Development and verification of an energetic machine tool model on the example of a turning machine
Development and verification of an energetic machine tool model on the example of a turning machine

Simon D. Züst

Master Thesis
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Andreas Leuenberger
Adam Gontarz
Lukas Weiss

Prof. Konrad Wegener
Abstract

In the time of increasing resources limitations and energy saving as global task, the design and development of products with neat consumption over the whole life time is mandatory. In order to realize a minimal energy consumption of a product, an optimization over the whole life-cycle is required [WZ02, GTA+08]. Since machine tools have the most significant energy demand during use phase [ZZ09], energetic optimization of machine tools have to focus on the duty time of the machine.

In this context, a framework to model energetic behaviour of machine tools is in development at the Institute for Machine Tools and Manufacturing (IWF) at the Federal Institute of Technology (ETH) in Zurich. The purpose of this framework is to use the little information available in the early development phase, an predict the energy use and thermal impacts during the use phase of the product. This is intended to be done by component models connected to a machine model. Within the machine model, a certain flexibility is demanded, in order to use the model for different machine tool applications.

The goal of the following master thesis is to provide the existing framework with component models, and test the implementation by applying it on an existing turning machine. Thereby, component models represent the energetic and thermal behaviour of machine tool components. Requirements for this implementation are given by the master thesis of M. Lang [Lan12]. The author designed the requirement list together with partners in the Swiss industry. During the procedure, the system modelling is done first, followed by measurements taken on the test-bench. The measurement data is used to validate and analyse the model. During this steps, continuous knowledge transfer with M. Lang has been done to achieve the requirements by the industry.

By introducing the concept of generic components, the modularity of the model is realized. A generic component is defined by a distinct set of inputs and a set of outputs. The mapping between the in- and outputs is described by physical models, where different physical models can be of the same generic type. Since component models of the same generic type have the same in- and outputs, they can be exchanged. The framework with the implemented component models is used to model the test-bench machine. This model consists of all relevant electro-mechanical components and a thermal model of the spindle cooling system. The selection of relevant components is done based on the estimated power class.
Comparisons of the simulations with measurements taken on the test-bench machine gave the following result. In general, three types of errors have been investigated: Not modelled constant consumers, parametrization errors and component model errors. The first two error types are caused during the use of the framework, where errors of the last type are caused during implementation. To use the simulation data for further analysis, an internal accuracy requirement of $\pm 20\%$ was set as goal. Using only fact-sheet information about the installed components on the test-bench machine, the requirement can only be satisfied during operation modes with high power demands. Including also experience of other machines and measurements, the precision can be improved to $\pm 10\%$ relative error in total power consumption over all operational states. This is mainly due to the compensation of not modelled constant consumers by an estimated constant power. Since, the achievable precision has a significant dependants on the available information about the machine, existing data of previous measurements on other machines can be used to improve the model. Simulation of the thermal behaviour of the spindle cooling system is able to represent the long time behaviour, such as average heat release to environment. Short time behaviour – such as precise temperature development – does not fulfil the desired precision due to parameter incertitudes and errors.

From this work, the following conclusion is made: Energetic modelling of machine tools by connection generic component models is possible within the desired precision. Further, qualitative analysis of a machine tool by the framework can be done, as shown by a sensitivity and influence-interference analysis during the procedure. The requirements by M. Lang regarding the simulation and model components are achieved. Need for action exists in the missing interfaces for configuration, such as a connection to CAM software. Future work has to focus on implementation of more component models and analysis procedures. Also the test on other machine types is recommended.
Zusammenfassung

Im Zeitalter von verknappenden Ressourcen und globaler Einsparung von Energie, ist die Entwicklung von verbrauchsarmen Produkten notwendig. Um eine minimaler Energieverbrauch eines Produktes zu erreichen, muss dieses über seine ganze Lebenszeit optimiert werden [WZ02, GTA 08]. Da Werkzeugmaschinen einen dominanten Verbrauch während der Nutzung haben [ZZ09], müssen energetische Optimierungen auf diesen Zeitabschnitt fokussiert werden.


Durch die Einführung des Konzepts der generischen Komponenten wird die Modularität und Flexibilität des Modells realisiert. Eine generischer Komponente wird dabei über bestimmtes Set von Ein- und Ausgängen definiert. Die Abbildung der Eingänge auf die Ausgänge wird durch physikalische Modelle beschrieben, dabei können verschiedene Modelle vom gleichen Typ generischer Komponente sein. Da aus der Definition folgend Modelle vom gleichen generischen Komponententyp die selben Ein- und


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Thema / Titel: Erstellen und Verifizieren eines Energiemodells anhand einer Drehmaschine

Problemstellung

Aufgabe

Arbeitsschritte:
• Verstehen der Drehmaschine (Aufbau, Komponenten)
• Stand der Technik: Energiemodelle von Werkzeugmaschinen
• Messtechnisches Erfassen der Energieflüsse der Drehmaschine
• Parametrisieren und Erweitern des Java-Energiemodells für die Drehmaschine
• Verifizierung der Modellergebnisse mit den Messergebnissen
• Kritische Hinterfragung des Vorgehens (Fehlerabschätzung)
• Zwischen- und Schlusspräsentation sowie schriftliche Ausarbeitung
Acknowledgment

The following master thesis at the institute for machine tools and manufacturing gave me the possibility of an insight and contribution to ongoing machine tool model and simulation software development. I would like to thank my supervisors Andreas Leuenberger and Adam Gontarz for their competent support in methodology, expertise and practical work on the machine tools. Further I thank David Hampel for his introduction and support on the EMod framework and Jens Boos for his expertise during the measurements. To the group of Lukas Weiss I thank for the interesting and entertaining discussions, as for the comfortable work environment. My gratitude goes also to my father, who supported me in inspiring discussion and by his expert knowledge.

Special thanks to my dear girlfriend Prisca, she always gave me the back-support needed.
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<tr>
<td>$A$</td>
<td>Area, cross section</td>
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<tr>
<td>$a_p$</td>
<td>Cutting depth</td>
<td>$[mm]$</td>
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<tr>
<td>$b$</td>
<td>Chip height</td>
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<tr>
<td>$C$</td>
<td>Consumption</td>
<td>$[\text{var}]$</td>
</tr>
<tr>
<td>$c_d$</td>
<td>Drag coefficient</td>
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<tr>
<td>$c_{p/v}$</td>
<td>Internal heat capacity</td>
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<tr>
<td>$d$</td>
<td>Damping constant</td>
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<tr>
<td>$\varepsilon$</td>
<td>Error, deviation</td>
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<tr>
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<td>Force</td>
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<tr>
<td>$f$</td>
<td>Feed rate</td>
<td>$[\text{mm, mm/rev}]$</td>
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<tr>
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<tr>
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<td>Number, count</td>
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<td>Power</td>
<td>$[W]$</td>
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<tr>
<td>$p$</td>
<td>Pressure</td>
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<tr>
<td>$S$</td>
<td>State, operational level or surface of a body</td>
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<td>$T$</td>
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<td>t</td>
<td>Time</td>
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<td>\vec{i}</td>
<td>Input vector of a system</td>
<td>[var]</td>
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<td>\vec{x}</td>
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<td>\vec{y}</td>
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<td>\alpha</td>
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<td>\gamma</td>
<td>Adiabatic exponent</td>
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<td>\lambda</td>
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<td>\mu</td>
<td>Friction coefficient</td>
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<td>\omega</td>
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<tr>
<td>\Pi</td>
<td>Pressure ratio or parameter set</td>
<td>[Pa/Pa]</td>
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<td>\pi</td>
<td>Parameter</td>
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<tr>
<td>\rho</td>
<td>Density</td>
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<tr>
<td>\sigma</td>
<td>Variance</td>
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</tr>
<tr>
<td>\vartheta</td>
<td>Temperature</td>
<td>[K]</td>
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Indices

- amb: Ambient
- amp: Amplifier, amplification
- ax: Axis
- brk: Brake
- c: Cut
- cair: Compressed air
- cc: Chip conveyor
- ccoil: Cooling coil
- cf: Cooling fluid
- cl: Clamp
- cmp: Component
- comp: Compressed
- cr: Critical
- ctrl: Control, controlled
- dmd: Demand
- el: Electrical
- f: Feed
- fac: Factorial
- filt: Filtered, post-processed
- fl: Fluid
- fld: Field
- fr: Friction
- G: Gravitation
- g: Gas, compressible fluid
- init: Initial (state value)
- loss: Loss, losses, leakage
- lub: Lubricant
- M: Motor, drive
- mch: Machine
- N: Normal, perpendicular
- P: Process
- p: Passive
- realiz: Realization
- ref: Reference (point)
- rep: Repetition
- sc: Spindle cooling
- th: Thermal
- tr: Threshold
<table>
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<tr>
<td>AS</td>
<td>Active sum</td>
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<td>CAD</td>
<td>Computer aided design</td>
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<tr>
<td>CAM</td>
<td>Computer aided manufacturing</td>
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<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>DEQ</td>
<td>Differential equation</td>
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<tr>
<td>EE</td>
<td>Elementary effects Method</td>
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<tr>
<td>EER</td>
<td>Energy efficiency ratio</td>
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<td>EMF</td>
<td>Electromagnetic field</td>
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<tr>
<td>EMod</td>
<td>Energy model (machine tool) by <em>inspire</em></td>
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<td>ETH</td>
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<td>FID</td>
<td>File identification number</td>
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<td>GUI</td>
<td>Graphical user interface</td>
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<tr>
<td>SID</td>
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<td>SMB</td>
<td>Small and medium-sized businesses</td>
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<tr>
<td>XML</td>
<td>Extensible markup language</td>
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<td>ZOH</td>
<td>Zero order hold</td>
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Introduction

1.1 Motivation

Looking at the current situation, energy efficiency and saving a huge topic over society, politics and industry. While supporting the use of alternative, regenerative energy sources, the minimization of energy waste is a required action. When speaking of energy waste, production of waste heat is always connected. Wast heat is not only a problem of energy costs, but requests also certain actions: Heat release can affect precision and thermal stability of machines and productions. When a heat loss occurs, countermeasures might be requested, which also consume energy and produce heat loss. This makes energy wast not only a financial problem, but the activator for a whole chain of processes and influences. By designing products with a neat energy demand over the whole life cycle, secondary negative effects can be minimized [WZ02, GTA+08].

The Swiss industry is one of the world leading manufactures of machine tools. Like other active products, machine tools have a dominating energy demand during the use phase. As most of the machines produced in Switzerland are exported, a substantial contribution to global efficient energy use can be made by optimizing the use phase of a machine tool [ZZ09]. During the early development phase, the most influence can be taken on the final product. But, only a little information is available during this time and no prototype for measurements is available. A machine tool is in general an assemblage of components, such as drives, pumps, fan and others. The energetic behaviour of the machine is thereby characterized by the connected components and interaction between them.

To deliver information about the energetic behaviour of the final machine during the early development phase, a method is requested, which can estimate the energy flows between the components based on the little information available. To do so, a machine tool models that represent the significant physical effects can be used. The requirements of such an energetic model would be a small number of demanded parameters and a great flexibility. The small number of parameters results from the little information available in the early development phase, where the flexibility is required to overcome the large number of different machine tool applications, types and configurations available.
1 Introduction

1.2 Related Work

The idea of machine tool models focusing on the energetic behaviour of the machine and its auxiliary devices includes multiple topics of research. On one side, there is the modelling of machine tools and components, on the other the idea of generic or modular models for flexibility in the applications. As mentioned above, the machine tool model for the early development phase would require such a flexibility. This energetic model has of course also to fulfil the demands of the industry to be of practical use, and be implemented in a useful framework. Further, a validation of the model is required and available methods to gather adequate data of the energetic behaviour of a machine tools have to be researched. In the following section, available literature and information about machine tool models relevant for this work are discussed. Further, information of the ongoing machine tool energy simulation framework development at the institute for Machine Tools and Manufacturing is given. Last, an overview of the existing methodologies to measure and evaluate the power flows on a machine tool and its auxiliary devices is provided.

1.2.1 State of the art in energy models for machine tools

A model is a description of effects and dynamics one is interested in. Which effects and dynamics are interesting and how those are described depends on the application. As for other applications, many different types and implementations of machine tool models do exist. Depending on the application of the model the type, the size and system boundary vary. In the next paragraph, a short summary about a selection of existing machine tool models is given. For a detailed analysis on existing machine tool models and simulation software used by the industry, it is further referred to M. Lang [Lan12].

As mentioned above, may different applications for machine tool models exist. This models reach thereby from machining process to manufacturing process. Starting at the smallest relevant system boundary, one is talking only about the process itself. Process models are often specific for a certain machine tool type and application – such as cutting with geometrically defined or undefined cutting edge. Process models for energetic models have to describe the relevant forces and velocities under certain process conditions. A well known process model by Kienzle and Victor for geometrically defined cutting edges is described in [KV57]. Within this model the acting cutting, feed and passive forces on the axes are described dependent on the cutting profile. The system boundary is in this case the immediate zone around the cutting tool, which allows this model only to describe the mechanical power of the cutting process. How the required mechanical energy is provided is not part of this model.

Extending the system boundary to enclose the main drive, the energy flow from electrical to mechanical power at the cutting edge becomes interesting. There exist various models, which lay the focus on this part of the machine tool. As described by Draganescu, Gheorghe and Doicin [DGD03], a statistical approach for the modelling of this system can be used. By doing designed experiments together with the response surface methodology, the authors identify the coefficients of a second order approach for the description of the electrical to mechanical power transformation efficiency in dependence of the process parameters. But to do so, this procedure requests an existing machine tool and a large set of measurements. This type of model is able to describe non-linear effects over a wide range of process parameters for the transmission of electric energy to mechanical power, which is a limited subsystem of a machine tool. As shown by Li and Kara, the an empirical approach is also possible including the auxiliary devices as well [LK10]. Still, measurements on an existing machine are required.

An other approach is, to derive physical models of the components followed by measurements to identify the system parameters. This has been done by Eisele, Schrems and Abele [ESA11] on the example of a
lubricant system containing a motor, a pump, valves and pipes. The authors mention in their paper the use of such a model in the system optimization. By changing component parameters and characteristics – which is possible due to the physical approach – the overall efficiency can be optimized. Using multiple components – which is the case for a machine tool – the interconnections of the devices becomes relevant for an energetic point of view. This is due to the influence and interference between the components over the connections. In such a system as in others, components can have a demand of energy or other resources. This demand has to be satisfied by a component upstream the energy or resource flow. Thereto, operation points of components are affected by other components of the same system. To determine the overall system power demand and efficiency, the component types and connections have to be investigated. To change a single component or interconnection between components, modular models are required. Verl and others describe such an approach in [VAH+$^+11$]. The authors introduce a generic component of a machine tool, with defined inputs and outputs. The model of the component maps the inputs to the outputs. By using such a structure, components become interchangeable and the connections between them can be varied. The authors have implemented the model in Matlab/Simulink in forward simulation model and have used S-functions to test real C-code of the machine controller.

Until now, statistical and physical models are discussed. Mixtures between the two mentioned model types are also possible. The approach of combining measured data with physical models in a modular machine tool model has been done by Avram in his PhD thesis [Avr10, AX11]. The author provides two databases for the model. The first one includes measurement data and key values for certain processes. A process is here defined on base of a single element of a work piece, called feature. Using different weighting factors, the author demonstrates how to select the optimal process for a given feature with respect to economy, technology and ecology. The second database, called Resources by Avram, includes the components and the system topology. A machine tool system consist of key values and components. Each component has again key values – such as parameters – and connections to other database entities. The relation between the entities of different types are given by the database connection. Example for connections are: drives, performs or consist of [Avr10, Figure 4.9]. As for the process, the author describes the optimization of the machine tool to machine a given work piece. For the system modelling, Avram uses physical models and black-box models. The physical models are very detailed and afford a large set of parameters.

Summing up, there exist various types of machine tool models. Physical, statistical and black-box models are used for process and machinery simulation [KV57, DGD03, ESA11]. This models concentrate on the machining process and the machinery performing the corresponding axis movement. Discussions for modular machine tool models exists [VAH+$^+11$], and the concept is proven working by [Avr10]. At this reference, part of the auxiliary devices are also modelled. Because of the great detail of the model, a large number of parameters is required.

1.2.2 Machine tool energy model (EMod)

In order to develop and implement a machine tool energy model, a framework called EMod is under development at inspire, ETH Zurich. The aim of this framework is to realize the concept of modular machine tool modelling with a small parametrization effort, but including also the auxiliary devices. Compared to the discussed models above, the implementation in a proprietary environment is abandoned. Within this framework, machine tools can be designed, configured and simulated. Further, the tool does support the user in the analysis of the generated data. For this procedure, a machining process has to be provided. During the early development stage of a new product, the influence which can be taken on the final product is higher compared the the following stages of the development process. On the other hand, only little information about the final product is available. This information is limited to basic
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The machine energy model will support the engineer and the industry at this stage. Thereby, the tool gives the possibility to test different machine and component configurations as a connection of different modules. Because no measurements or experiments are possible at this stage, models are required to describe the dynamics of the connected components. To do so, basic informations about the installed components is required. While the information about the product is growing during the development, the EMod framework has the demand to be able to add additional information to an existing machine configuration. This can be in the form of new machine parameters, machine structure or extended dynamics of components. In the current stage, the tool is still under development and part of finished or ongoing students projects [Lan12, Elb12] at ETH Zürich. The named work of M. Lang intends to analyse the requested features the framework has to include, in order to satisfy the demands of the machine tool industry, where the work of Ch. Elbe [Elb12] focuses on the analysis of simulation results. The following section shall explain the current stage of development and the indented final simulation procedure of the framework.

The framework contains three main steps. Those are configuration, simulation and analysis. As shown in figure 1.1, the configuration step is the input interface to the framework, where the analysis step forms the output interface. The three steps are supported by a model and a component database. The model database includes the physical description for certain machine components, where the component database contains the parametrisations for the models. Both sources are linked by a one-to-many relationship: One model can be parametrized by multiple parameter-sets, where a parameter-set belongs only to one model. A very simple example: A motor model requiring a motor efficiency as single parameter can be parametrized by different efficiencies of different motor types. But any motor efficiency belongs compulsory to the motor model.

**Figure 1.1:** Simplified structure of the EMod framework, developed at inspire. The three main steps are shown, as the physical model library which is linked to the component parameter database trough a one-to-many relation.
During the configuration, the user enters the component types and parameters of the machine tool. This step is simply the translation of the part list of the machine into the framework language. Based on previous measurements, components with a low power level can be neglected. A component may for example be a motor, the parameters may be the specific efficiency map. For these components, the interconnections have to be defined. In the case of the motor, the interconnections would be the powerline with the amplifier and the transmission of mechanical energy.

![Diagram](image)

**Figure 1.2:** Example for a component interconnections in the EMod framework: A motor has a connection to the power-line by $P_{el}$ and to the transmission of mechanic power by $(\omega, T)$

To simulate the model, the user will further enter a sequence of machine states and process definitions. Machine states describe the current action of the machine tool, for example processing or off. Where the process definition describe the in cycle specific actions during the process as time series. During the simulation, the power and process material consumption for the given machine state time series and process is calculated by the physical models. The result of the simulation will then be passed to the analysis, which analyses the data and creates a report as output.

In the current development state, the core of the framework is implemented in Java. The reason to do so, is the demanded independence of operational systems on proprietary software of third parties. This implementation consists of all functions required to read and save configurations, to run simulations and to save the created data. Further, objects to implement physical models, such as abstract classes or the objects which defines the linking between two components, are available. Still due are the model database, the component database and the analysis of the data. For all three points, the prove of concepts have already be made [LH11b]. The goal of the framework development is to provide a suitable implemented model database and analysis of the created data to fulfil the targets described in the head of this section.

From the first, internal list of requirements, an extended version has been designed including the voice of the industry [Lan12]. By using literature, generalized survey and personalized interviews with industrial partners, Lang extended the former list of requirements in order to satisfy the demands of the industry. The result of his analysis are summarized at this point in the form of the requirement specification:

1. Parametrisation of the machine
   a) The user has to be able to define a machine tool consisting of components. Each component is characterized by key values available in factsheets.
   b) Connections between the components have to be considered
   c) The simulation shall build upon a reference process. To assist the user interfaces to CAM software has to be realized.
   d) General data must be provided by the framework, such as material or tool parameters
   e) To store and reuse model and component information, a database has to be provided to store and create machine elements and configurations

2. Simulation and calculation
   a) Continuous simulation is required, further quasi static simulation is advised
   b) The possibility of reading intermediate result must be given
3. Output data

The requirements on the output data focus on the analysis part of the framework. This part is not within the coverage of this work, but is discussed in [Elb12].

4. Energetic behaviour

a) The following set of components is obligatory for the implementation: Spindle, axe, cooling, filtration, chip conveyor, compressed air, dust collection system, hydraulic aggregate, pneumatic aggregate, pump, hydraulic/pneumatic components, transmission

b) Basic control and steering components must be available.

c) The possibility to implement own components must be granted

5. Thermal behaviour

The possibility of modelling thermal effects is mandatory. The central point is thereby the thermal flows to the ambient.

6. Simplifications

Simplification which allow to reduce the number of parameters, without significant loss of precision are desired. Anyhow, all simplifications made have to be shown as allowable.

a) Accelerations over a small time

b) Where ever possible, effects with a minor contribution to energy demand – such as vibrational or frictional effects – have to be neglected.

c) Emissions – such as noise or dust – to the environment, except thermal, are not in the focus and can therefore be neglected.

d) The process simulated on the machine model can be assumed as optimal. Process optimization is not the goal of the framework.

1.2.3 Energy consumption measurement and analysis of machine tools

For existing machine, the analysis of the component and state specific energy consumption can be done over measurements. This approach delivers of course more detailed results, but requests an existing machine. Detailed power measurements on different machine tools have been done at the institute for machine tools and manufacturing (IWF) at ETH Zürich, together with inspire AG. For this purpose, a measurement system has been developed, which is capable of measuring the total and component specific energy and resource consumption of machine tool [GHWW10].

