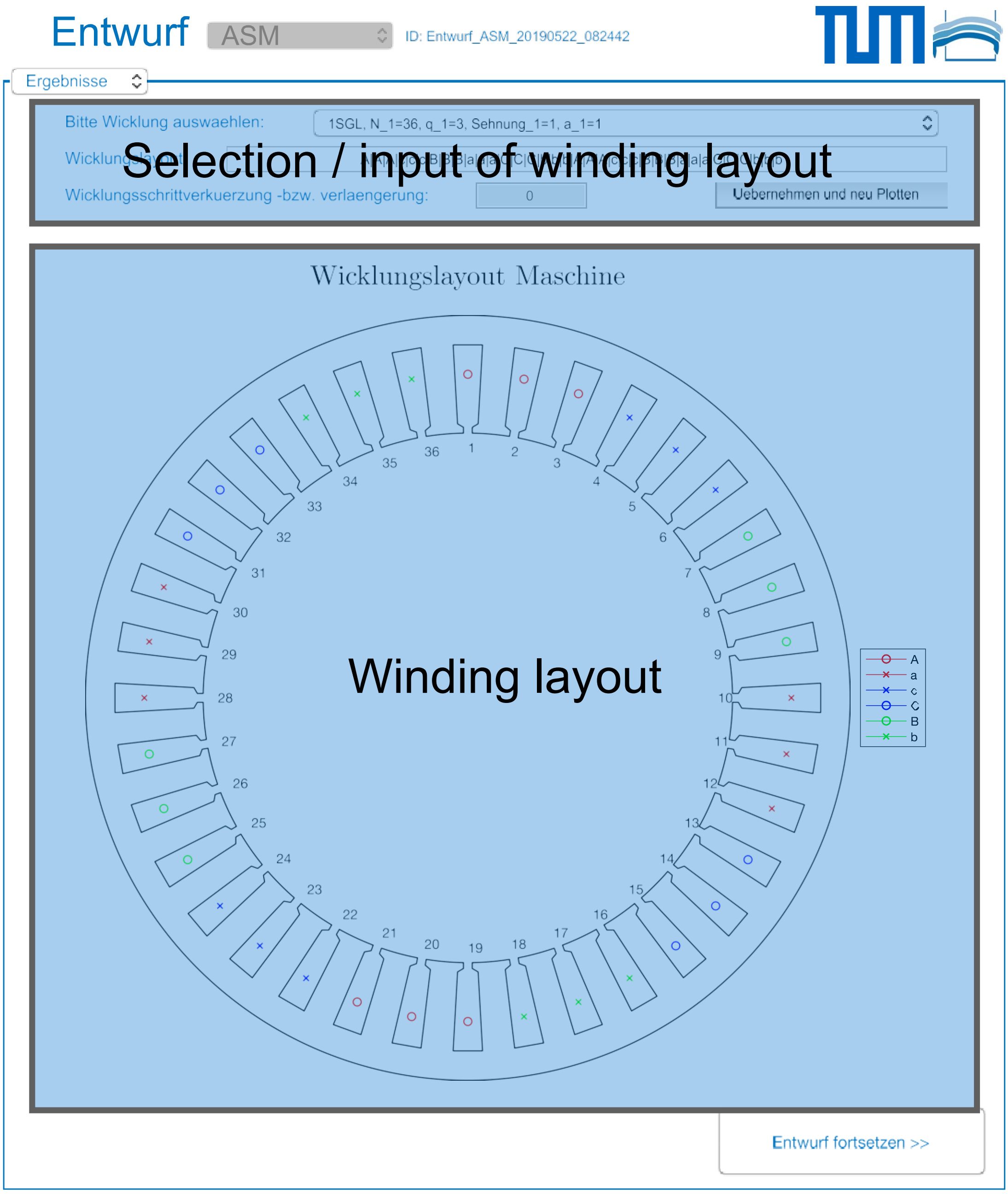

Figure 12: Manual Option - Entering or Selecting a Winding for Design

of the longitudinal and transverse axis inductance and the concatenated flux of the PM can be corrected. This makes it possible to feed the data obtained from an FEM simulation back into the MEAPA tool and improve the analytical estimates of the design process.

A further function is the adaptation of the geometry of the magnets and the magnet arrangement. It should be noted here that values for the longitudinal and transverse axis inductance and the concatenated flux of the PM from an external calculation must always be specified for the adapted geometry. These values can be determined with the exported CAD data of the adapted geometry, for example, using an FEM program.