Further, measurement analysis procedures have been designed and know-how in the measurement of different types of machines has been gained. An example of designed evaluation tools is the retrofit indicator [GWW10]. This tool evaluates different components dependent on their energetic behaviour in order to identify those with a significant energetic improving potential. An other form of analysis is the function oriented consumption. The power consumption of the components are thereby assigned to one or more machine functions. There exist different approaches, to perform this analysis.

Li and others [LZKH11] assign the measured power demand to different systems of the machine tool, such as hydraulic or cooling system. The authors further show the difference between the actual mechanical power demand of the process and the measured total power demand of the machine. Thereby, the
difference between static and dynamic consumer is introduced. The goal of the authors is to minimize the static consumption of machine tools. With the goal of self-optimizing of machine tools with respect to energy consumption, Schmitt and others [SBB11] use a state machine to represent different operational modes. Each operational mode refers to a state, where only one state can be active at the same time. The state transitions are given by the control and the machine tool model.

Functional oriented analysis has also been developed by Gontarz and others [GWW11]. The author define the five functions machining, process conditioning, tool/part handling, machine conditioning and waste handling. Evaluations of measurements by the authors according to their introduced machine functions show a significant or dominating energy consumption by non machining functions. With this analysis, it is shown, that the auxiliary devices of a machine tool have a contribution to the total power consumption which is not negligible. Especially during the power optimisation of machine tools, potential for improvements is located in the components, which have a supporting function for the machining function.

1.3 Overview

From the past sections, the following information can be taken: There exist various approaches of energetic machine tool models. Only a small fraction of them focuses not only on the process zone, but also on the auxiliary devices. Further the concept of modular model, to overcome the problem of different machine configurations as been discussed and tested in literature. There exist the very detailed model GREEM, which also includes the auxiliary devices. Due to its large amount of details, it is very intensive in parameter demand. The negligence of the auxiliary components is from the energy consuming point of view inconsistent with measurements done on machine tool. Energy measurements have shown a substantial, if not dominating part of the total power demand coming from the auxiliary devices. A model, which fulfils the demand of flexibility in component connections and configurations, low parametrization effort and modelling of all machine tool components is missing. Such a model would be requested to assist the development of new machine tools in an early phase.
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2.1 Problem specification

From the previous chapter, the available models for machine tools and the results of previous energy measurements are known. Further, great potential in energy savings by the industry through efficient and effective machine tool design is located [ZZ09]. Measurements by *inspire* have also show potential optimization possibilities, which are machine tool specific. This measurements of different machine tools further show, that a significant if not dominating part of the total energy demand is not used as mechanical process power, but for the auxiliary devices. Such devices are cooling systems, hydraulic aggregates, climatic systems, compressed air supply and others. An additional problem is here the over dimensioning of such aggregates. The total installed power is not required to realize the desired action, and leads thereto to bad efficiencies.

Optimizations of a machine tool in the sense of energy use must therefore include the whole machine tool system and its subsystems. To do so in an early development stage, models to predict the energetic behaviour are required. This models can be strictly physical models, models based on measurements of other machines or any combination between the two. Many of the available machine tool models focus on the process zone; auxiliary devices are neglected. There exist also detailed models, including the auxiliary devices. Due to the great detail of the models and the demand of a large set of parameters, the appliance in early development is only practical if all component specifications are known. For a study of concepts, where no detailed information is available, simple models are required. Given the available models and the possible employments, a shortcoming exists in the area of energetic models applicable in the early stage of development.

In order to provide a tool to assist the development of machine tools from the energetic point of view, a framework by *IWF* is under development. This framework will enable to configure and simulate machine tools by the use of component models connected together by defined links. The use and functionality of such modular models has been shown in [VAH+11]. Currently, the general functions of the framework have been designed an implemented, missing are the component models and the configurations. Regard-
ing the use of the model, a list of requirements has been established by M. Lang [Lan12]. The author has used available literature information, combined with industrial and IWF internal requirements. The industrial requirements resulted from a survey among Swiss SMB.

2.2 Terminology

Discussing models in this work, the difference between *machine model* and *component model* is important. Using the definition in [BG01], the difference between functional and working interrelationship can be made. The functional interrelationship describes the connections between the sub-functions of a machine tool, where the working interrelationship describes the physical effects of a sub-function. A sub-function is thereby an element with a declared function and is called *machine component* in this work. An example of a machine component is a drive or a pump. The declared functions would be transforming electrical energy to mechanical energy, or volumetric flow respectively. When speaking of a component model, a set of equations describing the physics of a single machine devices is meant. To use a component model, component specific parameters might be requested. A machine model consists of different machine component models with their parameter sets. The machine model is thereby described by a list of parametrized components and the set of all connections between these components. This connections represent the functional interrelationship.

Some additional comments have to be made concerning notation of flows and derivatives, as for continuous and discrete time systems. In order to differ between differential equations and flows the following notations are used: When speaking of a change over time in the sense of a differential equation, a dot is drawn over the variable:

\[ \dot{x} = \frac{d}{dt}x(t) \]  

(2.1)

While speaking of a flow – for example mass flow – an asterisk instead of a dot is used:

\[ ^{*}x \]  

(2.2)

This difference is made to explicit differ between differential equations with states and algebraic equations with variables. Within the context of a DEQ in system modelling, a state is a level variable for an energy storage [Guz08]. An example of a state is the temperature of a homogeneous body. The temperature is thereby a level variable for the internal thermal energy of the body. In general, states have a law describing their change over time. Variables can change their value immediately, where an infinite amount of energy is required to perform a step on a state.

Talking about physical models and simulations in the framework, continuous and discrete time descriptions will be used. In order to differ between the two domains, the following notation is used: A continuous signal \( x \) is written with round brackets as

\[ x(t) \]  

(2.3)

For the discrete time representation of the same signal with sample time \( T \), the time step \( k \) is written in square brackets:

\[ x[k] \triangleq x(k \cdot T) \quad \forall k \in \mathbb{Z}_0 \]  

(2.4)

Any further symbols and acronyms used for the following work are listed on page XVII and following.
2.3 Goal of this thesis

Within this thesis, a contribution to the existing machine energy model EMod, developed at IWF shall be done. The work consist thereby of the modelling and validation of new system components, the parametrisation of an existing machine tool and the implementation into the existing framework described in section 1.2.2. Within the whole procedure, the requirements made by the industry [Lan12] have to be used as guidelines and quality criterion for the model. Motivated by the input of Professor K. Wegener, regarding the success of the IWF tool Achsbaukasten, the continuing injection of information into the model during the development process of a machine shall be enabled. In other words, a part of a machine tool model must be changeable without affecting the other parts. In order to guarantee a certain reliability for the simulated data, demands on the precision are required. Given by the internal specifications, a relative error of ±20% is tolerated, when comparing the model results to trusted data. Because of the estimated error in measurement of ±5% to ±10% [GHWW10] in the energy measurement, the demanded accuracy limit results. To guarantee the use and portability of the model for other machine tools, the errors have to be analysed critically.

From this description the following four points are synthesized, describing the goal of this work:

A Provide component models to the EMod framework. The components must be suitable to describe the power consumption of a machine tool. First considerations for the thermal modelling have to be made.

B Follow the requirement list of [Lan12] regarding the model configuration and simulation, and discuss failed requirements.

C Ensure the placement of new information into an existing model. This as do be done on the level of component model and machine model.

D Achieve a maximum relative error band of ±20% and analyse the simulation results with respect to errors and portability of the model for other applications.

The testing of the framework with the implemented models has to be done on the existing test-bench with the turning machine Schaublin 42L. Suitable methods, to acquire data for model validation and analysis from the test-bench have to be found and discussed.

2.4 Proceeding

To fulfil the goals described above, two main tasks are set: System modelling and model validation. The results from both steps have to be used together with the list of requirements from [Lan12] to evaluate and discuss the model. During the system modelling, specifications for the models have to be derived, in order to guarantee the desired functionality. This specifications have to deal with simulation methods, planned model components and implementation into the existing framework.

Based on this information and system boundaries the physical models will be derived. The focus will thereby be on the models required for the appliance on the available test bench. This resulting system equations are implemented into the existing framework. To finish the system modelling, the framework with the implemented models will be used to model the machine of the test bench. After the system modelling, the validation and the analysis of the model is applied. The goal is to quantify the simulation results by comparing them to measured data. Appearing errors have to be identified and discussed. Based on this information, the discussion of the work has to be done. This includes the knowledge gathered
2 Procedure

during the system modelling, the validation results and the possibility to generalize the error analysis and
the comparison to the requirement list by M. Lang. Summarising the explanations above, the proceeding
can be simplified by the following list of steps:

1. System modelling,
   a) Definition of specifications to fulfil the general model requirements
   b) Derivation of physical component models
   c) Implementation into EMod
   d) Employ on the test bench machine

2. Validation and analysis
   a) Definition of methodologies to collect trusted data
   b) Gathering of trusted data and performing of simulations
   c) Comparison between the simulated and trusted data
   d) Identification and quantification of model errors

3. Discussion and conclusion

2.5 Methodology

To complete the goals described above, different methods and tools are used. For the system modelling,
the procedure of [GS07] is used. The models have to be implemented in Java for the existing framework.
To do so, Eclipse is used. The evaluations and the analysis of the simulation and measurements is done
in Matlab by Mathworks. When ever possible, the evaluation functions and methods tool-box by inspire
[Leu11] are used.
System modelling

In order to understand and simulate the system of a machine tool, a model is required. The model has to fulfil the requirements defined in chapter 2 and [Lan12]. To do so, the specifications for the model are derived and discussed first. After the required steps according to the specification are taken. In the end, the resulting model and its implementation are compared and verified against the specifications. The precision and analysis of the model are discussed in chapter 4 and are thereto not part of the following sections and specifications.

3.1 Specification

From the goal and requirements described in chapter 2, several limitations to the required model can be derived. The formulation of specifications for the system modelling is indispensable, in order to satisfy the limitations and requirements. In the following section the specification derived from the definitions in chapter 2 is discussed. The result oriented reader may skip to the summary at the end of this section, where the important points for the system modelling are listed. Starting now with the derivation for the system modelling specifications: The requirements on the final model from the last chapter can be summarized into the following points:

- Definition of elementary machine components
- Implementation into the *EMod* framework
  - Use of the available functions and objects
  - Creation of a model library
  - Creation of a component database
- Test of the model with the turning machine *Schaublin 42L*
• First consideration for thermal modelling

According to the discussion above, the resulting model will consist of configurable subsystems – such as drives, axes and others – which will be combined and configured to represent a certain machine tool. Looking at the energy flow in a machine tool, one starts with the supply – electrical, cooling fluid and others – which is transported and transformed through various auxiliary devices and ends as mechanical energy or heat loss. For a certain machine tool, the process is assumed to be given. Optimization or detailed modelling of the process is thereby not part of this thesis. A defined task of the machine, for example the work piece movement, may be done in various ways: Linear axis, hydraulic system and others. The model has to guarantee a certain degree of flexibility to handle changes in its subsystems. Because of that, changes in any component must not change the process itself within this model. In order to realize this requirement, the model has to be designed and evaluated such, that changes upstream the energy flow do not force to change subsystems downstream the energy flow. A simple example: A motor does provide mechanical power and consumes thereto electrical power. Changes in the power supply of the motor must not change the model parts representing the mechanical power supply by the motor.

The resulting specification is, that subsystem models must not have any influence to the systems equations of the subsystems downstream the energy flow. Out of this specification, a quasi-static simulation (QSS), also known as effect-cause simulation, has been chosen. The opposite would be a dynamic simulation. The QSS method is also used in automotive industry [GS07], to estimate the consumption for a certain driving cycle. Within this method, the calculation during the simulation takes place in the reverse direction to the energy flow. In the example of a machine tool, the requested process energy would be calculated first, using an adequate process model. From the process energy demand, the required energy for the main drive and the axes are calculated, and so on. The same is valid for the auxiliary devices, where dependent on the component state, a consumption is calculated. This consumption is realized by the connected component upstream the energy flow. The advantages of this method is the flexibility of the model, which is requested here. In a QSS, only system parts upstream the energy flow are influenced by a change at a certain point of the model. A difficulty is, that after the model is implemented in the simulation framework (see section 1.2.2), the direction of evaluation within each subsystem is given. If a subsystem is represented by the function $f$ which is invertible, the relation between the input $P_{in}$ and the $P_{out}$ is the following:

$$P_{out} = f(P_{in}) \iff P_{in} = f^{-1}(P_{out}).$$

(3.1)

This information is lost after the implementation. Using dynamic simulation, the direction of evaluation might not be known for each model configuration a priori. This problem could be solved, using for example an implementation of Modelica [Fri04], which is not part of the simulation framework. A further advantage of QSS are the shorter simulation times, compared to dynamic simulation. This is due to the reduced number of differential equations which have to be solved during the simulation. The resulting specification on the system modelling, is to implement the components system equations in a way suitable for QSS.

To realize the exchange of certain subsystem models, QSS simulation alone is not enough, even if it realizes certain functionality to do so. To change a subsystem model – where the change relates to its physical model or component type – the interfaces of the old and the new subsystem have to show equality over a certain degree. This can be achieved by defining generic components. A generic component includes all information needed to define the interface for the subsystem. Given the simple example of a motor, the interface is given by the rotational speed, the provided torque and the consumed power to realize the desired output. Subsystem models of the same generic component type have thereto the same interface and can be exchanged. This specification could also be derived from the first requirement in the list above: Definition of elementary machine components.
At the end, the whole model will be validated by using the turning machine *Schaublin 42L*. To do so, the model has to be configured for this machine in the *EMod* framework. This process consists of three parts: The process settings, machine configuration and the components parameters. For the first point, we are talking about process forces and speed. Since, the forces have to be known in order to calculate the required process power. Taking measured forces, we would limit ourselves to processes which have already be measured. To avoid this problem, the model is specified to include a simple process model.

Out from the discussion and requirements above, a summary and short description of the resulting specifications for the system modelling:

**Identification of generic components:** Defining generic components with a defined subsystem interface allow the exchange of different models of the same generic type. The components have to be general enough to apply on different machines, but avoid high complexity within one component.

**Process forces model for turning:** The model shall be built up around a reference process. The calculation of the process forces out of process information shall be implemented, to investigate the influence on the final results.

**Component models for quasi static simulation:** Enables the flexibility with the model and the component interconnection, required by the tool. Fast dynamics are not modelled here. The identification of fast dynamics is part of the system modelling, where the term fast is relative to the other dynamics in the current component model. By reducing the model by the fast dynamics, the parameters to describe those dynamics are not requested in the parameter set. This reduces the effort in model configuration.

**Generic thermal model:** Creation of a set of basic thermal components, which allow the user to model the thermal behaviour of the machine in an early stage. The thermal model must take in account, that the thermal behaviour of a machine tool is not component specific, but machine specific.

**Implementation of the models in *EMod***: Using the available framework, the derived models have to be implemented. Information – as for the generic components – has to be collected and documented to be used as programming guideline for future implementations.

**Appliance of the model implementation on the test bench:** To analyse the framework, the test bench machine *Schaublin 42L* has to be implemented in the framework. This includes the machine configurations (components and their interconnection) and the parametrisation.

The past six points describe the specifications for the models implemented in the framework on the level of system modelling. The results of the following sections has to be verificated against this specifications at the end of this chapter. This step is required, since if one or multiple specifications are matched, the requirements by M. Lang [Lan12] can not be fulfilled. This requirements are mandatory for the current work.

### 3.2 Identification of generic machine components

Given by the specification, a set of generic machine components has to be identified. The term generic relates to a characterization of the components by their function, regardless of the component type. A simple example would be an electrical drive: There exist various types of electrical drives, such as synchronous or asynchronous motors. But the function is the same for all drives: Transforming electrical
power into mechanical power. The advantage of this concept is shown, if one wants to change the components system equations. This can be the case during the development process, if new parameters or characteristics are known and shall be implemented in the model. In this case, the model would be growing during the development process. If the new and the old component belong to the same generic type, a change in the subsystem of the machine model will not request to change anything outside of the affected subsystem. This statement does of course only hold, if the generic type of the subsystem stays the same, e.g. a motor stays a motor.

The target of the model is to handle the relevant energy flows within a machine tool. When talking about energy flows over the system boundary of a machine tool, we are talking about electrical and thermal flows; further material flows may be considered. The flow of electrical power between machine components is well defined by the interconnections between the components. Talking about thermal flows, one has to differ between forced and free heat exchange. When talking about free heat exchange between the components, the machine structure and the ambient, certain information about the machine geometry and materials is requested. As mentioned above, the thermal behaviour is not compulsory a component specific characteristic, but can be a machine specific characteristic. To separate the component and machine specific characteristics, all generic machine components are threaten as electro-mechanical components. To simulate the thermal characteristic of the whole machine tool, a set of generic thermal elements is derived later in section 3.5. In the following, the required set of generic machine components is derived for the electro-mechanical part of the machine only.

Each electro-mechanical generic component is uniquely defined by a certain type of inputs and outputs combination. According to the specifications for the system modelling, the QSS method shall be used. This forces the inputs of a component to be downstream the energy or material flow relative to the components outputs. With respect of this definition and the requirements resulting from the specification, the following set of generic components has been derived. It is further summarized in table 3.1. The question of completeness is part of system model verification in section 3.8. Given now the description of the defined generic components:

**Constant consumer:** Given a state of operation, the consumption – power, material flow or others – is constant. The input is thereby the state, where the output is the constant consumption.

**Motor:** A given rotational speed and torque demand is mapped to a power demand. Dependent on the point of operation, a heat loss from the component and the current efficiency are calculated.

**Amplifier:** An amplifier reacts on a certain power demand from the component downstream the energy flow. It maps this power to a supply and control power demand, which is used to satisfy the downstream power use. Further the heat losses through non-ideal effects are calculated.

**Linear axis:** A linear axis represents the mechanical part of a translational axis. Given a translational speed and force along the axis, the required torque and rotational speed is calculated to perform the movement under the given conditions.

**Transmission:** Converts a certain mechanical power flow to an other, according to its underlying physical law.

**Fan:** A fan is used to move a compressible fluid over small pressure gradients. The operational level of the fan is given as input. From this, the power demand and the resulting mass flow is calculated. The operational level is given as the relation of the demanded volumetric flow to the maximal flow.

**Hydraulic:** Transformation of hydraulic power into force and speed. The used fluid can be compressible or incompressible, depending on the physical model.
3.3 Cutting process

**Pump:** A component of the type pump moves an incompressible fluid. For a given mass flow demand and a state of operation, the requested power is calculated. Further, the required input mass flow and created heat loss are calculated. The input mass flow may differ from the demanded mass flow, if a reservoir in the component exists.

**Heat exchanger:** A heat exchanger extracts a certain amount of thermal energy, dependent on its operational level. It requests therefore a certain power.

**Compressed air:** The production of compressed air is related to an energy effort. Within the generic type *compressed air*, a volumetric air flow at certain conditions is mapped to a power demand. The calculated power demand relates to the energy requested to produce the compressed air.

Each implemented physical model of a component has to be of a generic type. This requests from the model to have certain in- and outputs. The list of possible input/output combinations is shown in table 3.1.

The most general form of a component model can be described by an input vector $\vec{u}$, an output vector $\vec{y}$, and a state vector $\vec{x}$. The number of elements for each vector may vary, where at least one element is required for the input and the output vectors. As mentioned above, these elements are given by the generic type. The state vector describes the storages or levels in the model: If the state vector is not empty the component has a memory about the past states. Examples for such memories are mass or heat storages. Those are the resulting memory about past mass and heat flows from and into the storage. The functions $\vec{f}$ and $\vec{g}$ are now defined as the mappings of $\vec{x}, \vec{u}, \vec{y}$ to the state change and to the output:

\[
\dot{\vec{x}}(t) = \vec{f}(\vec{x}(t), \vec{u}(t), t) \quad (3.2)
\]
\[
\vec{y}(t) = \vec{g}(\vec{x}(t), \vec{u}(t), t) \quad (3.3)
\]

Of course, the system equations (3.2f) have to be causal; in other words: The state change $\dot{\vec{x}}$ and system output $\vec{y}$ only depend on current and past values of $\vec{x}$, $\vec{u}$ and $\vec{y}$. Other limitations, such as autonomous or linear system equations $\vec{f}$ and $\vec{g}$, are not required at this point. The task during the system modelling of the components is to find a mapping of the input, state and time to the system's state changes and outputs. This mapping is derived from the physics of the component.

3.3 Cutting process

The goal of the cutting process model is to map the process parameters to the resulting process forces. For this model, the following turning process parameters are considered: Rotational speed of the spindle $\omega_C$, the translational speeds of the z-axis $v_z$ and x-axis $v_x$, as the cutting depth $a_p$. Further, informations about the work piece and cutting tool are required, such as the material type, the cutting tool type and the angle of setting $\kappa$ between the work piece and cutting tool. The derivation and verification of cutting process model is a research topic for its one. One approach is the description of the cutting force by Kienzle and Victor from 1957 [KV57]. Kienzle and Victor describe the cutting forces in relation to the dimensions of the chip cross section and the in-feed. To apply this model on the current problem, the movement of the cutting tool is limited along the z-axis, such that the x-velocity becomes zero ($v_x = 0$).
### Table 3.1: Description of the generic machine components defined by there in- and outputs.