In 13 the user interface of the design results for an ASM is shown. The "Continue to analysis" button continues the calculation process and transfers the design variables to the analysis.

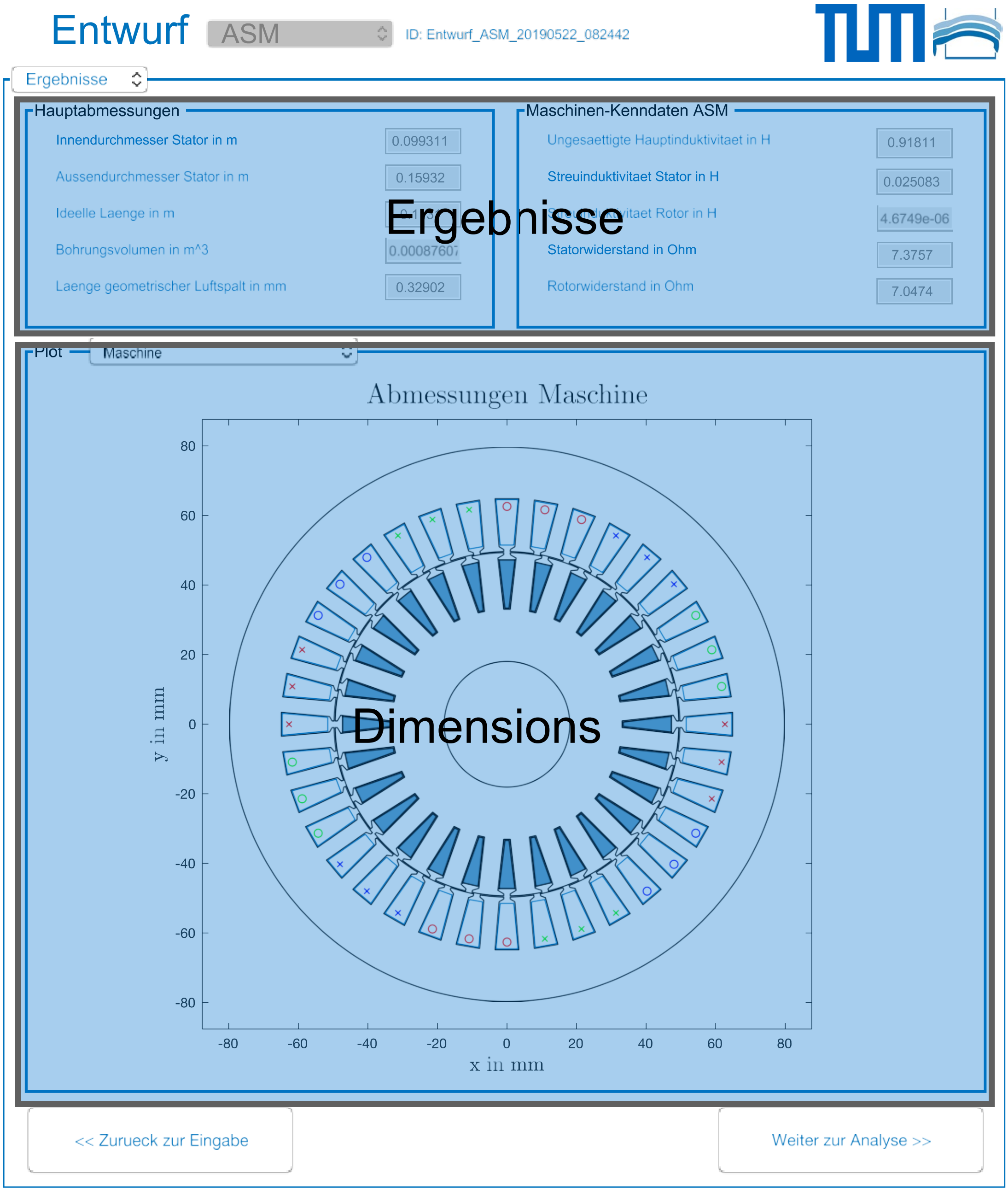

Figure 13: Results of the design process and representation of the geometry

3 Analysis

The analysis is used to calculate characteristic diagrams for the previously designed machine. For this purpose, the currents and voltages are first calculated using a motor or generator model. Then the individual loss components are determined. Finally, the efficiency map is generated.

3.1 Structure of the scripts

The structure of the scripts for the respective machine type is visibly subdivided analogously to the procedure in the code. The derivation and explanation of the engine and generator model can be found in the work of Jonathan Erhard.

The scripts are based on linear and steady-state considerations. In addition, there is no thermal check or similar. The user is therefore requested to feed the machine only with realistic data (i_max and u_max).

V/A: linear & stationary consideration:

- no saturation
- no cross-coupling of the inductances
- Inductances are not current dependent
- no dynamism
- chained flow of PM constant

The tables of contents of the analysis scripts are listed below. The auxiliary functions contain the functions for the optimization problems and their nonlinear constraints and are used several times.

Table of contents Analysis ASM and PMSM

A) Preprocessing
B) Torque control
  B.1) Motor model
  B.2) Generator model
C) Loss calculation
D) Map creation
E) Postprocessing
F) Auxiliary functions
  F.1) Optimization_M
  F.2) Optimization_i

3.2 User interface

In the *Analysis user* interface, the user can define the input parameters for the analysis and the calculated maps are displayed. The user interface is shown in Fig. 14.

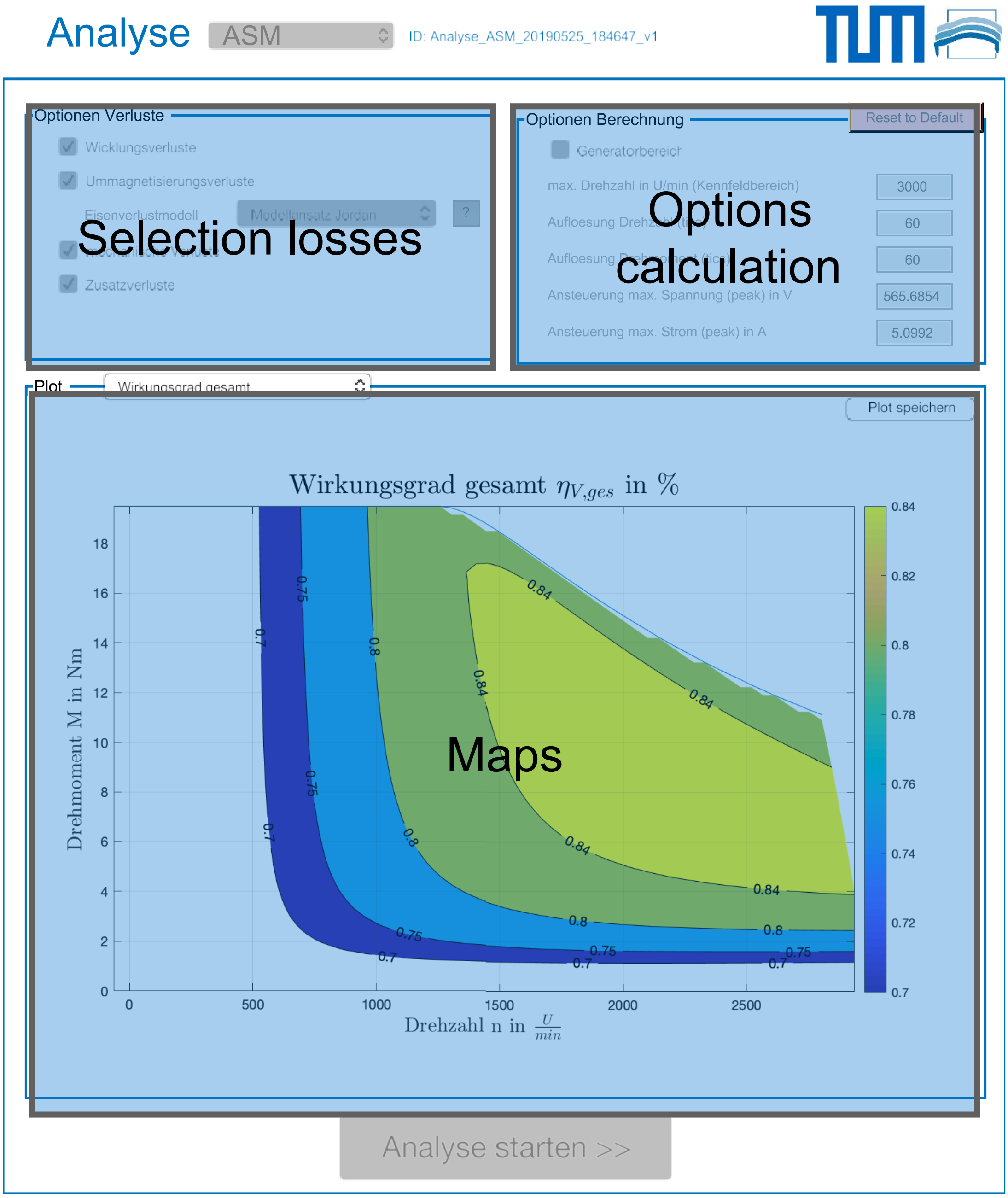

Figure 14: Input of the input parameters and display of the results for the analysis

The options include the selection of losses and settings for the calculation of the maps. In the user interface, the loss components that are to be taken into account in the calculation of the efficiency can be selected. For the calculation of the iron losses, the iron loss model can be adapted if required. For the options concerning the calculation, the generator range can be activated and the maximum speed of the map range can be defined. The analysis of the machine is carried out up to the maximum