<table>
<thead>
<tr>
<th>Generic component</th>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant consumer</td>
<td>$S_{cmp}$ [-] state of the component</td>
<td>$P_{tot}$ [W] resulting consumption</td>
</tr>
<tr>
<td>Motor</td>
<td>$T$ [Nm] demanded torque</td>
<td>$P_{tot}$ [W] resulting power demanded</td>
</tr>
<tr>
<td></td>
<td>$\omega$ [rpm] demanded rotational speed</td>
<td>$\dot{Q}_{loss}$ [W] thermal losses</td>
</tr>
<tr>
<td></td>
<td>$\eta$ [-] current efficiency</td>
<td></td>
</tr>
<tr>
<td>Amplifier</td>
<td>$S$ [-] operational state</td>
<td>$P_{sply}$ [W] resulting supply power</td>
</tr>
<tr>
<td></td>
<td>$P_{dmmd}$ [W] power demanded from the amplifier</td>
<td>$P_{tot}$ [W] total power demand by the amplifier</td>
</tr>
<tr>
<td></td>
<td>$P_{ctrl}$ [W] resulting control power</td>
<td>$\dot{Q}_{loss}$ [W] thermal losses</td>
</tr>
<tr>
<td>Axis</td>
<td>$F_{ax}$ [N] force along the axis</td>
<td>$T$ [Nm] resulting torque</td>
</tr>
<tr>
<td></td>
<td>$v_{ax}$ [m/s] translational speed of the axis</td>
<td>$\omega$ [rpm] resulting rotational speed</td>
</tr>
<tr>
<td>Transmission</td>
<td>$\omega_{dmmd}$ [rpm] demanded rotational speed</td>
<td>$\omega$ [rpm] resulting rotational speed</td>
</tr>
<tr>
<td></td>
<td>$T_{dmmd}$ [Nm] demanded torque</td>
<td>$T$ [Nm] resulting torque</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\dot{Q}_{loss}$ [W] thermal losses</td>
</tr>
<tr>
<td>Hydraulic</td>
<td>$F_{dmmd}$ [N] demanded force</td>
<td>$p$ [Pa] resulting pressure</td>
</tr>
<tr>
<td></td>
<td>$v_{dmmd}$ [m/s] demanded displacement speed</td>
<td>$\dot{m}$ [kg/s] resulting mass flow</td>
</tr>
<tr>
<td>Pump</td>
<td>$S$ [-] operational state</td>
<td>$P_{tot}$ [W] resulting power demand</td>
</tr>
<tr>
<td></td>
<td>$\dot{m}_{dmmd}$ [kg/s] demanded mass flow</td>
<td>$\dot{m}_{in}$ [kg/s] mass flow into the pump</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\dot{Q}_{loss}$ [W] thermal losses</td>
</tr>
<tr>
<td>Fan</td>
<td>$u$ [-] operational level (0...1)</td>
<td>$P_{tot}$ [W] resulting fan power</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\dot{Q}_{loss}$ [W] thermal losses</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\dot{m}$ [kg/s] created mass flow</td>
</tr>
<tr>
<td>Heat exchanger</td>
<td>$S$ [-] operational state</td>
<td>$P_{tot}$ [W] resulting power demand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\dot{Q}_{th}$ [W] forced heat flow</td>
</tr>
<tr>
<td>Compressed air</td>
<td>$V_{dmmd}$ [m$^3$/s] demanded air flow</td>
<td>$P_{tot}$ [W] resulting power demand</td>
</tr>
<tr>
<td></td>
<td>$p_{amb}$ [Pa] ambient pressure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\vartheta_{amb}$ [K] ambient temperature</td>
<td></td>
</tr>
</tbody>
</table>
The equations stated in [KV57] are:

\[ F_c = b \cdot h^{1-z_c} \cdot k_{c1.1} \]
\[ F_f = b \cdot h^{1-z_f} \cdot k_{f1.1} \]
\[ F_p = b \cdot h^{1-z_p} \cdot k_{p1.1} \]  

(3.4)

The indices \( c, f \) and \( p \) relate to the cutting, feed and passive force. The dimension of the chip is given by its length \( h \) and width \( b \) as shown in figure 3.1 on the right hand side. Further, the Kienzle parameters \( z \) and \( k_{1.1} \) are required. The specific force \( k_{1.1} \) describes the resulting force for a chip with \( h = b = 1 \text{ mm} \), where the increment factor \( z \) models the effects of increasing cutting depth. To apply the model above, the relation between \( \omega_C, v_z \) and the chip dimensions have to be made. As stated, no movements of the \( x \)-axis during the cut are made. Further, a work piece with constant diameter is assumed. The reduction in radius of the work piece due to the cut is thereto constant and for further used defined as \( a_p \). The displacement along the \( z \)-axis \( f \) during one rotation can be calculated as

\[ f = \frac{2 \cdot \pi \cdot v_z}{\omega_C}. \]  

(3.5)

As one can see in figure 3.1, the cross section \( A \) of the chip is given as \( A = f \cdot a_p = b \cdot h \). With the angle of setting \( \kappa \), the calculation of \( h \) and \( b \) is

\[ b = \frac{a_p}{\sin \kappa} \]  

(3.6)
\[ h = f \cdot \sin \kappa. \]  

(3.7)

Summarizing the results from above, the resulting forces for a cutting process with rotational speed \( \omega_C \), displacement speed \( v_z \) along the \( z \)-axis and a constant cutting depth \( a_p \) is

\[ F_c = \frac{a_p}{\sin \kappa} \left( \frac{2 \cdot \pi \cdot v_z}{\omega_C} \cdot \sin \kappa \right)^{1-z_c} \cdot k_{c1.1} \]
\[ F_f = \frac{a_p}{\sin \kappa} \left( \frac{2 \cdot \pi \cdot v_z}{\omega_C} \cdot \sin \kappa \right)^{1-z_f} \cdot k_{f1.1} \]
\[ F_p = \frac{a_p}{\sin \kappa} \left( \frac{2 \cdot \pi \cdot v_z}{\omega_C} \cdot \sin \kappa \right)^{1-z_p} \cdot k_{p1.1}. \]  

(3.8)

One has now to identify the six Kienzle parameters. Those parameters are specific for each tool type and wrought material combination. If values for the used combination are available in literature, this values can be used for model parametrization. If not so, the parameter identification can be done by using measurements of the three forces for known conditions. Since this measurement can be done machine independent, they are not a violation of the assumption that no machine to measure on exists. This process is later discussed in section 4.2.3. The equation set (3.8) forms the turning process model, with the inputs \( \tilde{u}_P = [a_p, v_z, \omega_C]^T \) and the output \( \tilde{y}_P = [F_c, F_f, F_p]^T \).

3.4 Electro mechanical components

In the following section, the derivation of the system equation of the above described electro-mechanical components is discussed. This part includes only the physical and mathematical aspects of the models,
where the implementation of the equations in the EMod framework is described later in section 3.6. During the identification of generic machine components, the list of table 3.1 has been derived. As already mentioned, different component models can be of the same generic type. The goal of the following chapter is to derive the system equation for the components needed to model the test-bench machine. Since the test-bench machine *Schaublin 42L* has no hydraulic components, in the following section at least one model for each generic type in table 3.1 is derived, except for the hydraulic components.

### 3.4.1 Constant component

Certain elements in a machine tool system are simple on/off components. Dependent on the state of the machine, the component consumes a fixed amount of resources. This component type has been fully described by Leuenberger and Hamp [LH11a]: Given the set of states of the machine as $S_{\text{mach}} = \{S_{\text{mach},i} | i = 1, 2, \ldots, N_{\text{mach}}\}$ and the states of the component as $S_{\text{comp}} = \{S_{\text{comp},j} | j = 1, 2, \ldots, N_{\text{comp}}\}$, where $N_{\text{mach}} \geq N_{\text{comp}}$. A certain state of the component causes a defined output $y$, where the component state is caused by the machine state. One needs thereto two mappings: First the mapping of the machine state to the component state $\sigma(S_{\text{mach}})$, second the mapping of the component state to the output $\Sigma(S_{\text{comp}})$. This leads to the equations for a constant component:

$$S_{\text{comp}}(t) = \sigma(S_{\text{mach}}(t))$$  \hspace{1cm} and \hspace{1cm} $$P_{\text{tot}}(t) = \Sigma(S_{\text{comp}}(t)).$$  \hspace{1cm} (3.9)

The first mapping is already realized by the simulation control of the framework. The constant component model has thereto only to include the second mapping $\Sigma$. To do so, the component state is defined as $S_{\text{comp}} \in \{1, 2, \ldots, N\}$ with $N$ component power levels. The mapping $\Sigma$ can be realized by a vector $\vec{P} = [P_1, \ldots, P_N]^T$, having all power levels of the component as elements, such that

$$P_{\text{tot}}(t) = P_{S_{\text{comp}}(t)}.$$  \hspace{1cm} (3.10)

This simple reading of vector elements fully describes the constant component model with input $u = S_{\text{comp}}$ and output $y = P_{\text{tot}}$.

### 3.4.2 Asynchronous motor

A model of an electrical motor has already been developed within the framework described in section 1.2.2 by Leuenberger and Hamp [LH11a]. For the sake of completeness, the motor model is commented in the following section.
3.4 Electro mechanical components

For a given rotational speed $\omega(t)$ and torque $T(t)$, the corresponding mechanical power is $P_{\text{mech}}(t) = \omega(t) \cdot T(t)$. To establish this operational point, the motor will request a certain power $P_{\text{tot}}(t)$ from the control unit. The amount of energy depends on the operational point $(T, \omega)$ and further ambient influences as the temperature $t_{\text{amb}}$. Within a machine tool, thermal stability is an important factor. If the temperature varies over a large range, losses in precision may become a problem. Further, damages to the machine, for example in the spindle bearing due to thermal expansion, are a latent risk. Resulting from this information, a thermal stabilized motor is assumed and thermal influence on the motor efficiency are neglected.

An electrical motor has several losses, such as static friction, dynamic friction, thermal effects and others. Modelling all these effects would be far beyond the scope of this application. Thereto, a lumped parameter approach is chosen. Thereby, all effects are represented by a single parameter $\eta$, called motor efficiency. The motor efficiency is defined as:

$$\eta(t) = \eta(T(t), \omega(t)) = \frac{P_{\text{mech}}(t)}{P_{\text{tot}}(t)} \Rightarrow P_{\text{tot}}(t) = \frac{T(t) \cdot \omega(t)}{\eta(T(t), \omega(t))}$$ (3.11)

If $\eta(T, \omega)$ is known, the electrical power demand can be calculated from the mechanical power demand. The situation, where only rotational speed and no load are required, can not be represented by the model above. Since the mechanical power is zero for this operational point, the calculated electrical power is zero too. Like at any other operational point, the drive has to compensate friction by producing a torque, which establishes a constant rotational speed. This friction is included in the efficiency $\eta$ for all $T > 0$. In order to solve the problem described, a frictional torque $T_{fr}$ is introduced, such that

$$P_{\text{tot}}(t) = \omega(t) \cdot T_{fr} \quad \text{if} \quad T(t) = 0.$$ (3.12)

The losses, such as friction and resistors, cause thermal losses. Out of this reason, the heat flow released by the motor us assumed to be:

$$Q_{\text{loss}}^*(t) = P_{\text{tot}}(t) - P_{\text{mech}}(t)$$ (3.13)

Together with the efficiency map, equations (3.11-3.12) define the motor model with input vector $\vec{u} = [\omega, T]^T$ and output vector $\vec{y} = [P_{\text{tot}}, Q_{\text{loss}}, \eta]^T$. At last, some remarks about the efficiency map: Given a set of $N_T$ torque operation points and $N_\omega$ speed operation points as $\Omega_{\text{map}} = \{T_i \mid i = 1, 2, \ldots, N_T\}$ and $\Omega_{\text{map}} = \{\omega_j \mid j = 1, 2, \ldots, N_\omega\}$ with a known efficiency map $H_{\text{map}} = \{\eta(T_i, \omega_j) \mid T_i \in \Omega_{\text{map}}, \omega_j \in \Omega_{\text{map}}\}$, the efficiency for a given $(T, \omega)$ can be approximated by using linear interpolation within the efficiency map:

$$\eta(T(t), \omega(t)) = \text{interpol}(H_{\text{map}}, (\Omega_{\text{map}}, \Omega_{\text{map}}), (T(t), \omega(t)))$$ (3.14)

With function interpol($X, Y, x$), linear interpolation of $y(x)$ out of the existing set of $N$ points $\{(x_i, y_i) \mid x_i \in X, y_i \in Y, i = 1 \ldots N\}$ is meant. The more points in the efficiency map are given, the less error is introduced by the interpolation. By applying linear interpolation, discontinuities in the map can not be displayed.

### 3.4.3 Servomotor

The motor model introduced in the last section is of course not the only one for the generic component type motor. In difference with a motor from the section above, a servo motor is assumed to be a motor...
3 System modelling

![Equivalent circuit used as model of a servo motor with amplifier. Given the internal resistance \( R_a \), the armature voltage \( U_a \) and current \( I_a \), causing the motor torque \( T_a(t) \) at rotational speed \( \omega(t) \).](image)

Given now as input the requested torque \( T(t) \) and the requested rotational speed \( \omega(t) \). Assuming a small time constant for the mechanical part of the system – which is the case as shown in [GE 98b] – the requested speed can be met immediately. The torque given by the motor has to be the requested torque plus the friction torque: \( T_a(t) = T(t) + T_{fr} \). Using the approach described in [GS07], the behaviour of the motor is described as

\[
T(t) = \kappa_a \cdot I_a(t) \quad \text{and} \quad U_i(t) = \kappa_i \cdot \omega(t). \quad (3.15)
\]

From the equations above, the armature current \( I_a(t) \) and the EMF voltage \( U_i(t) \) can be calculated, as the armature voltage \( U_a(t) \) and the voltage drop over the internal resistance can be calculated by using Kirchhoff’s current law:

\[
U_r(t) = I_a(t) \cdot R_a = \frac{T(t) + T_{fr}}{\kappa_a} \cdot R_a(t) \quad (3.16)
\]
\[
U_a(t) = U_i(t) + U_r(t) = \kappa_i \cdot \omega(t) + \frac{T(t) + T_{fr}}{\kappa_a} \cdot R_a \quad (3.17)
\]

For the electrical power \( P_{el}(t) \) needed for the motor, one has to include the number of pole pairs \( p \). The heat loss emitted to the environment is given by the thermal loss of the amplifier and the frictional loss. This leads to the final descriptions

\[
P_{el}(t) = I_a(t) \cdot U_a(t) \cdot p = \frac{p \cdot T(t) + T_{fr}}{\kappa_a} \cdot \left( \kappa_i \cdot \omega(t) + \frac{T(t) + T_{fr}}{\kappa_a} \cdot R_a \right), \quad (3.18)
\]
\[
Q_{\text{loss}}(t) = p \cdot \left( \frac{T(t) + T_{fr}}{\kappa_a} \right)^2 \cdot R_a. \quad (3.19)
\]

Compared to the motor model above, the power demand for zero load is non zero and does not request special case handling. On the other hand, frictional losses due to high velocities are not modelled. This is
not requested here, since servo motors are applied for axis movements, where rotational speeds compared to the spindle speed are slow.

The input and output vectors are the same as for the previous model. This is further an example for interchangeable models: Because both models have the same interface, either the motor or the servo motor model can be used at the same place. One has now to choose the right model dependent on the application.

3.4.4 Amplifier

For AC drives, which are often applied in machine tools, an amplifier is requested. The amplifier takes electrical power from a source – for example a DC source – and creates a desired power signal $P_{dmd}$ at the output as shown in figure 3.2. This signal is characterized by its voltage and current peaks, as its frequency. For this process, a certain amount of electrical power $P_{ctrl}$ is consumed for the control logic. Further non-ideal losses do occur by the transformation from the source energy to the desired output energy form. For the following model, it is assumed, that the control power and the losses result in a thermal heat release.

For the amplifier model two operational states are distinguished: The first state – called on – with a non-zero power demand, where the second state has a zero power demand and is called off. For the operational state input $S$, the following definition results: $S \in \{1, 0\}$. The first case is modelled with a Willans approximation:

$$P_{tot} = P_{supply} + P_{ctrl} = P_{dmd} \cdot \frac{1}{\eta(P_{dmd})} + P_{ctrl}$$  (3.20)

The term $\eta$ describes the energy conversion efficiency at the operation point $P_{dmd}$. With the assumption above, the thermal losses are described as

$$*Q_{loss} = P_{tot} - P_{dmd} = P_{dmd} \cdot \left(\frac{1}{\eta(P_{dmd})} - 1\right) + P_{ctrl}. \quad (3.21)$$

With the introduced states above, the final amplifier is given as

$$P_{tot}(t) = \begin{cases} P_{dmd} \cdot \frac{1}{\eta(P_{dmd})} + P_{ctrl} & \text{if } S(t) \neq 0, \\ 0 & \text{if } S(t) = 0, \end{cases} \quad (3.22)$$

where one has to provide the efficiency map $\mathcal{H}_{amp}$ for a set of operational points $P_{dmd}$, such that $\eta(P_{dmd}) \in \mathcal{H}_{amp}, \forall P_{dmd} \in P_{dmd}$. For a given power demand $P_{dmd}(t)$ the corresponding efficiency is calculated by linear interpolation within $\mathcal{H}_{amp}$. This is done for each input vector $\bar{u} = [S, P_{dmd}]^T$, and the mapping to the output vector $\bar{y} = [P_{tot}, P_{supply}, P_{ctrl}, *Q_{loss}]^T$.

3.4.5 Linear axis

Given a linear axis driven by a servo motor as shown in figure 3.3(a). The rotational speed and torque of the motor are translated into a linear movement and force by a ball screw. The moving part has a mass $m$ and a position described by $s(t)$. The active forces are the process force $F_P(t)$, the motor force $F_M(t)$, gravitational force as $F_G$, frictional forces $F_{fr}(t)$ and the inertia of the mass as shown in figure 3.3(b).
3 System modelling

(a) Model of the linear axis driven by a ball screw.  
(b) Free punch of the linear system with the introduced forces

Figure 3.3: Model of a linear axis with a process force $F_p$ and a torque $T_m$ by the servo motor. The axis with moving mass $m$ encloses an angle $\alpha$ with the vertical of the machine.

With the angle $\kappa$ between the translational direction and the direction of gravitation, the following DEQ for the displacement $s(t)$ can be derived:

$$\ddot{s}(t) \cdot m = F_M(t) + F_G \cdot \cos \kappa - F_{fr}(t) - F_p(t)$$  \hspace{1cm} (3.23)

The gravitational force is calculated as

$$F_G = m \cdot g.$$ \hspace{1cm} (3.24)

The frictional force can be separated into a normal part due to coulomb friction and a viscous part due to the oil film:

$$F_{fr}(t) = F_N \cdot \mu \cdot \text{sign} \dot{s}(t) + \dot{s}(t) \cdot d,$$ \hspace{1cm} (3.25)

where $F_N = F_G \cdot \sin \kappa$. The linear displacement $\dot{s}(t)$ caused by the motor and the ball screw due to an angular velocity of $\omega(t)$ is given by the transmission $k$ as

$$\dot{s}(t) = k \cdot \omega(t).$$ \hspace{1cm} (3.26)

Equating the mechanical power of the motor with the one of the linear movement, one obtains $F_M(t) \cdot k = T(t)$, where the torque $T(t)$ is produced by the servo motor. Using the equations above and replacing the terms in (3.23), the required motor torque is calculated as

$$T(t) = k \cdot [\ddot{s}(t) \cdot m - m \cdot g \cdot \cos \kappa + m \cdot g \cdot \mu \cdot \sin \kappa \cdot \text{sign} \dot{s}(t) + \dot{s}(t) \cdot d + F_p(t)]$$ \hspace{1cm} (3.27)

Assuming slow movement $v$ of the axis, and thereto relative small inertia and friction forces compared to the process forces, (3.27) and (3.26) can be simplified to

$$T(t) = k \cdot (F_p(t) - m \cdot g \cdot \cos \kappa)$$ \hspace{1cm} (3.28)

$$\omega(t) = \frac{v}{k}$$ \hspace{1cm} (3.29)
3.4 Electro mechanical components

which are only dependent on the process force and a gravitational term including the mass of the moving part, and have the input/output vectors $\vec{u} = [F_p, v]^T$ and $\vec{y} = [T, \omega]^T$.

3.4.6 Linear transmission

The purpose of a transmission is to transform mechanical energy from one form to another. During this process, certain losses may occur. This form of mechanical energy is thereby characterized by the double rotational speed $\omega$ and a torque $T$, and the resulting mechanical energy is of course $P_{\text{mech}} = \omega \cdot T$. In this part, a linear transmission model will be derived. For the following model, it is assumed that thermal losses are dominant [ST10], where vibrational losses and others are negligible. Given a certain torque demand and rotational speed demand $(\omega_{\text{dmd}}, T_{\text{dmd}})$, the mechanical power to realize this demand by the transmission is the sum of the resulting demanded mechanical power and the transmission losses:

$$P_{\text{dmd}}(\omega_{\text{dmd}}, T_{\text{dmd}}) = \omega_{\text{dmd}} \cdot T_{\text{dmd}} + P_{\text{loss}}$$  \hspace{1cm} (3.30)

Given further the transmission $k$, such that the relation between the demanded rotational speed $\omega_{\text{dmd}}$ and the resulting rotational speed $\omega$ is of a linear form:

$$\omega_{\text{dmd}} = k \cdot \omega.$$  \hspace{1cm} (3.31)

Of course, the resulting mechanical power $\omega \cdot T$ has to be equal to the demanded power (3.30). In this model, the losses $P_{\text{loss}}$ will be described by a transmission efficiency $\eta$, where

$$P_{\text{loss}} = (1 - \eta) \cdot \omega \cdot T.$$  \hspace{1cm} (3.32)

With this information, the model can fully be described by the mapping of the demanded rotational speed and torque $(\omega_{\text{dmd}}, T_{\text{dmd}})$ to the resulting rotational speed and torque $(\omega, T)$ using the transmission ratio $k$ and the efficiency $\eta$:

$$\omega = \frac{\omega_{\text{dmd}}}{k},$$

$$T = \frac{k}{\eta} \cdot T_{\text{dmd}}$$ \hspace{1cm} (3.33)

Since the losses are assumed to be thermal, the created heat flow is

$$Q_{\text{loss}} = P_{\text{loss}} = \omega_{\text{dmd}} \cdot T_{\text{dmd}} \cdot \frac{1 - \eta}{\eta}$$ \hspace{1cm} (3.34)

The systems behaviour, describing the relation between the input vector $\vec{u} = [\omega_{\text{dmd}}, T_{\text{dmd}}]^T$ and the output vector $\vec{y} = [\omega, T, Q_{\text{loss}}]^T$, is fully stated by the equations (3.33) and (3.34).