Speed. The distance between two operating points in the grid is defined with the two input parameters *resolution speed* and *resolution torque.* A higher resolution is associated with a higher number of calculations, which directly increases the calculation time. The two control parameters define the current or voltage limits. By variation, the machine can be operated with different limits, for example to test a possible overload operation. It should be noted once again that the model is based on a number of simplifications and no thermal tests, and that the values should therefore be adjusted with care. The standard values entered correspond to the nominal values of the machine.

The calculation of the characteristic diagrams starts with the "Start analysis" button. The full load characteristic is calculated with the function *fct Optimization_M.* Depending on the machine type, the adapted system equations are stored in the function. The function fct *nonl-con_Optimization_M* contains the machine-dependent constraints of the optimization program. The calculation of the currents for the operating points is then carried out by solving of the optimization problem, which is described in the functions *fct optimization_i* and *fct nonlcon_optimization_i* is implemented. Both optimization problems are suitable for calculating both the motor and the generator operating ranges by simply adjusting the operating limits. When calculating the currents, the optimization is accelerated by using the currents determined from the previous steps as starting values.

After calculating the currents, the remaining variables and the losses are determined and then displayed in the form of characteristic diagrams in the user interface. The user can display the desired map via a selection menu. In addition, the respective map can be saved as a "figure" in the results folder using the "Save plot" button.

4 Other

4.1 Changelog

Version number	Editor	Changes
v0.1	(each)	-
v0.2	(each)	-
v0.3	(each)	-
v0.4	(each)	• Incompatibilities with file naming in Windows fixed • Estimation of longitudinal and transverse inductances again Added
v0.5	(each)	• Excel export fixed
v0.6	(each)	• Script mode added to bypass the GUI
v0.7	(each)	• Bug fixes
v0.8	(each)	• Feedback of the selected iron sheet parameters in GUI • Warning notice Inductances • Warning Exceeding the guide values of the inductances

4.2 Connection of the models / program structure

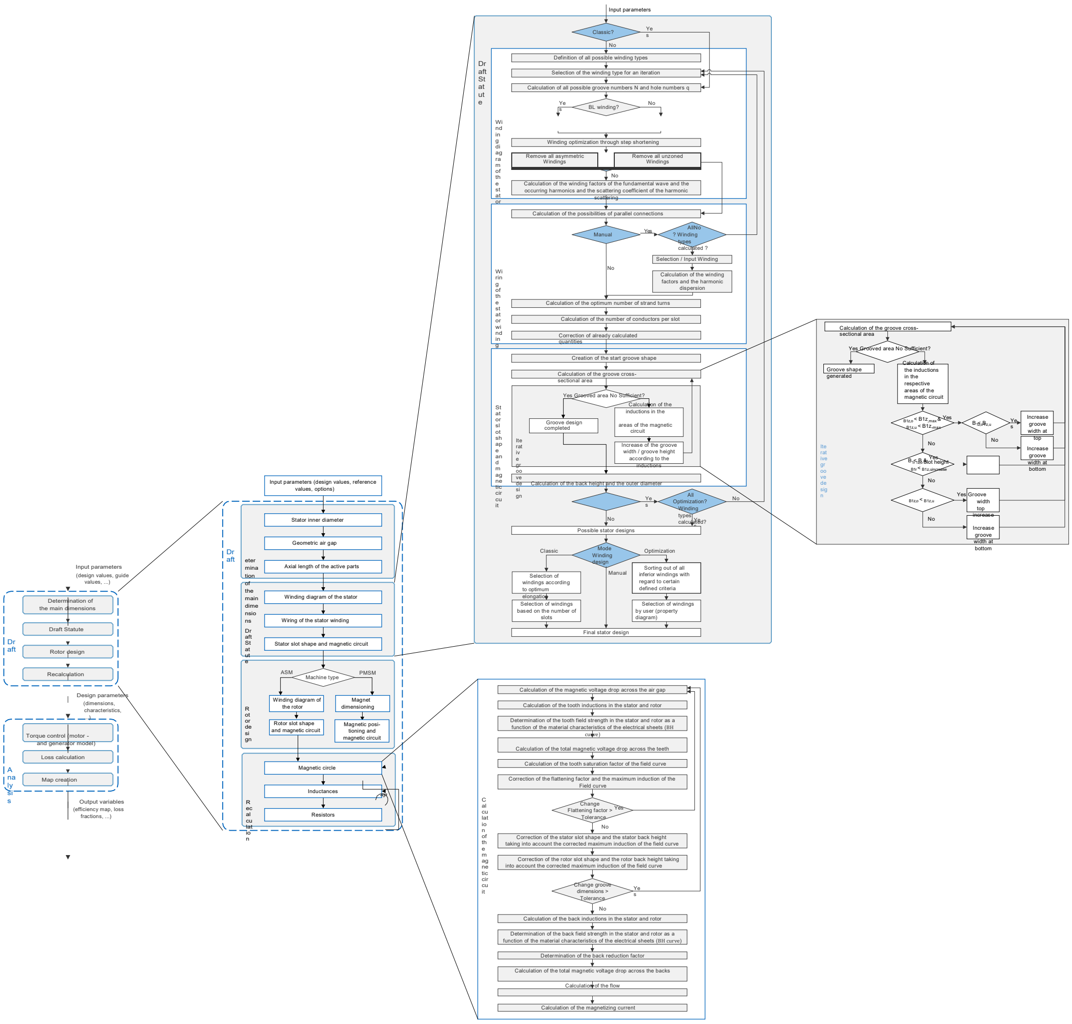

Figure 15: Relationship of the models / program structure

4.3 Brief overview of improvements compared to Horlbeck model

General

- complete documentation in the code, in the form of this quick guide and in the form of the work of Jonathan Erhard
- a tool for ASM and PMSM
- Structured and simple design
- complete graphical user interface
- Data for electrical sheet based on real data from manufacturer's specifications
- Export of the results to Excel and "dxf
- Data storage system

Draft

- Determination of main dimensions similar, mainly removal of "magic numbers" from code → completely parameterizable via GUI
- Draft statute completely revised:
  - Winding design and interconnection according to novel design process, therein include:
    - Use only the actual possible strains.
    - Actual design/distribution of windings.
    - 3 winding calculation options:
      - Selection of the "best" winding (optimization)
      - Manual selection (Manual)
      - Automatic selection (Automatic)
    - Extension of winding combinations by consideration of fracture hole windings (incl. toothed coil windings)
  - Iterative slot generation and precise parameterization of the slot geometry
- Rotor design PMSM:
  - Variants of magnet arrangement in rotor added (SPMSM, IPMSM)
  - Precise parameterization of the magnet geometry + variation in GUI
  - Feedback of the actual inductances due to the dimensions and ge- ometry of the PM possible by:
    - rough estimation according to empirical formulas.
    - Correction of values in GUI after FEM calculation.

- Rotor design ASM:
  - Discrepancies in rotor design resolved
  - Iterative slot generation and precise parameterization of the slot geometry
- Recalculation:
  - Recalculation of the magnetic circuit designed differently:
    - Dual correction loop for improved recalculation.
    - Adaptation of the tooth geometry and output of a warning if the preset reference values are exceeded.
    - Inaccuracies in determining the back reduction factor circumvented.
  - Calculation of leakage inductances based on actual slot dimensions or harmonics
- Complete description of the geometry of the machine → "dxf" export

Analysis

- Equations of the field-oriented control form the basis for the motor or generator model → Current minimum optimization
- Iron loss model according to Jordan (+ actual electrical sheet parameters)
- Generator operation