3.4.7 Fan

In a machine tool, fans can be used for process or machine conditioning. By moving a fluid, heat and dust can be extracted from the machine. Heat extraction is related to the thermal effects on the machine. A fan has thereto two parts: An electro mechanical part and a thermodynamic part. In this section, only the electro-mechanical part is discussed, where a fan creates a certain pressure difference $\Delta p$ at a rotational speed $\omega$ which leads to a volumetric flow $\dot{V}$. The mechanical power over the fan is
The pressure ratio over a fan is in the range of 1 to 1.1 [Wik12], which implies \( \Delta p \leq 0.1 \cdot p_{\text{amb}} \).

Assuming a constant density of the fluid across the fan will thereto cause an error of \( \Delta \rho = \frac{\partial \rho}{\partial p} \cdot \Delta p_{\text{air}} \approx 0.12 \text{kg/m}^3 \).

This error value is the upper limit and is in the range of 10% for nominal conditions [DIN90]. In general, the pressure drop of a fan is in the size of 100 Pa [Pfa, Rec07]. Under such conditions, the relative error is in the range of <1%, which allows the assumption of an incompressible fluid. Using the equation of Bernoulli for laminar flow with a density \( \rho_{\text{air}} \) through the fan with opening area \( A_{\text{fan}} \), the volumetric flow can be approximated as

\[
V^*(t) = v(t) \cdot A_{\text{fan}} = c_d \cdot A_{\text{fan}} \cdot \sqrt{\frac{2 \cdot \Delta p(t)}{\rho_{\text{air}}}}.
\]

The parameter \( c_d \leq 1 \) describes the frictional losses and influence of non-laminar flow. Assuming a known operation point \( (P_{\text{mech,ref}}, \Delta p_{\text{ref}}, \omega_{\text{ref}}, V_{\text{ref}}) \) and combining (3.35) and (3.37), one obtains a proportional law for the mechanical power demand as

\[
\frac{P_{\text{mech}}(t)}{P_{\text{mech,ref}}} = \left( \frac{\Delta p(t)}{\Delta p_{\text{ref}}} \right)^{3/2}.
\]

As described in [Rec07], the ratio of the fan pressure drops for two operational points is equal to the ratio of the corresponding rotational speeds to the square, which on the other hand is equal to the ratio of the corresponding volumetric flows to the square. Using this information, the mechanical power demand is described as

\[
P_{\text{mech}}(t) = P_{\text{mech,ref}} \cdot \left( \frac{\omega}{\omega_{\text{ref}}} \right)^3 = P_{\text{mech,ref}} \cdot \left( \frac{V^*(t)}{V_{\text{ref}}} \right)^3.
\]

To establish the required mechanical power, a total power demand \( P_{\text{tot}} \) by the fan occurs. The difference between the total and mechanical power demands form the heat losses:

\[
Q_{\text{loss}}^*(t) = P_{\text{tot}}(t) - P_{\text{mech}}(t)
\]

With this information and a known operation point from the characteristic curve of the fan, two applications and implementations in the model are possible: A simple on/off fan or a demand controlled fan. In both cases, a reference point \( (P_{\text{el,ref}}, V_{\text{ref}}) \) is needed. Given the input \( u \) as the ratio between the demanded volumetric flow and the reference volumetric flow, the relevant system equations are

\[
\begin{align*}
\dot{m}^*(t) &= V_{\text{ref}} \cdot \rho_{\text{air}} \cdot u(t) \quad \text{and} \quad P_{\text{tot}}(t) = P_{\text{el,ref}} \cdot u^3(t).
\end{align*}
\]

Where the output vector is \( \dot{y} = [P_{\text{tot}}, Q_{\text{loss}}, \dot{m}]^T \). For a on/off fan, \( u(t) \) is limited to the values \{0, 1\}. One has to remember, that a constant fan efficiency \( \eta_{\text{fan}} \) is assumed. It is thereto recommended, to chose the reference point close to the real operation conditions.
3.4 Electro mechanical components

![Figure 3.4: Model for a pump with pressure tank. The compressed gas is shown in grey and is characterized by the volume $V_g(t)$. Within the the tank, a mass of $m_{fl}(t)$ fluid is stored under the pressure $p_{fl}(t)$. From the tank, a demanded mass flow $\dot{m}_{fl,dmd}$ is extracted, where $\dot{m}_{fl,in}$ is added by a pump.]

3.4.8 Pump

A hydraulic pump is producing a pressure difference, which leads – dependent on the pipe geometry – to a mass flow. To handle high peaks in mass flow, a pressure tank is often used. Such a tank consists of two chambers: One with the fluid and the other filled with a compressible gas. To separate the two, different approaches such as membranes exist. The model of the pump with pressure tank is shown in figure 3.4.

Compared to the gas, the working fluid can be assumed as incompressible. The conservation of mass for the chamber with the fluid is thereto

$$\frac{d}{dt}m_{fl}(t) = \dot{m}_{fl,in}(t) - \dot{m}_{fl,dmd}(t).$$ (3.42)

Given the initial volumes of the fluid and the gas in the tank as $V_{fl,init}$ and $V_{g,init}$, the volume of the gas at time $t$ is

$$V_g(t) = V_{g,init} + V_{fl,init} - \frac{m_{fl}(t)}{\rho_{fl}}.$$ (3.43)

For the compression chamber usually nitrogen is used, which allows the assumption of an ideal gas. Neglecting the influence of the separator and the fast dynamics of the fluids, the pressures in both chambers are equal at any time $t$: $p_{fl}(t) = p_g(t)$. With the assumptions above and the initial pressure $p_{g,init}$ of the gas, the pressure of the fluid is

$$p_{fl}(t) = p_{g,init} \cdot \frac{V_{g,init}}{V_g(t)} = p_{g,init} \cdot \frac{V_{g,init}}{V_{g,init} + V_{fl,init} - \frac{m_{fl}(t)}{\rho_{fl}}}.$$ (3.44)

The outflow $\dot{m}_{fl,out}$ is given by the fluid consuming devices, where the inflow $\dot{m}_{fl,in}$ is generated by the pump, and depends on the pressure difference $p_{fl}(t) - p_{amb}$. Dependent on the state of operation $S$ the pump is allowed to run or not, where the relation between mass flow and pressure gradient is described by the characteristic map $f_{pump}$ of the pump. For a pump with only one power level $P_{tot,pump}$ and a simple hysteresis controller and two operational states on and off such that $S \in \{1, 0\}$, the inflow is
3 System modelling

\[ m_{fl, in} (t) = \begin{cases} 
  f_{pump}(p_{fl}(t) - p_{amb}) & \text{if } p_{fl}(t) < p_{fl, max}, S = 1 \text{ and pump was on} \\
  f_{pump}(p_{fl}(t) - p_{amb}) & \text{if } p_{fl}(t) \leq p_{fl, min}, S = 1 \text{ and pump was off} \\
  0 & \text{if } p_{fl}(t) > p_{fl, min} \text{ and pump was off} \\
  0 & \text{if } p_{fl}(t) \geq p_{fl, max} \text{ and pump was on} \\
  0 & \text{if } S = 0 
\] (3.45)

Given the switch on pressure \( p_{f, min} \) and switch off pressure \( p_{f, max} \) of the hysteresis controller. The power level is

\[ P_{tot}(t) = h(m_{fl, in} (t)) \cdot P_{tot, pump}, \] (3.46)

where \( h(.) \) is the unit step function. If one has a pump without a pressure tank, the term \( d/dt m(t) \) in (3.42) must always be zero. This forces the in- and outflows to be equal: \( \dot{m}_{fl, in} = \dot{m}_{fl, out} \). One can see, that the derivation of the power \( P_{tot} \) is the same, as for the pump with pressure tank.

For both situations – with or without tank – the pump has several losses. Such losses are for example friction in the drive shaft bearings or ohmic losses in the pump motor. Assuming all losses to be thermal, the heat release is equal to the difference between the pump power and the mechanical power of the fluid:

\[ \dot{Q}_{loss}(t) = P_{tot}(t) - \frac{\dot{m}_{fl, in}(t)}{\rho_{fl}} \cdot (p_{fl}(t) - p_{amb}) \] (3.47)

The system pump is described by the system equations (3.45), (3.46), (3.47) and the input/output vector \( \vec{u} = [S, \dot{m}_{dmd}]^T \) and \( \vec{y} = [P_{tot}, \dot{m}_{in}, \dot{Q}_{loss}]^T \). If the system includes a reservoir, the model has the state \( x = m_{fl} \), which requires an initial condition \( x_{init} \).

3.4.9 Heat exchanger

Different devices inside a machine tool need certain thermal conditions to operate proper. To prevent the components from overheat produced by friction and other non-ideal processes, heat exchangers can be used. Such an aggregate can move thermal energy against the temperature gradient. To do so, thermal energy is extracted from the hotter side and released to the cooler side; in general bounded in a transport medium such as air or water. In this section, only the electrical part of the system is modelled. The goal is thereby to describe the consumption of electrical power by the heat exchanger. Thermal effects are only regarded if requested for the calculations of the electrical power demand. An example for a thermal effect which is related to the energy demand is the amount of heat energy extracted by the heat exchanger.

The model of a cooling unit is derived with the example of an air cooled heat exchanger as shown in figure 3.5. Later on, the application of the derived system equations on other systems is shown. In general, three electrical consumers are available: One to move the cooling fluid to the cooler, one to drive the cooling cycle and a third to extract the heat from the cooler. In this example the devices are a pump, a compressor and a fan consuming the electrical powers \( P_{pump}, P_{comp} \) and \( P_{fan} \). In the previous section – section 3.4.8 – the pump model is already described. The following section will thereto only discuss the compressor and the fan. It is assumed, that the cooling fluid is pumped fast through the heat exchanger, such that only conduction heat transfer has to be taken into account.
For the cooling circle, similar to the pump efficiency, an energy efficiency ratio (EER) \( \varepsilon_{\text{cooling}} \) is introduced, such that

\[
\varepsilon_{\text{cooling}} = \frac{Q_{\text{th}}^*}{P_{\text{comp}} + P_{\text{fan}}} = \frac{Q_{\text{th}}^*}{P_{\text{tot}}},
\]  

(3.48)

where \( Q_{\text{th}}^* \) describes the amount of thermal energy extracted by the heat exchanger. The heat exchanger has thereby a fixed operational point defined by \( P_{\text{tot},he} \), which is given due to the dimensioning of the aggregate. The control of the heat exchanger is done by the component state \( S \in \{1, 0\} \). The power consumption is thereto

\[
P_{\text{tot}}(t) = \begin{cases} 
P_{\text{tot},he} & \text{if } S(t) = 1 \\ 
0 & \text{else} 
\end{cases}
\]  

(3.49)

If the module is running, the generated heat flow can be described by

\[
Q_{\text{th}}^*(t) = \varepsilon_{\text{cooling}} \cdot P_{\text{tot}}(t).
\]  

(3.50)

The parameters for the electric energy consumption and the EER are given by the data sheet of the supplier. As mentioned at the beginning of this section, the model is not limited to air cooled heat exchangers, since \( \varepsilon \) can also be derived for other systems. Summarising the heat exchanger model includes equations (3.49-3.50), input \( u = S \) and output vector \( \vec{y} = [P_{\text{tot}}, Q_{\text{th}}]^T \).

### 3.4.10 Compressed air

Compressed air has various applications in machine tools, such as cooling, material remove or sealing air. The production of compressed air is very energy demanding process, relative to the potential energy available in the pressurised medium. The losses are mainly due to thermal effects during the compression. As shown in previous measurements [GWW10], the energy demand of a machine tool in the form of compressed air can be significant. To include the energy content of the pressurized air, the process model shown in figure 3.6(a) is used.

Air is taken at ambient conditions \( p_{\text{amb}} \) and compressed to \( p_2 \). This process takes place fast and is assumed to be adiabatic. The compressed air is cooled down isochoric to ambient temperature \( \vartheta_{\text{amb}} \) and
3 System modelling

The pressure $p_{\text{supply}}$ is the demanded supply pressure. When the air is used in the machine, it is expanded fast to ambient conditions $p_{\text{amb}}$. Extracting thermal energy from its surrounding, it is expanded isobaric to ambient temperature $\vartheta_{\text{amb}}$.

For an adiabatic process, no heat exchange takes place. The change in the internal energy is equal to the work done on the gas. Given the temperature $\vartheta_2$ after the compression, the change in the internal energy, which is equal to the work done, is

$$ P_{\text{cair}}(t) = c_{p,\text{air}} \cdot (\vartheta_2 - \vartheta_{\text{amb}}) \cdot m_{\text{cair}}(t), \quad (3.51) $$

with the internal heat capacity $c_p$. For air, the properties of an ideal gas hold. The temperature at point 2 can therefore be calculated by the ideal gas equation

$$ p \cdot V = \vartheta \cdot R \cdot m. $$

The specific gas constant $R$ for air is known by

$$ R = c_{p} - c_{v} \text{ and } c_{p} = \gamma \cdot c_{v}. $$

To apply the discussed formula, a reference volume has to be chosen. To ensure the use of standardized values, the standard cubic meter $V_n$ defined by DIN 1343 [DIN90, GWW10] is chosen. This sets the values $V_n = 1$ m$^3$, $p_n = 1.013$ bar and $\vartheta_n = \vartheta_{\text{amb}} = 273.15$ K. After the isochoric cooling, the air has again ambient temperature. One can thereto write

$$ p_c \cdot V_n = p_{\text{amb}} \cdot V_1. $$

The ideal gas properties of air allow to describe the maximum pressure $p_2$ with the isentropic coefficient $\gamma$ as

$$ p_2 = p_{\text{amb}} \cdot \left( \frac{V_1}{V_n} \right)^\gamma = p_{\text{amb}} \cdot \left( \frac{p_c}{p_{\text{amb}}} \right)^\gamma. \quad (3.52) $$

The temperature $\vartheta_2$ can be calculated over the ideal gas equation. Using (3.52) one gets

$$ \vartheta_2 = \frac{p_2 \cdot V_n}{R \cdot m} = \vartheta_2 \cdot \frac{p_2 \cdot V_n}{p_{\text{amb}} \cdot V_1} = \vartheta_{\text{amb}} \cdot \left( \frac{p_c}{p_{\text{amb}}} \right)^{\gamma^{-1}}. \quad (3.53) $$

Combining (3.51) and (3.53), the final expression for the power flow through compressed air is given in (3.54) with a mass flow described by the volumetric flow and the density at ambient conditions:

$$ P_{\text{cair}}(t) = c_{p,\text{air}} \cdot \vartheta_{\text{amb}}(t) \cdot \left[ \left( \frac{p_{\text{supply}}}{p_{\text{amb}}(t)} \right)^{\gamma^{-1}} - 1 \right] \cdot \rho_1 \cdot V_1(t) = C_{\text{cair}} \cdot \vartheta_{\text{amb}}(t). \quad (3.54) $$

With $P_{\text{tot}} = P_{\text{cair}}$ from (3.54), the input vector $\vec{u} = [V_{\text{dmd}}, p_{\text{amb}}, \vartheta_{\text{amb}}]^T$ is mapped to the output $y = P_{\text{tot}}$. In difference with [GWW10], the energy demand is here described by the pressure level $p_c$ available at the supply chain and not by the maximum pressure $p_2$ during the production of compressed air. Inserting the values $c_{p,\text{air}} = 1013$ J/kgK, $\vartheta_{\text{amb}} = 273$ K, $\gamma = 1.4$ and $p_c/p_{\text{amb}} = 8$; one obtains a benchmark value for compressed air of $C_{\text{cair}} = 7.2$ kW/m$^3$min. By this benchmark, the consumed compressed air is brought into a relation ship with the power requested to realize the desired supply. The value $C_{\text{cair}}$ is further in the same range as the one mentioned in [GWW10].

**Throttle**

As mentioned at the begin of the compressed air system modelling, compressed air can be used as sealing air or for material removal. In both cases, the air flows through a throttle with given area $A$ from a high pressure level $p_c$ to a lower pressure level $p_{\text{amb}}$. The temperature of the pressurized air is assumed to
3.4 Electro mechanical components

(a) $p$-$V$ diagram for the air compressor model. The isentropic compression 1-2 from ambient conditions to nominal volume is done by the compressor. Following the isochoric temperature drop 2-3. Using the compressed air includes a isentropic expansion 3-4 to ambient pressure and a isobaric expansion 4-1 to ambient temperature.

(b) Throttle function $\psi$ dependent on pressure ratio $\Pi$. Important points are the critical ratio $\Pi_{cr}$ and the threshold ratio $\Pi_{tr}$. The implemented function is shown as solid line, where the real function is shown as dashed (−−) line.

Figure 3.6: $p$-$V$ diagram for the compressed air model and throttle coefficient $\psi$ in relation to the pressure ratio $\Pi$.

be ambient temperature $\vartheta_{amb}$. The velocity in a throttle is limited by the speed of sound: If the actual pressure ratio is below the critical pressure ratio, the mass flow is limited. As shown in [Her06], the mass flow through a throttle with opening area $A$ can be calculated as

$$m(t) = c_d \cdot A \cdot \frac{p_c}{\sqrt{R \cdot \vartheta_{amb}}} \cdot \left( \frac{p_c}{p_{amb}} \right).$$  \hspace{1cm} (3.55)

Ambient conditions are given by $p_{amb}$ and $\vartheta_{amb}$, where $R$ is the specific gas constant for the fluid. The parameter $c_d$ includes frictional losses and non-ideal effects of the throttle. The throttle function $\psi$ depends on the pressure ratio $\Pi = p_c/p_{amb}$:

$$\psi(\Pi) = \begin{cases} 
\sqrt{\frac{2}{\gamma + 1} \cdot \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}}}, & \text{if } \Pi < \Pi_{cr} \\
\Pi^{-\frac{\gamma}{\gamma - 1}} \cdot \left( 1 - \Pi^{1 - \frac{\gamma}{\gamma - 1}} \right), & \text{if } \Pi \geq \Pi_{cr}
\end{cases} \hspace{1cm} \text{and} \hspace{1cm} \Pi_{cr} = \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}}$$  \hspace{1cm} (3.56)

Looking at the plot of the throttle function in figure 3.6(b) one can see, that the function is only defined for $\Pi \leq 1$, and the derivative of $\psi$ is infinity at $\Pi = 1$. Implementing this formula can lead to two types of problems: The simulation will work with discrete time steps. Using numerical integration on the mass flow of a throttle into a closed pressure tank can lead at time-step $k$ with $\Pi[k - 1] < 1$ to $\Pi[k] > 1$. In reality, such a pressure ratio would force the fluid to flow back until $\Pi = 1$ is reached. But the throttle function is not defined for $\Pi > 1$, and returns only positive values. Another problem may occur if at time-step $k$ the throttle function is $\psi[k] = 1$. Using solvers which require information on the derivative of a signal, the solver will fail, because $\dot{\psi}[k] \to \infty$. To overcome these problems the approach describe in [GS07, GO10] is used: After a treshhold pressure $\Pi_{tr}$ close to 1, the function $\psi(\Pi)$ is approximated by an third order polynomial:
The parameters $a$ and $b$ are chosen such, that the curve \( \psi \) becomes differentiable for any \( \Pi \). To do so, one as to set the parameters to

\[
A = \frac{\psi'_{tr} \cdot (\Pi_{tr} - 1) - \psi(\Pi_{tr})}{2 \cdot (\Pi_{tr} - 1)^3}
\]

\[
b = \psi'_{tr} - 3 \cdot a \cdot (\Pi_{tr} - 1)^2\]

and

\[
\psi'_{tr} = \frac{\partial \psi}{\partial \Pi} \bigg|_{\Pi = \Pi_{tr}}
\]

The resulting function \( \psi(\Pi) \) is shown in figure 3.6(b). Looking at the plot, one can see, that the effects of back-flow and infinity derivative as described above do not occur any more.

### 3.5 Generic thermal energy model

Nearly every component in a machine tool has heat losses. These heat losses are mainly due to friction, ohmic losses and non ideal processes. The thermal state and stability of the machine components and structure is strongly affected by the heat flows generated through losses. Two interesting points of view are possible: Steady state conditions and time constants. The steady state characterizes the situations where all temperature levels and gradients in the machine are constant. The second point of view is the thermal time constants. These constants characterize the temperature and heat flow development over the time until steady state is reached. The first view is very interesting to compare different mode of operation – i.e. at high usage [RMP00], where the second view is interesting for time critical processes as for example described in [LZKH11]. From the view of system modelling, the thermal time constants are related to the energy storages. An energy storage can be the internal thermal energy of a body at a certain temperature level. The effects of these parameters can only be seen, if the system is not in steady state. The location of the steady state is on the other hand defined by the connections between the energy storages. Such a connection can for example be thermal conduction. To model the thermal dynamics of a machine tool, the identification of thermal energy storages and transfers is essential.

In the following section the generic model components for the thermal behaviour of a machine tool is derived. This model is limited to represent the thermal states of certain machine components. The effects of the thermal states to the machine precision have been discussed in various papers [LTK03, SVE95, BT99] and are thereto not part of this thesis. As for the electro-mechanical component models, the idea of generic components shall be implemented in the framework.

### 3.5.1 Thermal energy flows

The thermal state and dynamic of the machine can strongly affect the efficiency and precision of the machine tool. The thermal state of a machine is often controlled and stabilized. To do so, thermal energy is extracted from certain parts of the machine – in example the spindle drive – and transported into other components. In addition, different temperatures of the components and the structure lead to temperature driven heat flows in the machine. Looking at the thermal behaviour, one has to separate two kinds of energy flows: Controlled flows and free flows. The first type, controlled flows, is characterized by a governed energy exchange. An example is the thermal flow in a cooling fluid. The heated fluid transports the thermal energy from the source to a certain destination, where it is stored or released under defined conditions. The second type, free flows, are driven by temperature gradients. For example heat
exchange with the cool ambient air is of this type. In the following, both types are quantified by physical models.

**Forced heat flow**

One of the simplest ways of controlled heat transfer is thermal energy bounded in a moving fluid. For the following model, two thermal levels $\vartheta_1$ and $\vartheta_2$ are considered. Between these two levels, a mass flow of a fluid with internal heat capacity $c_p$ takes place. It is assumed, that the fluid is leaving level 1 with temperature $\vartheta_1$ and has no thermal losses until reaching level 2. Thereto the fluid enters level 2 with temperature $\vartheta_1$. In reality, heat flows through the surrounding walls due to temperature gradients take always place. Situations, where the heat losses during transport become negligible compared to the internal energy transported by the fluid, can be assumed to have no heat losses. This is especially the case for fast moving fluid. In this case the therm fast relates to the time the fluid need to go from one level to the other, compared to the time constant of the heat transfer through the walls.

After reaching level two, the fluid is cooled down to temperature $\vartheta_2$. The heat transfer is the energy which is released during the cool down of the fluid. This energy can be described by

$$^*Q_{12}(t) = c_p \cdot \dot{m}(t) \cdot (\vartheta_1(t) - \vartheta_2(t)),$$

where $^*Q_{12}$ is the heat transport from level 1 to level 2. The input vector is here $\vec{u} = [\vartheta_1, \vartheta_2, \dot{m}]^T$ and the output signal is $y = ^*Q_{12}$. As mentioned above, heat losses during transport are neglected. This is only possible, for fast moving fluids and short pipes between level 1 and 2 as explained above. For connections where the heat loss becomes significant, the model described in section 3.5.2 shall be considered.

**Free heat flow**

Looking at a body with a temperature distribution $\vartheta(t, \vec{x})$ in an environment with temperature $\vartheta_{amb}$, two effects are dominating at low temperature differences: Heat conduction and convection. Heat conduction describes the heat flow in a body or fluid without material flow. The heat transfer takes place at atomic level over the exchanges of kinetic energy between molecules. This phenomena is described by the following partial DEQ:

$$\dot{\vec{q}} = -\lambda \cdot \nabla \vartheta$$

Where $\dot{\vec{q}}$ is the local heat-flux density and $\lambda$ the heat transfer constant. Given the idea of a thin sheet with infinite dimensions with temperatures $\vartheta_1$ and $\vartheta_2$ on both surfaces, the heat flow has only one direction. In steady state, $\dot{\vec{q}}$ must further be constant over the whole sheet to guarantee conservation of energy. With this information, the heat flow through a wall with surface $S$ and thickness $d$ can be approximated by

$$\dot{Q}_{cond,12}(t) = \lambda \cdot \frac{S}{d} \cdot (\vartheta_1(t) - \vartheta_2(t))$$

At the surfaces of the wall presented to a fluid, heat convection takes place. Generally, this leads to a surface temperature which is not equal to the fluid temperature and thereto to thermal resistance. This effect forms a boundary region in the fluid at the surface with non uniform temperature, and can be
described by a heat transfer constant $\alpha$. For a surface at temperature $\vartheta(t)$ and a fluid $\vartheta_{fl}(t)$, the heat flow from the wall to the fluid is

$$\dot{Q}_{\text{conv}}(t) = \alpha \cdot S \cdot (\vartheta(t) - \vartheta_{fl}(t)).$$

(3.62)

In general, wall may consist of various layers with different thermal characteristics, and the surfaces may be presented to different fluids. For thin walls with negligible mass, one can neglect the energy stored in the wall layers. This implies, that the heat flow through all layers and the boundary region of the attached fluid must be equal. For the most general situation of a wall with $N$ layers of thickness $d_i$ and heat transfer constants $\lambda_i$, presented to a fluid with $\alpha_l$ on the left side and another fluid with $\alpha_r$ on the right side, using the information above with (3.61) and (3.62) the following formula results:

$$\dot{Q}_{lr}(t) = k \cdot S \cdot (\vartheta_l(t) - \vartheta_r(t)) \quad \text{and} \quad k = \left[1/\alpha_l + 1/\alpha_r + \sum_{i=1}^{N} \frac{d_i}{\lambda_i}\right]^{-1}$$

(3.63)

With this model, the heat flow from the left side to the right side is characterized by a heat resistance $k$. This resistance is formed by the layer dimensions and thermal characteristics, as by the heat convection on both sides. This model requires a input vector $\vec{u} = [\vartheta_l, \vartheta_r]^T$ and gives the output signal $y = \dot{Q}_{lr}$.

### 3.5.2 Thermal energy storages

Within a machine tool and its components different thermal storages exist. A thermal storage in characterized by a temperature $\vartheta$ and a thermal inertia. The temperature is an effect of the internal energy $U$ of the component, where the thermal inertia limits the change of internal energy. In other words, a immediate change of temperature – or internal energy – is only possible with an infinite amount of energy. The general form of an thermal storage is described by

$$\frac{d}{dt} U(t) = f(U(t), \dot{Q}_{\text{in}}, \dot{Q}_{\text{out}})$$

(3.64)

$$\vartheta(t) = g(U(t)),$$

(3.65)

where $\dot{Q}_{\text{in/out}}$ are the thermal energy flows into to and from the storage. The connection between the state $U(t)$, the state change and the output $\vartheta(t)$ are described by the functions $f$ and $g$. In the following sections, two types of storages will be discussed: First a homogeneous storage, where the thermal energy density is constant. Second, the model for a layer storage will be derived.

#### Homogeneous storage

Given a body or medium with constant mass $m$ and internal heat capacity $c_p$. For this system an homogeneous temperature $\vartheta(t)$ distribution, and thereto constant energy density, is assumed as state. Given are further an inflow and an outflow of thermal energy as inputs to the system. This inputs can be formed with the thermal flow models discussed above. As output of the system, the body temperature $\vartheta(t)$ is taken. A model is now required to describe the changes on the system state and the output. To realize the assumption of homogeneous temperature distribution, perfect mixing of entering energy with the system energy is demanded. The internal energy change of the system can be described by the first law of thermodynamics [MS06, 44ff]:

$$\frac{d}{dt} U(t) = c_p \cdot m \cdot \frac{d}{dt} \vartheta(t) = \dot{Q}_{\text{in}}(t) - \dot{Q}_{\text{out}}(t) - P(t).$$

(3.66)
The work done by the system is described by \( P(t) \). In this case, only thermal energy is extracted from the system. The system equation for the temperature \( \vartheta \) for a homogeneous storage is thereto

\[
\frac{d}{dt} \vartheta(t) = \frac{\dot{Q}_{in}(t) - \dot{Q}_{out}(t)}{m \cdot c_p}
\] (3.67)

The inputs are \( \vec{u} = [\dot{Q}_{in}, \dot{Q}_{out}]^T \), where the output is \( y = \vartheta \). In order to apply this model on a component, the assumption of perfect mixing and homogeneous temperature has to be verified.

**Layer storage**

For a homogeneous thermal energy storage, we assumed a unique temperature over the whole storage. Given for example a pipe with inflow on one and outflow on the other side. Changes in the inlet temperature will need a certain time until they can be measured at the output. One can thereto no longer speak about a homogeneous storage. As we have seen above, the heat flow through the wall depends on the ambient and the storage temperatures. This implies, that heat flow through the wall takes place at different temperature gradients for this example. Because of this reasons, the model for a layer storage with heat exchange is modelled in the following lines.

For the sake for simplicity, a long pipe with a constant cross section \( A \), a thin wall of thickness \( d \) with surface \( S \) and a fluid with a total mass \( m \) are taken. Slicing the pipe into \( N \) small sections will lead to \( N \) short pipes of length \( L/N \) and surface \( S/N \). Taking \( N \) large enough, the temperature inside a pipe element can be approximated as constant. From (3.63) we know, that the heat loss over the surface for the \( i^{th} \) part is

\[
\dot{Q}_i(t) = \frac{S}{N} \left[ \frac{1}{\alpha} + \frac{d}{\lambda} \right]^{-1} \cdot (\vartheta_i(t) - \vartheta_{amb}),
\] (3.68)

where \( d \) is the thickness of the wall and \( \alpha \) and \( \lambda \) characterize the heat flow as described in section 3.5.1 above. Because of the assumption of homogeneous temperature within a pipe element, the exit temperature is equal to the element temperature. The heat flow into the \( i^{th} \) element through mass is thereto given as

\[
\dot{Q}_{m,i}(t) = m(t) \cdot c_p \cdot (\vartheta_i(t) - \vartheta_{amb}).
\] (3.69)

Applying the first law of thermodynamics to a pipe element results in the following differential equation for \( \vartheta_i \):

\[
\frac{d}{dt} \vartheta_i(t) = \frac{N}{m} \cdot \dot{m}(t) \cdot (\vartheta_{i-1}(t) - \vartheta_i(t)) - \frac{S}{m \cdot c_p} \cdot \left[ \frac{1}{\alpha} + \frac{d}{\lambda} \right]^{-1} \cdot (\vartheta_i(t) - \vartheta_{amb})
\] (3.70)

The temperature \( \vartheta_0(t) \) is equal to the inflow temperature, where \( \vartheta_N(t) \) is equal to the outflow temperature of the entire pipe. The total heat loss over the storage wall is given as sum over all element heat losses, which depends on the average temperature \( \vartheta \) over all elements:

\[
\dot{Q}(t) = \sum_{i=1}^{N} \dot{Q}_i(t) = \sum_{i=1}^{N} \frac{S}{N} \cdot \left[ \frac{1}{\alpha} + \frac{d}{\lambda} \right]^{-1} \cdot (\vartheta_i(t) - \vartheta_{amb})
\] (3.71)

\[
= S \cdot \left[ \frac{1}{\alpha} + \frac{d}{\lambda} \right]^{-1} \cdot (\vartheta(t) - \vartheta_{amb})
\] (3.72)
Figure 3.7: Model for a thermal layer storage: Given a pipe with surface $S$ and fluid mass $m$. The surface has the thermal properties $\lambda$, $\alpha$ and $d$, and is exposed to an ambient temperature at $\vartheta_{\text{amb}}$. For the model, the system is divided into $N$ parts.

A layer storage model consists of a series of homogeneous storages with heat and material transfer. Increasing the number of elements $N$ reduces the difference between the model and the behaviour of an ideal layer storage in theory. But in reality, large $N$ increases also the computational effort and influence of quantisation errors, dependent on the application. To model such a layer storage, (3.70) and (3.72) with $N$ states $\vec{x} = [\vartheta_1 \ldots \vartheta_N]^T$ are required. The interface of the model is the input vector $\vec{u} = [\dot{m}, \vartheta_{\text{in}}, \vartheta_{\text{amb}}]^T$ and the output vector $\vec{y} = [\dot{Q}, \vartheta_{\text{out}}]^T$. Further, the initial state values $\bar{x}_{\text{init}}$ are demanded. As mentioned, the influence of the inflow temperature $\vartheta_{\text{in}}$ on (3.70) is $\vartheta_0 = \vartheta_{\text{in}}$, where the outflow temperature is calculated as $\vartheta_{\text{out}} = \vartheta_N$.

### 3.6 Implementation

All the derived models are implemented into the EMod framework. To do so, the existing programming guidelines and object types have been used. For certain model types, additional actions have been required. This actions are mainly required to deal with ODE implementations and the parametrisation of thermal models. The following chapter will first explain the general implementation of a component. Afterwards, the named specialities are discussed, and the mathematical and control components are introduced. Further, mathematical operations and basic control elements are implemented to support the user of the framework. The introduces control elements are a simple switch control and hysteresis control, where the mathematical operations are a signal adder and a gain.

#### 3.6.1 General component model implementation

For the implementation of a component, three steps are required: First the creation of a jUnit test, second the implementation of the physical model and third the creation of at least one parameter file. The aim of the jUnit test, is to assure the correct implementation of the derived model. Test on model precision compared to measured data is not part of this step. A jUnit test basically compares the values calculated by the implementation for given arguments to the expected output values derived previously for this arguments. This expected values can be derived by measurements or by suitable calculations. The use of jUnit tests becomes relevant twice. The first time, when implementing the derived model in the framework as explained in the next paragraph. When the tests are passed, the implementation is correct in the sense of the tested functionality. This tests can be used a second time, when applying changes to the models during future work. If the tests are still passed after a code change, the previous functionality would be correct.
3.6 Implementation

has not been influenced negative.

After this step of test implementation, the models derived in the past section are implemented as Java code. Each component model is thereby translated into a class. For this translation two objects of the framework are important and will be discussed briefly: The class IOContainer and the abstract class APhysicalComponent. The class IOContainer describes an input/output-container. In- and outputs of a component define the interface of the component known as vectors $\vec{u}$ and $\vec{y}$. So for each element in the two vectors, an object of the type IOContainer has to be initialized. The container combines the informations about the port; such as name, unit and current value. A small remark about the interconnections between two containers: The interconnections between the elements are realized by the object type IO-Connection, having a source and a target of the type IOContainer. Each model class extends the abstract class APhysicalComponent. Its functionality shall be explained using the following code extract:

```java
public abstract class APhysicalComponent {
    protected List<IOContainer> inputs;
    protected List<IOContainer> outputs;
    protected double sampleperiod;
    ...

    public IOContainer getInput(String name) {...}
    public IOContainer getOutput(String name) {...}

    public abstract void update();
    ...
}
```

This code extract does of course not represent the whole class, only the parts needed for the explanation are included. In line two and three, the objects inputs and outputs are created. This lists will include all inputs and outputs of the model. Further a variable sampleperiod is initialized. This variable is used to store the sample time in seconds, which is requested for models with a state. This sampleperiod relates to the sample time $T$ as used in section 3.6.2. The functions on lines six and five handle the inputs and outputs. By using the name of the desired port, the function returns the corresponding IOContainer object. From this object, the current value and other information can be extracted. The following function on line eight is the most important one concerning the model. At each call, the function will update the values on the outputs, using the values of the inputs and mapping them to the outputs according to the implemented physical model. This abstract function is overwritten by the model class.

Step two of the model implementation includes the creation of the model class which extends the discussed abstract class. First, the inputs and outputs are created by using the object type IOContainer and added to the corresponding lists. Using the constructor of the model class, the parameters for the component can be loaded from the database. To do so, functions are provided by the framework. The physics of the model is implemented into the update() function. Given the example of a motor with constant efficiency $\text{eff}$, the inputs $\text{rotSpeed}$ and $\text{torque}$, and the output $pTotal$ for the electrical power, the update function would look like this:

```java
public abstract void update() {
    /* P_total = omega*T/eta */
    pTotal.setValue( rotSpeed.getValue() * torque.getValue() / eff );
}
```

At last, parameter files have to be generated. Of course, this parameter files are dependent of the component to be implemented. The requested parameters for each component model can be seen in appendix A. For the motor model as for others, different parameter files of different vendors and motor types can exist. In order to show the required form and name spacing, a dummy parameter file is created for each model. This files include reasonable, but fictive parameter values. By using them for the discussed jUnit test as well, the correctness of the implementation can be guaranteed. The file type used for the parameter
3 System modelling

files is xml. Using the example of the motor again, the parameter file would look like this:

```xml
<properties>
    <comment>
        Model parameter definition
        ===========================
        Model : Motor
        Type : Example
        Parameters
        Efficiency [1]
        of the motor [0...1]
    </comment>
    <entry key="Efficiency">0.78</entry>
</properties>
```

The sum of all component parameter files build the machine component database. Each parameter file belongs to one component model only. Any further information is given by the code documentation in the framework.

3.6.2 ODEs implementation

Certain component models are described by differential equations. Since time is the only independent variable in this application, only ordinary DEQ must be considered. The framework has a fixed step size during the simulation, such that the simulated time between two successive calls of a component's `update()` function is constant. This forces the models ODEs to be discretized for the implementation. Important is thereby, to keeps stable operation in continuous time also stable in discrete time. In this case the term stable means stable in the sense of Lyapunov. If this is not realized, numerical instabilities may occur.

For a continuous time system, the stable pole region is the left half plane of the complex set, where for a discrete time system all poles within the unit circle are stable. During the discretization of a system equation, all continuous time poles are mapped to discrete time poles. Since dependent on the method applied, the stable poles of the continuous system can be mapped to unstable poles in the discrete domain, one has to be careful. The simplest choice would be Euler forward integration:

\[
x[k + 1] = x[k] + T \cdot f(x[k], u[k], k\cdot T)
\] (3.73)

Where \( f \) is defined in (3.2). As mentioned, in the discrete time domain an equilibrium point of a system is known to be stable if all poles of the linearised system are within the unit circle. Since the integration method above maps the stable poles \( \pi_{c,a} \) where \( \text{real}(\pi_{c,a}) < 0 \) to discrete poles \( \pi_{d} \in \{ x | \text{real}(x) > 0 \} \). This does not guarantee stability. The models which require such an integration procedure are the thermal homogeneous storage and thermal layer storage. Both are described by first order differential equations. Given the pole \( \pi_c = -1/\tau \) of the continuous first order system, the resulting pole in discrete time domain is \( \pi_d = T/\tau - 1 \). If the time step \( T \) is smaller than the time constant \( \tau \) of the system, the discrete pole is within the unit circle. The time constants of the thermal system are in general in the size of minutes or hours [ISO01, p38]. Time steps used in the framework are in the range of one to five seconds. Thus \( T \ll \tau \) and all stable continuous time poles are mapped to stable discrete time poles. Because of this argumentation, the implementation of the ODEs has been done using Euler forward integration. In order to assure a mapping from stable continuous time poles to stable discrete time poles for system of second order or higher, Tustin emulation is suggested. Tustin emulation, also known as
bilinear transformation, is defined as [Guz09]:

\[
x[k + 1] = x[k] + \frac{T}{2} \cdot (f(x[k], u[k], k \cdot T) + f(x[k + 1], u[k + 1], (k + 1) \cdot T))
\] (3.74)

Inserting the corresponding model function for \( f \) into (3.74) and solving for \( x[k + 1] \) gives the desired description for the update function.

### 3.6.3 Thermal model parametrisation

For the electro-mechanical components, a parameter set belongs to one machine component model and is stored in the *machine component database*. Thermal subsystem modelled in the framework can include none, one or multiple machine components. The parametrisation of the thermal model can therefore be machine or component specific. For example the thermal behaviour of a spindle is component specific, where the thermal behaviour of the machine structure is machine specific. Not all parameter information for the thermal models can therefore be stored in the *machine component database*. To solve this problem, the following definition is made: Each thermal model component has an additional property compared to an electro-mechanical component. This property, called *parentType*, indicates if the thermal model parameters are machine or component specific. In the case of the motor, the parent type is *Motor*. If the property is left empty, the parameter file is loaded from the machine configuration. Otherwise, as for the example of the motor, the properties of the *machine component database* are loaded. If the thermal parameters are component specific, they are append to the parameter file of the corresponding component with the prefix *thermal*.

Additional to the parameters, the thermal components do request initial conditions on temperatures. This information is not only machine, but even simulation specific. To assure the possibility of simulations with different initial conditions for the same machine configuration, the initial states are stored in the simulation configuration.

### 3.6.4 Mathematical operations and basic control

During the modelling, additional functions might be requested, which can not be defined as a component. This are mathematical operators an basic control elements. Examples for such elements are gains or simple signal routings. The following lines explain the functions which have been implemented during this work. This are: Sum, multiplication, hysteresis and switch. As explained, each port is defined by an object of the type *IOContainer*, which are linked by objects of the type *IOConnection*. During the initialisation of the model various tests are performed by the framework, to ensure the correct component linking in the model. To this tests belong the check of the signal unit and the empty input check. During the unit check, all *IOConnection* objects are tested to have source and target with the same unit. Where the empty input test checks all available inputs to be member of exactly one *IOConnection* object. In other words, each input must be connected to one, and only one output of an other component or simulation signal. Simulation signals are for example rotational speed given by the process definition. The created mathematical objects must pass these tests without special treatment.

Starting with the sum: The sum operator has to provide a desired number of inputs. Each input has either a plus or minus flag. During the update, all inputs are summed up, where the one with minus flags are counted negative. The result is passed to the output. The implementation has an important difference compared to the description in section 3.6.1: The input objects are not created by the class constructor; which causes the *input* list to be empty until the model initialisation. If in the given component connection list an output is connected to the plus or minus port of a sum block, a new *IOContainer* object is
created and added to the input list. The object is marked to be counted plus or minus. To assure the use of the right unit, the unit of a sum block is given as property by the user. With this implementation, the use of sums of signals is possible and the object passes the named tests.

Similar is the implementation of the gain and the hysteresis. The signal unit is again given by the user. The element gain has only one input and one output. Further the property gain is given by the user. The element returns at each update the product of the input and the gain. The hysteresis has a desired amount of inputs. The same technique to create new inputs as for the sum element is used. The element has two state values: high and low. If a lower threshold is crossed by any of the inputs and the state is high, the state changes to low; the action is vice versa for the upper threshold. The threshold and the output values during the high and low state are given by a machine specific parameter file.

The second control component – the switch – has two fixed inputs. One is the signal input and the other the control input. In the machine configuration, a threshold value and a switch direction are given as parameters. If the control input is greater than the threshold, while a positive switch direction is given, the signal is passed to the output. Same thing happens, if the control input is below the threshold and the switch direction is negative. For all other cases, zero is passed to the output.

### 3.7 System modelling Schaublin 42L

To test the functionality of the implementation, the test bench machine Schaublin 42L is modelled using the framework. As in the system modelling, the difference between the electro-mechanical part and the thermal part of the model is made. To test the thermal model, only the cooling cycle of the spindle is modelled. This small subsystem allows to test all of the created thermal models. During the following section, the topology of the system is discussed first, where in a second step the parametrisation is explained. This steps focus on the information gathering to model the machine in the framework. Out of this information, the machine configuration can be derived. The documentation of the machine configuration in the framework can be found in appendix B.

Before the modelling of the machine with the implemented components is started, a brief summary about the test-bench machine: On the test-bench, a turning machine of the type Schaublin 42L TMI3 is available. The total installed power is listed as 46 kW, where 15 kW are for the main drive of the spindle. In total three translational axes are available: Two for the movement of the revolver platform and one for the tail-stock. Beside the spindle, an additional rotational axis is available to rotate the tool platform of the revolver. The drives are supplied and controlled by a Fanuc control. In order to assist the process, a chip conveyor and cutting fluid supply are mounted on the machine. The cutting fluid supply is realized by a single pump. For the thermal stabilization, an external module supplies the machine with tempered cooling fluid. Thermal stabilization is only done for the spindle. The electronics and control components are mounted within a cabinet on the back of the machine. Cooling of the cabinet is done by two fans. For the operation of the grips and to seal the spindle bearings, compressed air is used. The supply is given by the shop-floor-sided installation.

### 3.7.1 Electro-mechanical system

During the modelling of the electro-mechanical part of the test-bench machine, a selection of components with a significant power level has been done first. Since the test machine has – as other machine tools – a large number of components, the effort must focus on those with a significant contribution to the total energy demand. The selection of the components to be modelled has been made based on the
informations about installed power in the components [Sch99b]. Additional information was taken from the expertise given by authors of [GWW10]. In the following section the selected components based on the argumentation above and their interconnections are discussed.

To derive and represent the topology of the system, a cause and effect diagram is used. As discussed in section 2.5 the calculation – and thereto also the diagram – follows from the effect to the cause. The methodology used to derive the cause and effect diagram is the same as introduced in [Guz08]. In order to identify the components of the electro-mechanical system and the electrical connections in the system the electro diagram [Sch99b] has been consulted. The results of the system modelling is shown in figure 3.8, where the components are explained in table 3.2. Following a short explanation of the electro-mechanical model:

The machine has in total five axes: The spindle (C1), the revolver (B1), the x-axis (X1), the z-axis (Z1) and tail-stock (Z3). Axes C1 and B1 are rotational, while the other three are translational. To model the behaviour of the three translational axes, the linear axis model is used. This model is extended by the use of two constant consumption models, in order to model the brake behaviour. The torque demand from the axes models is connected over a switch control with the motor models; if the brakes are on, no torque is transmitted to the motors. For the spindle drive, the motor model with the efficiency map is implemented, while the other drives are servo motors and modelled with the servo motor model. All drives are supplied with power by amplifiers. The drive of C1, B1 and Z3 have their own amplifiers, while X1 and Z1 share the same amplifier. All amplifiers have two power sources: The power supply module (PSM) for the drives power and a control/brake power transformer for the control power. Modelling of the PSM is done by a sum element.

The auxiliary devices include the cutting fluid pump, the spindle cooling unit, a chip conveyor, compressed air supply and two cabinet fans. The spindle cooling unit can be divided into a heat exchanger and a pump for the cooling fluid. The two named pumps are of course modelled by the pump model, as the fans and the heat exchanger are implemented by the corresponding models. The state of the heat exchanger is given by a hysteresis control dependent on the temperature in the heat exchanger and the cooling fluid tank. Where the pumps and the heat exchanger are provided with power by the line filter, the fans take their power from the same transformer as the amplifier control. This transformer is thereto modelled as a sum of power demands. The chip conveyor has only one power level, and is therefore represented by a constant consumer, which is provided with power by the line filter. For the cutting process, providing the axes with the forces and velocities informations, the Kienzle model is used. All consumption of electrical power comes from the line filter. Which is assumed to be perfect, and therefore modelled by a simple sum of the consumer powers.

During this modelling, three functions on the machine are neglected. Those are the tail-stock dynamic, the revolver dynamic and the part clamping. The reason to do so is the following: Looking at the tail-stock and revolver dynamics, slow movements and low duty cycles compared to other process components can be seen. The same observance can be made for the part clamping, where the time taken for opening and closing compared to the process time is small. Out of this reasons, the dynamics of the three described components have been neglected in the machine model. Of course, this assumptions must be proved in the following validation of the model. For the sake of completeness, the drives of the tail-stock and revolver are modelled, missing are only the requested calculations of the torque and speed demands.

3.7.2 Thermal subsystem

Modelling of the thermal behaviour of a machine tool is much more complex than the modelling of the electro-mechanical part. Where the power flows of the electrical power is limited to the lines, thermal
Figure 3.8: Topology of the modelled electro-mechanical system shown as effect-cause diagram. Ambient influences, mode of operation – such as on/off, application control signals and the system boundary are shown as dashed lines (−−).Where physical signals are drawn as solid lines (−). Connections of signals have to be read as sum of the signals. Further, the connections to the thermal part of the system are drawn in grey.
### Table 3.2: List and model type of all components used to model the test bench machine Schaublin 42L with the framework. For certain components more than one model is used to express the whole function.

<table>
<thead>
<tr>
<th>Component</th>
<th>Name</th>
<th>Used model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting process</td>
<td>C1_Torque</td>
<td>Kienzle</td>
</tr>
<tr>
<td></td>
<td>X1_Force</td>
<td>Kienzle</td>
</tr>
<tr>
<td></td>
<td>Z1_Force</td>
<td>Kienzle</td>
</tr>
<tr>
<td>Spindle motor</td>
<td>C1</td>
<td>Motor</td>
</tr>
<tr>
<td>X1-axis motor</td>
<td>X1</td>
<td>Servomotor</td>
</tr>
<tr>
<td></td>
<td>X1_Brake</td>
<td>Constant consumption</td>
</tr>
<tr>
<td>Z1-axis motor</td>
<td>Z1</td>
<td>Servomotor</td>
</tr>
<tr>
<td></td>
<td>Z1_Brake</td>
<td>Constant consumption</td>
</tr>
<tr>
<td>Tailstock motor</td>
<td>Z3</td>
<td>Servomotor</td>
</tr>
<tr>
<td>Revolver drive</td>
<td>B1</td>
<td>Servomotor</td>
</tr>
<tr>
<td>X1-axis</td>
<td>X1_ax</td>
<td>Linear axis</td>
</tr>
<tr>
<td>Z1-axis</td>
<td>Z1_ax</td>
<td>Linear axis</td>
</tr>
<tr>
<td>Tailstock-axis</td>
<td>Z3_ax</td>
<td>Linear axis</td>
</tr>
<tr>
<td>Spindle amplifier</td>
<td>C1_amp</td>
<td>Amplifier</td>
</tr>
<tr>
<td>Axis amplifier</td>
<td>Ax_amp</td>
<td>Amplifier</td>
</tr>
<tr>
<td>Tailstock amplifier</td>
<td>Z3_amp</td>
<td>Amplifier</td>
</tr>
<tr>
<td>Revolver amplifier</td>
<td>B1_amp</td>
<td>Amplifier</td>
</tr>
<tr>
<td>Cutting fluid pump</td>
<td>CuttingFluidPump</td>
<td>Pump</td>
</tr>
<tr>
<td>Spindle cooling</td>
<td>SpindleCoolingCompressor</td>
<td>Heat exchanger</td>
</tr>
<tr>
<td></td>
<td>SpindleCoolingPump</td>
<td>Pump</td>
</tr>
<tr>
<td>Chip conveyor</td>
<td>ChipConveyor</td>
<td>Constant consumption</td>
</tr>
<tr>
<td>Fan</td>
<td>Fan_in</td>
<td>Fan</td>
</tr>
<tr>
<td></td>
<td>Fan_out</td>
<td>Fan</td>
</tr>
<tr>
<td>Compressed air</td>
<td>CompressedAir</td>
<td>Compressed air</td>
</tr>
<tr>
<td>PSM</td>
<td>FanucTotalPower</td>
<td>Sum</td>
</tr>
<tr>
<td>Transformer</td>
<td>ControlBrakePower</td>
<td>Sum</td>
</tr>
<tr>
<td>Line filter</td>
<td>TotalPower</td>
<td>Sum</td>
</tr>
</tbody>
</table>
heat flows are temperature gradient driven and thereto not always controlled. This free heat flows request parameters which are not component, but machine specific. It is possible to estimate these parameters, but the precision of the estimation is difficult to determine. The first modelling of a thermal system with the framework will thereto focus on a subsystem of the machine, in order to evaluate the functionality and precision of the implemented models. The subsystem shall focus on a part of the test-bench machine, which allows to use all of the implemented generic thermal model components.

This demand is satisfied by the cooling cycle of the spindle as shown in figure 3.9. The spindle produces thermal losses during operation or while the position is controlled. This losses heat the spindle body. To control the spindle temperature, cooling fluid is pumped through a cooling coil in the spindle motor by a pump. This cooling fluid is thereby taken from the tank of the spindle cooler connected to a heat exchanger. Both, the spindle and the tank are modelled has homogeneous thermal storages, where the layer storage model is used for the cooling coil. Heat flows out of the spindle body are given by free heat exchange to the environment and the thermal flows to the cooling coil. The heat source is given by the motor losses. The cooling fluid tanks inflows are the forced heat flow by the cooling fluid returning from the cooling coil and losses created by the pump. Outflows of the tank are given by free heat exchange with the environment and the forced heat flow by the heat exchanger. The tank temperature is further equal to the inflow temperature of the cooling coil, where the mass flow trough the cooling coil is given by the pump. The same mass flow is of course used to model the forced heat flow to the tank.

Summarizing the model, we have three storages: Two homogeneous and one layer. Both homogeneous storages show free heat transfer with the environment and have an internal heat source. The layer storage is connected to both other storages, once trough forced heat transfer and once by free heat transfer over the surface.

### 3.7.3 Parametrisation

In the following section, the parameters which are specific for the machine tool and the used components are discussed. For some components, not all requested parameters have been available in the form needed for the model. In this cases, the calculations applied to receive the desired parameters from the available data is discussed. Additional to the component parameters, ambient parameters are introduced. This parameter set describes the ambient conditions of the machine, in the form requested by the model.
### Ambient parameters

All ambient conditions are described by two parameters: Temperature and pressure. For the temperature of the ambient – or shop-floor – $293 \text{ K}$ is used. This value resulted from a temperature measurement in the shop-floor at the test-bench. Ambient pressure is chosen to be at normal conditions. The values are shown again in table 3.3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>$\vartheta_{\text{amb}}$</td>
<td>K</td>
</tr>
<tr>
<td>Pressure</td>
<td>$p_{\text{amb}}$</td>
<td>Pa</td>
</tr>
</tbody>
</table>

Table 3.3: Parameters describing the ambient conditions of the machine

### Main drive

The main spindle of the test bench machine is induction AC motor of the type AMEFF100.46.4 build by Franz Kessler AG. The characteristics of the motor are described in [Kes96]. For the parametrisation of the component, an efficiency map for given mechanical powers and rotational speeds is required. For a given operation point ($\omega, T$), the efficiency of a induction AC motor in steady state is given by [KWS95] as

$$\eta = \frac{1}{\omega_{\text{fld}} + \frac{R_r \cdot R_s}{L_m^2 \cdot (\omega_{\text{fld}} - p \cdot \omega)} \cdot p \cdot \omega + \frac{R_r \cdot \omega_{\text{fld}} - p \cdot \omega}{p \cdot \omega} + \frac{P_{\text{amp}}}{\omega \cdot T_{\text{m}}}}.$$  \hspace{1cm} (3.75)

The parameters rotor resistance $R_r$, stator resistance $R_s$, rotor inductance $L_r$, stator inductance $L_s$ and mutual inductance $L_m$ need to be identified, where the rotational speed $\omega_{\text{fld}}$ of the magnetic field is dependent on the rotational speed of the drive. Of course, the mentioned parameters are not part of the model, but used at this point to make an educated guess about the spindle efficiency map. For the given application, the amplifier of the spindle is mounted in the electronics cabinet. To model the separated heat sources, the amplifier is modelled in a separate subsystem. Hence in (3.75) the amplifier power $P_{\text{amp}}$ is set to zero. Krause et al. further describe in [KWS95] the motor output torque as

$$T_m = \frac{3}{2} \cdot p \cdot \frac{R_r \cdot L_m^2 \cdot \Delta \omega \cdot U_a^2}{(R_r \cdot L_s \cdot \omega_{\text{fld}} + R_s \cdot L_r \cdot \Delta \omega)^2 + \left( R_r \cdot R_s - \omega \cdot \left(1 - \frac{L_m^2}{T_{\text{m}} \cdot L_r}\right) \right) \cdot L_s \cdot L_r \cdot \Delta \omega},$$ \hspace{1cm} (3.76)

where $\Delta \omega = \omega_{\text{fld}} - p \cdot \omega$. Within the descriptions in (3.75) and (3.76) frictional losses from the bearings of the spindle motor are not included. To do so, a friction torque $T_{fr}$ is introduced. The torque provided by the motor is the difference between the theoretical minus the frictional torque, where the total efficiency is given as

$$T_{\text{tot}} = T_m - T_{fr} \quad \text{and} \quad \eta_{\text{tot}} = \left(\frac{1}{\eta} + \frac{T_{fr}}{T_{\text{tot}}}ight)^{-1}.$$ \hspace{1cm} (3.77)

Given by the technical data sheet of the spindle[Kes96] and the electro diagram [Sch99b] are the number of poles $p = 2$. For three operational points the rotational motor speed $\omega = \{1500, 5700, 8000\}$ rpm, the rotational magnetic field speed $\omega_{\text{fld}} = \{54, 200, 276\} \cdot 2\pi$ rad/s, the motor torque $T_m = \{95, 25, 13\}$ Nm.
and the armature voltage $U_a = \{295, 295, 400\}$ V are provided too. Using the description above from [KWS95] for the motor torque, the missing parameters can be identified by minimising the difference between the rated torque and the calculated torque. This results in the parameter values

$$R_r = 1.32 \, \Omega, \quad R_s = 0.46 \, \Omega, \quad L_r = 70 \, \text{mH}, \quad L_s = 30 \, \text{mH}, \quad L_m = 50 \, \text{mH}, \quad T_f = 1 \, \text{Nm}. \quad (3.78)$$

With these values, the efficiency map for the AMEFF100.46.4 spindle motor can be calculated using (3.75). The result is shown in figure 3.10. Since the whole map is calculated by only three known points, the result has to be used critical. Especially since the algorithm *fmincon* by *Mathworks* used to solve the optimization problem depends on the initial conditions and on the limitations taken. The limitations and initial conditions taken for the results above are:

$$\begin{bmatrix} 0 \, \Omega \\ 0 \, \Omega \\ 0 \, \text{mH} \\ 0 \, \text{mH} \\ 0 \, \text{Nm} \end{bmatrix} \leq \begin{bmatrix} R_r \\ R_s \\ L_r \\ L_s \\ L_m \\ T_f \end{bmatrix} \leq \begin{bmatrix} 2 \, \Omega \\ 2 \, \Omega \\ 100 \, \text{mH} \\ 100 \, \text{mH} \\ 100 \, \text{mH} \\ 1 \, \text{Nm} \end{bmatrix}, \quad \begin{bmatrix} R_{r,\text{init}} \\ R_{s,\text{init}} \\ L_{r,\text{init}} \\ L_{s,\text{init}} \\ L_{m,\text{init}} \\ T_{f,\text{init}} \end{bmatrix} = \begin{bmatrix} 1 \, \Omega \\ 1 \, \Omega \\ 10 \, \text{mH} \\ 10 \, \text{mH} \\ 10 \, \text{mH} \\ 0 \, \text{Nm} \end{bmatrix} \quad (3.79)$$

**Servo motors**

In the test bench machine, four servo motors of *Fanuc SA* are installed to drive the x and z axis, to move the tail-stock and to rotate the revolver. Thereby, three different types are used: The $\alpha$C6/2000 for the x-axis, one $\alpha$C12/3000 for the z-axis and one for the tail-stock, and the $\alpha$M9/3000 for the revolver. Each
motor is equipped with a break [Sch99b] and an amplifier. All the requested parameters are given in the fact-sheets [GE 11, GE 01, GE 98b] published by Fanuc SA and the electro diagram [Sch99b] by Schaublin. The used parameters are shown in table 3.4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>αC6/2000</th>
<th>αC12/3000</th>
<th>αM9/3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque constant</td>
<td>κa</td>
<td>1.68</td>
<td>2.04</td>
<td>0.86</td>
</tr>
<tr>
<td>Speed constant</td>
<td>κi</td>
<td>0.56</td>
<td>0.68</td>
<td>0.29</td>
</tr>
<tr>
<td>Static friction</td>
<td>Tf</td>
<td>0.3</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Armature resistance</td>
<td>Ra</td>
<td>1.52</td>
<td>1.10</td>
<td>0.181</td>
</tr>
<tr>
<td>Pole pairs</td>
<td>p</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Brake power if open</td>
<td>–</td>
<td>18.0</td>
<td>27.0</td>
<td>18.0</td>
</tr>
</tbody>
</table>

Table 3.4: Parameters for the Fanuc servo motors driving the axis X, Z and the tail-stock. All parameters are found in the Fanuc product documentation [GE 11, GE 01, GE 98b], the information about the break is taken from [Sch99b].

Amplifiers

In the Schaublin 42L four amplifiers of the following types are installed: One spindle amplifier of the type Fanuc SPM 26 and three servo amplifiers of the types Fanuc SVM2-20/20, Fanuc SVM1-80 and Fanuc SVU1-20. The SVM2-20/20 servo amplifier provides the x and the z-axis with power, the others supply the revolver and the tail-stock drive. From the amplifier description manuals [GE 98a, GE 98b] the requested informations are gained. Given a set of operation points with corresponding heat losses, the amplifier efficiency can be estimated by interpolation. For the revolver amplifier, no data was given in the available fact sheets. Based on the maximum power and the geometric size, the values are estimated over the available amplifier data. The results of the parametrization are shown in table 3.5.

<table>
<thead>
<tr>
<th>Amplifier Typ</th>
<th>Power demand</th>
<th>Heat Loss</th>
<th>Control power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fanuc SPM 26</td>
<td>(15, 18, 22) kW</td>
<td>(189, 247, 349) W</td>
<td>30 W</td>
</tr>
<tr>
<td>Fanuc SVM2-20/20</td>
<td>(1.4, 2.8) kW</td>
<td>(73, 106) W</td>
<td>29.9 W</td>
</tr>
<tr>
<td>Fanuc SVM1-80</td>
<td>(1.4, 2.8, 3.8) kW</td>
<td>(70, 91, 106) W</td>
<td>29.9 W</td>
</tr>
<tr>
<td>Fanuc SVU1-20</td>
<td>(1.4, 2.8) kW</td>
<td>(73, 106) W</td>
<td>30 W</td>
</tr>
</tbody>
</table>

Table 3.5: Operation points used for the amplifier models. The parameters in italic are estimated, where the others are taken from [GE 98b] and [GE 98a].

Linear axis

The Schaublin 42L TMI3 has three linear axes, all driven by ball screws. In the horizontal, the z-axis and the tail-stock are operating. Since friction is neglected in the used model, gravitation has no effect in the horizontal. Because of the neglected gravitational and inertia effects, the identification of the masses is not requested for this two components. On the z-axis, the x-axis is mounted with a 35 degree angle to the vertical. The angle between the x-axis and the vertical has been measured on the machine, where the mass of the axis can be approximated by the sum of the revolver mass, the mass of the servo motor
driving the revolver and the structural mass. But one has also to include the weight compensation in the form of a hydraulic cylinder. Since the available fact sheets do not provide the requested informations about the masses of the mentioned parts, an other approach is requested: While moving the x-axis from the zero to the tool handling position, a variation of the pressure in the cylinder of 1.5 bar can be seen on the mounted barometer, where the cylinder has an approximate diameter of 5 cm. Assuming an ideal weight compensation around the zero position, the remaining weight at the tool handling position is

\[
m_{\text{ax},x} = \frac{\Delta p \cdot A_{\text{cyl}}}{g} \approx 30 \text{ kg}. \tag{3.80}
\]

For all axes, the transmission has been estimated by counting the number of revolutions of the servo motor output axis. Using the numerical information on the operators panel, the total displacement in the direction of the axis has been measured. Both informations together result in a transmission of \( k = 10 \text{ mm/rev} \) for the x-axis and \( k = 15 \text{ mm/rev} \) for the z and tail-stock axis. A summary of all discussed parameters is shown in table 3.6.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>X-axis</th>
<th>Z-axis</th>
<th>Tailstock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle to the vertical</td>
<td>( \alpha ) ( ^\circ )</td>
<td>35.0</td>
<td>90.0</td>
<td>90.0</td>
</tr>
<tr>
<td>Transmission ratio</td>
<td>( k ) ( \text{mm/rev} )</td>
<td>10.0</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Mass</td>
<td>( m ) kg</td>
<td>30.0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.6: Parameters for the linear x, z and tail-stock axis. All values have been measured on the test bench machine or are taken form manufactures informations [GE 01]. The moving mass has been neglected for axes moving in the horizontal.

Cabinet fans

To cool the cabinet with ambient air, two fans of same type are mounted on the cabinet. The fans are of the type Pfannenberg PF 3.000 and include a filter. The fans are not demand controlled, and therefore always on if the main switch is closed. The point of operation of the fans is given by the intersection of the characteristic curve of the fan and the characteristic curve of the filter. This operation point is taken as reference point described in section 3.4.7. Doing so helps minimizing errors in the simulation due to non ideal process, such as friction or boundary layer separation, which are not modelled here. All parameters used for the two cabinet fans are taken from the producers documentation [Pfa] and can be seen in table 3.7.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>PF 3.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical power</td>
<td>( P_{\text{el,ref}} ) W</td>
<td>45.0</td>
</tr>
<tr>
<td>Voluminal flow</td>
<td>( \dot{V}_{\text{ref}} ) ( \text{m}^3/\text{s} )</td>
<td>( 6.4 \cdot 10^2 )</td>
</tr>
<tr>
<td>Pressure drop</td>
<td>( p_{\text{ref}} ) Pa</td>
<td>104.0</td>
</tr>
<tr>
<td>Fluid density</td>
<td>( \rho_{\text{fl}} ) ( \text{kg/m}^3 )</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 3.7: Parameters at a reference point used for the fan models. All Parameters are described in the product description of the producer [Pfa]. The reference point is taken at the intersection of the characteristic curves of the fan and the filter.
3.7 System modelling Schaublin 42L

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>PV 80-180</th>
<th>VWK 21/1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical power</td>
<td>$P_\text{el}$</td>
<td>kW</td>
<td>1.75</td>
</tr>
<tr>
<td>Cooling fluid density</td>
<td>$\rho_{cf}$</td>
<td>kg/m$^3$</td>
<td>833.0</td>
</tr>
</tbody>
</table>

*Table 3.8: Static parameters used for the cooling fluid pump model. The pump parameters are taken from [Spa11], as the cooling fluid are taken from [Bla08].*

**Pumps**

To pump the cooling fluid to the spray valve of the tool, a pump of the type PV 80-180 produced by Spandau Vogel AG is installed. The information about this product is taken from the data sheets supplied by Spandau Vogel [Spa11]: The pump has an electric power consumption of 1.75 kW if operating, where the volumetric flow depends on the pressure gradient as shown in figure 3.11. The pump has further no reservoir. Parameter values for the gas and fluid volume, as controller settings and initial conditions are thereto not required. As cutting fluid, Vascomill 10 from Blaser Swisslube Inc. is used. According to the technical documentation [Bla08], this cutting fluid has a density of 883 kg/m$^3$.

The pump of the spindle cooler VWK 21/1 is also characterized by its pressure to volumetric flow map and its electrical consumption. For the pressure to volumetric flow map, the manufactures informations, as shown in figure 3.11, are used. The fact sheet further gives the electrical power demand of the pump as $P_{el,pump} = 135$ W. A summary of all mentioned parameters is shown in table 3.8 and figure 3.11.

![Figure 3.11: p-V maps for the installed pumps PV 80-180 drawn as solid line (–), and VWK 21/1 (LNY2841) drawn as dashed line (- -)](image)

**Spindle cooler (heat exchanger)**

The cooling fluid for the spindle is supplied by an external module. This module is of the type VWK 21/1 manufactured by HYFRA Industriekühlanlagen GmbH. The VWK 21/1 uses a coolant of the type R 134 a to temperize the water at 15°C. To do so, the heat is extracted by a compressor over the mentioned coolant, while heat transfer takes place over a heat exchanger and a fan to the ambient air. The energy efficiency ratio of the compressor, heat-exchanger and fan $\varepsilon_\text{cooling}$ is calculated by using the operational point given in [Hyf05]. The fact sheet shows a total heat transfer rate of $Q = 2.35$ kW and a compressor power of $P_{el,comp} = 0.74$ W. This results in an energy efficiency ratio of

$$\varepsilon_\text{cooling} = \frac{P_{el,comp}}{Q} \approx 3.14.$$  \hspace{1cm} (3.81)
### 3 System modelling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>VWK 21/1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal power</td>
<td>$P_{el}$</td>
<td>W 1000.0</td>
</tr>
<tr>
<td>EER cooler</td>
<td>$\varepsilon_{cooling}$</td>
<td>- 3.14</td>
</tr>
</tbody>
</table>

**Table 3.9:** Parameters used for the heat exchanger model. The parameters are calculated with informations provided by the manufacturer in [Hyf05].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Schaublin 42L, CLA A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply pressure</td>
<td>$p_{supply}$</td>
<td>bar 8.0</td>
</tr>
<tr>
<td>Density air</td>
<td>$\rho_{air}$</td>
<td>kg/m$^3$ 1.2</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>$c_{p,air}$</td>
<td>J/kgK 1004.5</td>
</tr>
<tr>
<td>Volumetric flow</td>
<td>$V_{\text{n,air}}$</td>
<td>m$^3$/s 0.77</td>
</tr>
</tbody>
</table>

**Table 3.10:** Parameters for the compressed air model. The volumetric flow results from experience on the test-bench machine.

The results of the calculations above is summarized in table 3.9. This values are used as parameter-set for the heat exchanger.

**Compressed air**

For the parametrisation of the compressed air, and the voluminous flow time series is required. The compressed air supply on the CLA A floor is labelled with 8 bar. There exist two demands of compressed air on the machine: Sealing air and the part clamping. As discussed, the demand for part clamping is assumed to be negligible compared to the sealing air flow. This statement has to be verified later.

Using the throttle model, the open area is required to calculate the ceiling air flow. As given in [Haa09, p.32], the air gap is in the range of 0.03 mm. With a bearing diameter estimated as 50 mm, an open area of 10 mm$^2$ results. The pressure of the cutting fluid pump is in the range of 3.6 bar. The required pressure for the sealing air is thereto $1.5 \cdot 3.5 \text{ bar} = 5.4 \text{ bar}$ [Haa09, Fig. 4.5]. Using (3.55) with $\psi = 0.4$ and $c_d = 0.5$, a volumetric flow of 1.8 l/s results.

From experience of previous measurements, it is known that the consumption of compressed air by the machine is in the range of 0.77 l/s under normal conditions. The estimation of the sealing air fails at this point due to the unknown – and thereto estimated – parameters. A compressed air demand is modelled by using the parameters in table 3.10. The miss fitting volumetric flow, calculated by the throttle model has to be discussed in the next chapter.

**Thermal subsystem: Spindle cooling cycle**

The parametrisation of the thermal model is not as straight forward as the electromechanical components. Especially the parameters for the free heat transfers are not available in the data sheets, and must therefore be estimated. In the following paragraphs, the sources for the available parameters are listed, and the calculations and estimations done for the missing parameters are explained. The results are shown in table 3.11.
Starting with the spindle: No informations about mass and thermal properties are given by the fact sheets. Measurements of the spindle geometry have resulted in a hollow cylinder with radii \( r_{o,i} = \{120, 25\} \text{ mm} \) and a length of \( l = 400 \text{ mm} \). Assuming, that \( 2/3 \) of the resulting volume are solid and of density \( \rho = 7800 \text{ kg/m}^3 \), the weight of the spindle is estimated as 60 kg, with the internal heat capacity of steel. With the same parameters, the surface is estimated to be 0.37 m\(^2\). The free heat transfer is driven by convection only. The spindle is inside the machine, where the air circulation is reduced. Anyhow, the sealing air leads to a certain flow in the air. Thereto the convection constant is chosen to be \( 5 \text{ W/Kkg} \). This relates to convection with air, where the air is not circulated [MS06].

The calculations for the cooler tank are very similar. The volume of water in the tank is given as 13 l [Hyf05]. Since water is used, a thermal mass of 13 kgs with internal heat capacity of \( c_{p,tank} = 4180 \text{ J/Kkg} \) results for the tank. The tank is located at the border of the component and takes about a quarter of the length of the component at the same height and depth. The whole component has a dimension of \( (l, b, h) = (800, 500, 200) \text{ mm} \). Due to the positioning of the component, only the top, end and front wall are exposed to the ambient. This results to a surface \( S_{tank} = 0.25 \text{ m}^2 \) for free heat transfer with the ambient air. The walls of the tank are made of plastic with a thickness of \( d_{tank} = 2 \text{ mm} \) and an estimated heat transfer constant \( \lambda_{tank} = 30 \text{ W/Km} \). The at surface convection with \( \alpha_{tank} = 6 \text{ W/Kkg} \) is assumed.

Regarding the cooling coil, no information is available. Only the cooling fluid is know to be water, resulting in the same internal heat capacity for the cooling coil as for the tank. Possible additives are neglected here due to the small concentration [Hyf11]. All geometric parameters are estimated on the base of the spindle geometry. The cooling coil has to operate as heat exchanger, which requests a thin separation layer with a high heat transfer constant. For a moving fluid, high convection constants can be assumed [MS06], which results in the values of table 3.11 under the point cooling coil.

The heat loss from the electro-mechanical components are used for the thermal model. There are two losses of components, which are considered for this example: Spindle losses and pumping losses. Losses of the spindle occur inside the component. It is therefore assumed, that all thermal losses directly heat the spindle body. For the cooling fluid pump, other affects must be considered: Pumps have a bad efficiency compared to electric drives, but only a part of the pump is in contact with the fluid. at this point, the assumption of 30% of the pump heat loss going to the fluid is made, where the other part heats the machine structure. This value bases purely on assumptions made by looking at the geometry of the pump.

### 3.8 Verification of results

In the beginning of the chapter, several specifications on the model have been discussed. this specifications are required to fulfil the requirements resulting from the goal of the thesis. As guidance for the following verification and discussion a small summary of the specifications:

- Identification of generic components
- Process force model for turning
- Component models for QSS
- Generic thermal model
- Implementation in EMod
Table 3.11: Parameters used for the different elements of the thermal model.
• Appliance on the test-bench machine

To complete the identification of the generic components, a definition of a generic components has been derived. The resulting list of generic components based on this definition is shown in table 3.1. For the process model, a Kienzle approach has been implemented. The system modelling has been divided into two parts; the first one developing the electro-mechanical models, where the second part deals with the thermal modelling. The results have been implemented as Java classes in the EMod framework, with the equations shown in appendix A. Further parameter files have been written and implemented as xml for the framework. Using the framework and the new implementations for the modelling of the test-bench machine, the discussed machine models with the explained parameters resulted. Comparing this short summary to the specification, the desired functionality can be verified.
Model validation and analysis

To quantify the quality of the data produced by the framework, the generated data has to be compared to trusted data. Based on the errors or deviation identified during this comparison, the model has to be validated against the specifications on simulation precision. Further, analysis of the error sources is required. This information has to be provided to discuss the portability of the model and the use of the framework and component models for other machines. The requirements on the data precision of the simulation is given as a maximum tolerated relative error. Since components may have different power levels, the resulting relative error depends also on the operational state of the machine and its components. For different applications, the time ratio of the available machine states varies. In order to allow a general conclusion about the precision, a set of operational state is defined. The validation and analysis of the model will be done for each of these states. Summarising the procedure required for the validation and analysis, includes the following steps:

1. Definition of operational states, in order to realize a application independent validation and analysis.
2. Acquisition of trusted data from the test-bench. This includes the methodology, procedure and processing of the data.
3. Generation of simulation data, suitable to be compared to the trusted data collected before, including the simulation configuration.
4. Validation of the model for each of the defined operational states by comparing the simulation results to the collected data from the test-bench. Includes also the localization of errors and differences.
5. Analysis of the identified model errors and differences, in order to conclude about portability of the model and framework components.

For all the steps above, a discussion of the used methodologies and a introduction of the used tools and equipment is included.
4 Model validation and analysis

4.1 Identification of operational states

During operation, a machine may have different levels or operational states. Such a state is defined in the current context by the power level taken by the components of the machine tool. In each operational state, the machine shows thereto a characteristic power drain and material consumption. Dependent on the power levels of the components, the machine tool model will show different relative errors compared with the measurement. The validation of the model and the analysis of its capabilities and characteristics has thereto to be made with respect to the operational state of the machine. In the following section, a set of states for both model parts – electro-mechanical and thermal – will be introduced. The states are thereby chosen based on the available experience of existing measurements and previous considerations in the framework design [LH11b, GWW10, GHWW10].

AIROFF This state represents the lowest energy level, the machine can take. The valve of the compressed air supply is closed, and the power supply is interrupted by the main switch. During this situation, the machine is not consuming either electrical power nor compressed air.

OFF While in the previous state, the compressed air supply was interrupted, the machine is now supplied with compressed air. Constant consumptions – as sealing air demand – are now active. The main switch is still interrupted, and the machine does not consume any electrical power.

STANDBY The machine is powered with electricity and the operational system is fully loaded. All auxiliary components are ready, but security options are on. This state occurs especially when the axes are not under control, but at fixed positions. An example for this state are open security doors.

READY If the machine is ready, all auxiliary devices are running, the axes are under control but the main drive is not running. In this state, a process could immediately be started with no significant delay.

PROCESS During the process, the main drive is running and process supports – such as cooling fluid – are active. Characteristic for this state are the process forces and high loads of the axes and main drives. In general, the machine reaches the highest average consumption during the process state.

This states hold for the electric part of the machine. Looking at the thermal dynamics of a machine tool, the time constants of the system are much larger than for the electric part. To validate and analyse the thermal model of the machine, the following four thermal machine states are introduced. In difference to the machine states discussed above, they do not include a certain thermal level of the machine. Moreover they describe a certain thermal dynamic of the machine. Following the four states and their definition:

WARMUP Describes the time, where the machine is started at ambient temperature, and heats up until long term thermal steady state (see: Idle) is reached.

IDLE The situation, where long time thermal steady state is reached. With long term steady state, a situation of repeating temperature characteristics in meant. This thermal state is characteristic, if the machine has finished the warm-up and no process is started, or if a process has finished and the machine is running in Ready state.

OPERATION During the Operation thermal state, heat releases due to the process occur. In general, the most significant heat flows and releases take place during this thermal state. As for the last state, long term thermal steady state is demanded.

COOLDOWN Takes place after the machine has been set to Off state. No active cooling system is running, only free heat transfer with the ambient takes place. Usually, this thermal state has the largest time constant of all four introduced thermal states.
4.2 Measurements

Of course, there exist thermal states between the introduced ones. This can happen, if the machine is for example turned on and a process is started immediately. The heat losses of the drives will heat the machine up rapid, until the pure Operation state is reached. In the data acquisition the horizon for each thermal state must be chosen long enough, in order to capture and identify the desired steady state behaviour.

4.2 Measurements

In order to validate a model and analyse its functionality and capabilities, assured reference data is requested. This data must be taken by a defined procedure under known ambient conditions. Measurements of energy and resources demand on machine tools is a well known procedure at inspire [GWW10]. Thereto, a suitable measurement system is installed on the test bench, in order to allocate data from the machine for the model validation and analysis. In the following section, the measurement system and the measurements taken are discussed. Further the processing of the measurement data for the following application in simulation, validation and analysis is explained.

4.2.1 Measurement system

For the measurements of the test bench machine in order to acquire validation data, three measurement systems have been installed. One for the process force measurement, one for the power consumption and the third for the temperature. In the following lines, the measurement systems will be introduced and the points of measurement are listed.

Staring with the energy measurement: Since the electric power measurement on machine tools is a well known process at IWF and inspire, the measurement system available at the institute has been used. The whole system consists of a electric sensor system, compressed air measurement and the required logging software. Following, a short summary of the measurement system, more detailed information can be taken from [GWW10]. To complete the task of electric power measurement, sensors of the type CLT 310 manufactured by Christ Elektoronik are used. This component is designed to measure various quantities of three phase alternating current [Chr09], but for this application only the measurement of the active power is relevant. Due to the limited current allowed by the measurement system, current transformers have to be used where ever the current is above 16 A [Chr09, p.2]. The installed transformers are produced by Siemens and have a transmission ratio of 50 : 5 [Sie11]. When ever possible, the measurement has been taken close to a fuse, in order to measure the power consumption of only one component per channel. Not all components are thereby measured separately, only the components where a significant power consumption is expected. The contribution of the sum of the small neglected components can be estimated by comparing the sum of the measured components to the measurement at the line filter of the machine. In order to measure the power flow by compressed air as well, a flow meter is installed in the main supply. All CLT and flow measurements are connected over a RS232 to USB interface with the measurement PC. To log the data, an in-house developed software by inspire is used. The resulting wiring of the machine is shown in table 4.1.

For the force measurement system, a dynamometer is used. This measurement system of the type 9121 by Kistler measures the applied force in three directions over four piezoelectric crystals [Kisa]. The generated electric charge is converted by three amplifiers [Kisb] into a voltage signal. This signal is read by a A/D converter and logged over an in-house implementation in Labview. This process is done with a sample frequency of 2000 Hz. The coordinate frame $K$ of the dynamometer is rotated by $-90^\circ$. 

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along the x-axis relative to the inertial frame $I$ of the machine. For a measured force $\vec{F}$ represented in the coordinate frame $K$ with three components along $K\vec{e}_x^K$, $K\vec{e}_y^K$, and $K\vec{e}_z^K$ as $K\vec{F}$, the following linear transformation can be used to calculate the display $I\vec{F}$ of the force in the inertial machine coordinate frame:

$$I\vec{F} = A_{IK} \cdot K\vec{F},$$

where $A_{IK} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix}$ \hspace{1cm} (4.1)

To measure the temperature at various locations of the machine, two measurement systems are used: PT100 hand held devices for slow dynamics and a capacitive sensor system TMP190 by Lion Precision [Lio11] for fast dynamics. The data acquisition for the hand held devices is done manually with an approximate sample time of five minutes, where the software by Lion Precision is used to read the TMP190 system. In total, four PT100 probes and seven channels on the TMP190 are available. As mentioned above, the probes are distributed, depending on the estimated time constants of the thermal processes. Temperatures of the ambient air, machine surrounding, machine housing and cutting fluid tank are regarded as slow dynamics. Where spindle, spindle cooler and cabinet temperatures are handled as fast dynamics. To ensure a constant measurement of critical temperatures, the spindle and the cooler tank are both equipped with two probes. This results in the probe locations as shown in table 4.2. For all probes – except for the two in the air – heat transfer paste is placed. Additionally, plastic bags are used to protect the probes in the fluids. Obviously, this set-up includes more temperatures than available in the thermal model of the spindle cooling system. The idea is to capture a complete image of the thermal behaviours on the modelled mechanical components. The data might later be used for error analysis or for further modelling of other thermal systems on the machine.

The discussed components build the measurement system used for the data acquisition for the model validation and analysis. The expected errors for measurements done with this installation is shown in table 4.3.


### Table 4.2: Positions of the temperature sensor probes of the two systems PT100 and TMP190 on the test-bench machine.

<table>
<thead>
<tr>
<th>Location</th>
<th>Sensors system</th>
<th>Probe(s)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting fluid tank</td>
<td>PT100</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Air above machine top</td>
<td>PT100</td>
<td>2</td>
<td>10 cm above surface</td>
</tr>
<tr>
<td>Machine top</td>
<td>PT100</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Ambient</td>
<td>PT100</td>
<td>4</td>
<td>2 m distance from machine, 1.5 m above ground</td>
</tr>
<tr>
<td>Spindle</td>
<td>TMP190</td>
<td>1, 2</td>
<td>probe 1 on top in the front, probe 2 on the side in the back</td>
</tr>
<tr>
<td>Spindle cooler tank</td>
<td>TMP190</td>
<td>3, 4</td>
<td>5 cm bellow fluid surface</td>
</tr>
<tr>
<td>Cabinet</td>
<td>TMP190</td>
<td>5, 6</td>
<td>probe 5 close to fuses, 6 at Fanuc rack</td>
</tr>
<tr>
<td>Exhaust air spindle cooler</td>
<td>TMP190</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4.3: Expected error for the measurement system used to capture validation data on the test-bench machine.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Unit</th>
<th>Expected error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power CLT only</td>
<td>P, W</td>
<td>≤ ±1.5 %</td>
</tr>
<tr>
<td>Power CLT with amplifier</td>
<td>P, W</td>
<td>≤ ±4.5 %</td>
</tr>
<tr>
<td>Power Compressed air</td>
<td>P, W</td>
<td>±3.5 %</td>
</tr>
<tr>
<td>Force</td>
<td>F, N</td>
<td>≤ ±0.3 %</td>
</tr>
<tr>
<td>Temperature TMP190</td>
<td>t, K</td>
<td>±1.0 K</td>
</tr>
<tr>
<td>Temperature PT100</td>
<td>t, K</td>
<td>±0.5 K</td>
</tr>
</tbody>
</table>

[Kisa, Kisb, Chr09, Sie11, Lio11]
4 Model validation and analysis

4.2.2 Design of experiment methodology

Dependent on the task, different measurements are required. To plan the measurements for each task, the methodology after Kleppmann [Kle08] will be used. Following this methodology, the terms command variable, actuating variable, factorial design and realization is important. Command variables are the measured sizes in which one is interested, where the actuating variables influence the command variables. In the case of this work, the command variables are mainly power demand, process forces and temperatures of certain machine parts. The set of actuating variables is different for each command variable. Examples for command variables in this context are process parameters, such as spindle speed. Each set of actuating variables with fixed values is called factorial level. A set of different factorial levels build the factorial design. Where a measurement set of a complete factorial design is called realization. By increasing the number of realizations, the statistical error of the whole measurement can be reduced.

To estimate the number of realisations required in order to achieve a desired precision, the author introduces the following procedure [Kle08, p.28f]: Given a measurement of a command variable with variance $\sigma$ and a factorial design with $N_{fac}$ factorial sets. If one wants to capture a minimal change of $\Delta y$ in the command variable with high significance, the number of realizations $N_{realiz}$ can be calculated by the following formula:

$$N_{realiz} \approx \left\lceil \frac{N_{rep}}{N_{fac}} \right\rceil$$

and

$$N_{rep} \approx \left\lceil 60 \cdot \left( \frac{\sigma}{\Delta y} \right)^2 \right\rceil$$

which leads to a total number of $N_{realiz} \cdot N_{fac} \geq N_{rep}$ measurements. To eliminate the influence of external effects with slow dynamics, the arrangement of the factorial levels in each realization is changed. This method of the factorial design and the number of realization will be used in the following chapter. The aim is to plan and realize measurements which are able to prove the required information and precision, while keeping the required effort minimal.

4.2.3 Measurement sets and configurations

As discussed above, the aim of the measuring is to validate and quantify the system model. Further, forces occurring during the process have to be identified and parametrised in a suitable form, in order to be use as information for the simulation. Since two model parts – electro-mechanical and thermal – exist, two separate validations have to be made. As mentioned in section 3.7, certain component dynamics are neglected. The measurement data has also to be able to quantify this decision. In a most general approach, one can thereto speak of two types of measurements:

- **Process forces measurements:** Focusing on the identification of the process forces describing parameters. Looking at very fast effects with very short time horizon (seconds)

- **Model validation measurements:** Different operations and process situations, in order to acquire data over a wide range of component states and operational points. The measurement settings shall be chose such, that different effects can be addressed to certain process parameters. This measurements can further be divided into the following aspects:
  - **Energy:** Focusing on the electrical part of the machine. In general short time constants and medium measurement horizon (hours)
  - **Temperature:** Aiming on the thermal behaviour of the machine, with long constants and extended measurement horizon (days)
4.2 Measurements

<table>
<thead>
<tr>
<th>Type</th>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Setting angle</td>
<td>$\kappa$</td>
<td>°</td>
</tr>
<tr>
<td></td>
<td>Corner radius</td>
<td>$r$</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>Cutting speed</td>
<td>$v_c$</td>
<td>m/s</td>
</tr>
<tr>
<td></td>
<td>Feed rate</td>
<td>$f$</td>
<td>mm/rev</td>
</tr>
<tr>
<td></td>
<td>Cutting depth</td>
<td>$a_p$</td>
<td>mm</td>
</tr>
</tbody>
</table>

Table 4.4: Parameters of the cutting tool produced by Iscar used for the force and energy measurements. The setting angle results in combination with a turning tool of the type PCLNL 2020 K–12 manufactured by Tesch [Isc11, Dia11]

<table>
<thead>
<tr>
<th>Material</th>
<th>51CrV4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Unit</td>
</tr>
<tr>
<td>Diameter</td>
<td>$d$</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>$R_m$</td>
</tr>
<tr>
<td>Tensile elastic limit</td>
<td>$R_e$</td>
</tr>
<tr>
<td>Breaking elongation</td>
<td>$A$</td>
</tr>
</tbody>
</table>

Table 4.5: Parameters of the wrought material used for the force and energy measurements, according to [FHN+05].

Out of this classification, three measurement settings are defined: One for the process forces, one for the energy validation and the last for the thermal effects. In the following, the general settings are discussed, followed by the sections including the three application specific measurements configurations.

In order to generate assimilable measurement results, the same wrought material and cutting tools are used. To enable measurement situations where all components of the machine tool operate at high loads, roughing of a material with a high specific cutting force is preferred. This is especially important for supporting components – such as cooling – which may not be used during low machine loads. Due to this reasons, the following materials and tools are chosen from the ones available in the stock for all measurements: As cutting cutting tools, a turning tool of the type Tesch PCLNL 2020 K–12 with cutting insert Iscar CNMG 432-GN IC 9150 is mounted on the dynamometer described in the section above. This installation forms a setting angle of 95 degrees. Further parameter can be taken from table 4.4. As wrought material, rods of 500 millimetre length and 42 millimetre diameter with the material parameters shown in table 4.5 are used.

The cutting parameters – as cutting speed, feed rate or infeed – are chosen specific to the target of the measurement series. The selection of appropriate settings, combination of parameter values and number of repetitions for the parameter combinations is done by the procedure of Kleppmann [Kle08] described in section 4.2.2. Each configuration definition consists thereby of three steps: First the identification and definition of the command variables and the cause variables, second the setting of the factorial design and third the estimation of the required number of realizations. During this process, limitations to the process parameters due to the machine, material or tool properties have to be respected. The resulting designs of experiments are shown in appendix C.
4 Model validation and analysis

Parameter identification measurement

To simulate the energetic behaviour of a machine tool, the applying process forces have to be known or estimated. According to the process model, described later in section 3.3, the specific cutting force $k_{1,1}$ and the increment factor $z$ are required as parameters. This parameters are specific for any cutting tool to work piece combination. One possibility to get this information would be to take the parameters from available literature [Per06]. This would lead to a first incertitude within the model. To identify all possible error source, the real parameters have to be known. In order to identify these parameters, a set of force measurements is taken under adequate circumstances. To do so, the command variables are chosen to be the forces along the x, y and z-axis. This forces can directly be measured by the dynamometer mounted on the revolver. According to [KV57], the cutting force $F_c$ for a given wrought material and tool combination is described by

$$F_c = b \cdot h^{1-z_c} \cdot k_{c,1}, \quad (4.3)$$

for a chip remove over length $h$ with thickness $b$. The forces applying on the x and z-axis can be described similar, see thereto section 3.3. The parameters $k_{c,1,1}$ and $z_c$ are material and tool specific, further the use of cooling fluid can have an influence. However, the wrought material and tool are always the same. To establish repeatable results, a new cutting insert edge is used for every cut and all cooling fluid is applied at every cut. The remaining two parameters in (4.3) – $h$ and $b$ – are dependent of the depth of cut $a_p$, the feed rate $f$ and the cutting speed $v_c$. This variables have thereto be chosen as the set of cause variables.

In the next step, the factorial design of the cause variables has to be defined. As shown in section 3.3, $b$ depends on the depth $a_p$ of the cut and $h$ depends on the feed rate $f$. In order to identify the parameters $z$ and $k_{1,1}$, a variation of the parameter $h$ – and thereto $f$ – is essential. This conclusion can be made by taking the calculations from section 4.2.4: If one formulates a least squares problem on (4.3) to identify the mentioned parameters, the result would be as stated in (4.6) and can be solved by (4.9). As one can see, the matrix $H^T \cdot H$ becomes singular if all measurements are taken at the same feed rate $f$, and thereto same chip dimension $h$. Since a matrix inversion of $H^T \cdot H$ is required, the identification of the requested parameters becomes impossible with the configuration of a constant feed rate. For the cutting depth – and thereto for $b$ – no problems occur, if the parameter is kept constant. Concluding from this analysis, the process parameter feed rate is varied over the measurements, where the cutting depth is held constant. Given by the expertise of the responsible laboratory engineer, a cutting speed of 100 m/s is chosen. This is mainly due to the hardness of the wrought part. For the same reason, the feed rate is kept in the lower range. For the feed rate the values 0.10, 0.12, 0.18, 0.20 mm/rev are selected. The cutting depth is limited by the 0.8 mm corner radius of the cutting insert from the lower, and by the hardness of the wrought material and the highest feed rate from the upper. From this limitations, a cutting depth of 1.2 mm is selected. Summarizing this considerations and conclusions, the factorial design shown in table 4.6 results.

To set the number of repetitions for each measurement, the accuracy of the measurement system is relevant. The relation between the applying force and the generated charge by the piezoelectric modules is given by the manufacturer as a linear correlation [Kisa]. This signal is converted to a voltage signal with a certain error. Given by [Kish], this error is in the region of $\pm 0.3\%$ for charges above 100 pC. The dominant forces are expected to be in the direction of the cutting force and to be in the range of some hundred newtons. For a conservative estimate of 800 N cutting force, the dynamometer would generate a charge of $-6320$ pC, which has an error of $\pm 0.3\%$. Assuming a normal distribution of the errors, a variance of $\sigma = 1.2$ N can be estimated. According to (4.3) and the given feed rates in table 4.6, the process forces will vary over the configurations with smallest and largest feed rates by the factor...
Table 4.6: Factorial design for the parameter identification measurement; including the system identification number (SID), the cutting depth \(a_p\), the feed rate \(f\) and the cutting velocity \(v_c\). Further, cutting fluid (CF) is used for all systems.

<table>
<thead>
<tr>
<th>SID</th>
<th>(a_p) [mm]</th>
<th>(f) [mm/rev]</th>
<th>(v_c) [m/min]</th>
<th>CF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2</td>
<td>0.10</td>
<td>100</td>
<td>yes</td>
</tr>
<tr>
<td>2</td>
<td>1.2</td>
<td>0.12</td>
<td>100</td>
<td>yes</td>
</tr>
<tr>
<td>3</td>
<td>1.2</td>
<td>0.18</td>
<td>100</td>
<td>yes</td>
</tr>
<tr>
<td>4</td>
<td>1.2</td>
<td>0.20</td>
<td>100</td>
<td>yes</td>
</tr>
</tbody>
</table>

\[
\left( \frac{h_{\text{max}}}{h_{\text{min}}} \right)^{1-z} = \left( \frac{f_{\text{max}}}{f_{\text{min}}} \right)^{1-z} \approx 1.6.
\] (4.4)

Stated by Klepmann [Kle08], the number of realizations in order to identify a change \(\Delta y\) in the command variable of a measurement-set is given by (4.2). The variance \(\sigma\) of the measured forces is estimated above. We further know, that the forces will vary by the factor 1.6. To see a change between all measurements, \(\Delta y\) has to be chosen dependent on the minimal expected force:

\[
\Delta y \approx \frac{1}{N_{\text{fact}}} \cdot (F_{\text{max}} - F_{\text{min}}) = \frac{0.6}{4} \cdot F_{\text{min}}
\] (4.5)

The minimal force is expected to occur along the x-axis and being in the size of 20 N, which leads to \(\Delta y = 3\) N. Inserting all this information into (4.2), results in three realizations of the factorial design in table 4.6. The full measurement configuration is shown in appendix C.1.

**Energy model validation measurement**

In order to validate the electro-mechanical model, a suitable set of measurements is required as well. This measurement must include the applying forces and power demands of the components and the machine. By comparing the measurement results to the simulated values, conclusions about the correctness of the model dynamics and the precision of the calculated values can be made. One has to differ between two questions which have to be answered:

- Is the negligence of components made during the system and machine modelling feasible?
- Are the simplifications in the derived models feasible and do the simulated components represent the relevant dynamics and obey the demanded precision?

To answer these questions, two types of measurements are required. A first type, which focuses on the dynamics and power demand of single neglected components under certain conditions. The components and conditions have thereby to be chosen according to the assumptions made in chapter 3. The second type of measurements has to capture the power demand of all modelled components and the total power demand of the machine over a time span of significant length. Where a time span of significant length has to be long enough to include also the slow dynamics, such as the switch on/off of components due to thermal conditions. In the following, the measurements of the first types are called *machine simplification validation measurements*, where the second type are called *model validation measurements*.
Staring with the first type of measurements, which have to investigate the power demand contribution of components neglected in chapter 3: The simplifications made include the negligence of the tool revolver, the part clamping with compressed air and the tail-stock. All other assumptions – such as neglected acceleration power for drives – are component model specific, and thereto part of the model validation measurements. For none of the three components a measurement during chipping is requested.

The assumption for the revolver is, that no significant contribution to the total energy demand is created during the tool change by rotating the revolver. As mentioned, the servo motor driving the revolver is supplied with a brake. So three interesting revolver dynamics exist: revolver position fixed by the brake, acceleration of the tool platform and constant rotational speed. To investigate the power consumption during all three described situations the revolver is rotated over one and three positions. Due to the installed measurement equipment and cables rotations over more than three positions are not desired. The direction of rotation is further switched after each rotation. This results in four measurement systems: Rotation over one and three position, each counter clock-wise and clock-wise. In order to identify irregularities in the measurement, each system is repeated three times, resulting in the measurement configuration shown in table C.2.

As for the revolver, for the clamping of the tool a negligible amount of power is assumed. To check this assumption, the closing and opening of the clamp on the main drive is measured. Thereto the clamp is opened and closed, while holding each position for 30 seconds, in order to identify possible difference in the measurement. There exist two measurement systems: First opening the clamp, second closing the clamp while clamping a part with a diameter of 42 mm. Again, each system is repeated three times, resulting in the measurement configuration of table C.3.

For the last point, the tail-stock, it is up to measure the power needed to realize a desired clamping force. This value can be used, to check if the tail-stock power has still to be included in the machine model. To do so, the tail-stock is closed with different clamping forces. From [Sch99a] one knows the operational range of the tail-stock to be between 1000 and 5500 newtons. Over this range, five clamping forces are selected for the measurements. Instead of repeating the configuration, the clamping force is applied over sixty seconds to ensure enough measurement points. Again the configuration is shown in appendix C, table C.4.

In difference to the machine simplification validation measurements described above, the measurements for the model validation have no focus on a specific component situation, but have to capture the power demand of all modelled machine components during different machining operations. The control and power level of some components depend on the thermal state of the machine. Even if the thermal behaviour of the machine is not in the focus of this measurement, the time constants of the thermal sub-systems have to be regarded during the set-up of the measurements. This procedure is required to have measurements of the different power levels for all components. Starting with this information, the minimum length of the measurement can be estimated. The critical component is thereby the spindle cooler compressor, which is switched on and off at certain cooling fluid temperatures. The fluid is heated by the spindle and pump losses, where the pump is running as soon as the machine is turned on. Taking the efficiency of the pump as 15% and the heat flow to the fluid as 30% of the total pump heat loss, a temperature rise of $2.6 \text{ mK/s}$ results. The temperature delta between the switch off and switch on temperature is 4 K. With the given temperature rise, thirty minutes would be requested to have a temperature raise of required delta. This calculation does not include heat losses to the environment, which would extend the requested time to heat the fluid. Thereto a measurement time of at least one hour is requested.

Similar as for the Kienzle parameter identification, cuts of equal cutting speeds shall be taken. Again the same limitations on feed rate and cutting depth are valid as above. To avoid taking measured data for the model validation under similar condition as the data for the parameter identification, an other measure-
4.2 Measurements

<table>
<thead>
<tr>
<th>SID</th>
<th>$a_p$ [mm]</th>
<th>$f$ [mm/rev]</th>
<th>$v_c$ [m/min]</th>
<th>CF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>0.15</td>
<td>100</td>
<td>yes</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>0.15</td>
<td>100</td>
<td>yes</td>
</tr>
<tr>
<td>3</td>
<td>1.2</td>
<td>0.15</td>
<td>100</td>
<td>yes</td>
</tr>
<tr>
<td>4</td>
<td>1.4</td>
<td>0.15</td>
<td>100</td>
<td>yes</td>
</tr>
<tr>
<td>5</td>
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<tr>
<td>6</td>
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<tr>
<td>7</td>
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<td>0.15</td>
<td>100</td>
<td>yes</td>
</tr>
<tr>
<td>8</td>
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<td>100</td>
<td>yes</td>
</tr>
<tr>
<td>9</td>
<td>2.4</td>
<td>0.15</td>
<td>100</td>
<td>yes</td>
</tr>
<tr>
<td>10</td>
<td>2.6</td>
<td>0.15</td>
<td>100</td>
<td>yes</td>
</tr>
</tbody>
</table>

*Table 4.7: Factorial design for the model validation measurement.*

ment set has to be created. The resulting factorial design is shown in table 4.7. With the given cutting speed and feed rate, the time to make a cut of 40 mm length at a diameter of 30 mm is about fifteen seconds. Having additional tasks – as the change of the cutting insert – between the measurements requiring two minutes time, one ends with a total time of 135 seconds per cut measurement. For the factorial design with ten systems, a time of 1350 seconds would be required. To realize the requested measurement time of one hour, three realizations of the factorial design are chosen. The resulting measurement configuration can be seen in table C.5.

**Thermal long time measurement**

Thermal time constants of machine tools are in general much larger than the ones of the electro-mechanical systems. It is thereto recommended, to use a large time horizon [ISO01, Annex C]. Further, a series of operation cases must be considered: Warm-up, leading to steady state, followed by a process where the largest heat flows occur. After the process, steady state is reached again, until cool-down of the machine takes place after switch-off. During the process, a significant amount of heat loss by the spindle is desired, in order to see the relevant thermal effects. To satisfy the demand of long measurement horizons and different operational cases, four measurement windows are defined:

- **Warm-up for 3 hours**: The machine is switched on at steady state, the goal is to identify the time constants of the warm-up process of the machine. The internal heat sources heat the machine up.
- **Process during 2 hours**: Operate the machine, such that the heat loss of the spindle can be estimated. The biggest heat release inside the machine must occur now, which allows the short measurement window of two hours.
- **Idle run during 5 hours**: Record the behaviour of the machine if no load is applied. During this time, the machine is still thermal stabilized.
- **Cool-down for 7 hours**: Switch off by the main switch and cool-down of the machine by free heat exchange with the ambient.
For the cool-down and the warm-up, only the time constants are of interest to validate the model. A record until steady state is thereto not required, which allows to avoid long measurements. For the other two operational conditions, not only the time constant, but the whole cycle of temperature gain by heat losses and cooling by the compressor is of interest. This explains, why the measurement horizons have been chosen over several hours, even if the internal heat sources of the process and the components reduce the time constants.

To produce a lot of heat release inside the spindle, an operational point with high losses is required. Thinking about frictional or ohmic losses, high speeds and high currents are ideal. High currents can of course be realized by high torque demand. The highest torque demands occur during the acceleration of the drive. The simplest way to produce a torque demand with a high average value, is to accelerate the spindle to a high speed, and change the rotational direction as soon as the speed is reached. Since this procedure is not a realistic scenario, the ISO radial roughing cycle $G74$ is used [DIN83, ISO09, Sch99a]. Doing so, the part is accelerated during the cut and decelerated while the tool moves back in rapid advance. With this procedure, the desired acceleration and deceleration is realized.

The measurement configuration for the thermal long time measurement consists of four parts: First the warm-up of the machine after the main switch as been turned on. Followed by two hours of constant machining, using the ISO roughing cycle. After, the machine is left without operation to reach steady state. Finally the main switch is turned off, and the cool-down is tracked. The complete measurement configuration and the machine programming can be seen in chapter C.

4.2.4 Measurement analysis

In the following lines, the results of the measurements described in the last section will be evaluated and analysed if requested. This steps is limited to the operations required to prepare the collected data for the model validation and analysis. As the temperature measurement has already an output in the form requested for the validation, no additional procedure is needed. The situation is different for the parameter identification measurement. One is not interested by the raw data, but in the resulting parameters for the Kienzle process model. The procedure of calculating the parameters out of the measurements by statistical methods is explained below. Additional analysis is also required for the model simplification validation measurement. Since only the power demand of a certain component under defined conditions is of interest, the required data is extracted from the measurements.

Parameter identification measurement

As shown in section 3.3, the Kienzle model of the cutting force requests two parameters – specific cutting force $k_{i1,1}$ and the increment factor $z_i$ – for each direction $i \in \{c, f, p\}$. This results in six parameters to be identified in total. In the following section, the force measurement will be used together with statistical methods to identify the requested six parameters. To calculate the parameters out of a single measurement, we have to bring (3.4) into an appropriate form. For each measurement $m$ and force direction $i$ we can do the following transformation of the Kienzle equation:
4.2 Measurements

\[ F_{m,i} = b_m \cdot h_m^{1-z_i} \cdot k_{i1.1} \]

\[ F_{m,i} = b_m \cdot h_m^{1-z_i} \cdot k_{i1.1} \]

\[ \log \left( \frac{F_{m,i}}{b_m \cdot h_m} \right) = -z_i \cdot \log h_m + \log k_{i1.1} \]

The force measurement \( F_{m,i} \forall m, i \in \{c, f, p\} \) are thereby defined as the mean measured force during the corresponding measurement in the specific direction. Performing some reshape on the last line, one can write the equation above in matrix form:

\[
\log \left( \frac{F_{m,i}}{b_m \cdot h_m} \right) = \begin{bmatrix} y_1 \\ \vdots \\ y_N \end{bmatrix} = H \cdot \pi_m
\]

\[ H = \begin{bmatrix} -\log h_1 & 1 \\ \vdots & \vdots \\ -\log h_N & 1 \end{bmatrix} \]

\[ \pi_m = [z_i, \log k_{i1.1}]^T \]

With the definition of the set of unknown parameters \( \pi \) as \( [z_i, \log k_{i1.1}]^T \), (4.6) is linear in parameters (LIP). Solving (4.6) for all measurements will lead to a \( \pi_m \) for each measurement. We know define \( \bar{y}, \bar{e} \) and \( H \) for all \( N \) measurements as

\[
\bar{y} = \begin{bmatrix} y_1 \\ \vdots \\ y_N \end{bmatrix}, \quad \bar{e} = \begin{bmatrix} e_1 \\ \vdots \\ e_N \end{bmatrix}, \quad \text{and} \quad H = \begin{bmatrix} -\log h_1 & 1 \\ \vdots & \vdots \\ -\log h_N & 1 \end{bmatrix},
\]

such that

\[
\bar{y} = H \cdot \pi - \bar{e}.
\]

The target is now to chose \( \pi \) with the aim to minimize the statistical expected error \( E(\bar{e}^T \cdot \bar{e}) \) by taking \( \pi_m = \pi \forall m \). Assuming and error \( e_m \) for each measurement, with \( e \sim N \). Minimizing the sum of all squared errors \( e_m \) will lead to a least squares problem. The solution for \( \pi_{LS} \) of the least squares problem is thereby know as

\[
\pi_{LS} = (H^T \cdot H)^{-1} \cdot H^T \cdot \bar{y}.
\]

At this stage, the Kienzle parameters can be calculated out of \( \pi_{LS} \) as

\[
z = \begin{bmatrix} 1 & 0 \end{bmatrix} \cdot \pi_{LS} \quad \text{and} \quad k_{11.1} = \exp \left( \begin{bmatrix} 0 & 1 \end{bmatrix} \cdot \pi_{LS} \right).
\]

To evaluate the identified parameters, the correlation coefficient \( r \) is used [Kle08]. This coefficient expresses, the fitting of the identified linear expression of the measured value on the actual measurement. The correlation coefficient is thereby defined as

\[
r = \sqrt{\frac{\text{corr}(H \cdot \pi, \bar{y})^2}{\text{corr}(H \cdot \pi, H \cdot \pi) \cdot \text{corr}(\bar{y}, \bar{y})}}.
\]

where \( \text{corr}(a, b) \) is the cross-correlation between \( a \) and \( b \). The results of this parameter identification can be seen in table 4.8. As one can see, the correlation coefficient is above 0.97 for all directions. The
4 Model validation and analysis

<table>
<thead>
<tr>
<th>Direction</th>
<th>$k_{1,1}$</th>
<th>$z$</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting</td>
<td>1768 N/mm²</td>
<td>0.31</td>
<td>0.97</td>
</tr>
<tr>
<td>Feed</td>
<td>610 N/mm²</td>
<td>0.63</td>
<td>0.98</td>
</tr>
<tr>
<td>Passive</td>
<td>462 N/mm²</td>
<td>0.51</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Table 4.8: Results of the Kienzle parameter identifications for all three directions. Further the correlation coefficient $r$ is shown.

Figure 4.1: Double logarithmic plot of the process forces and the chip dimension $h$. The measurements are plotted as crosses (+), where the Kienzle approximation is drawn as solid line. The units of $F_i$ is newton and millimetres for $h$.

The passive force shows an outlier, where the feed and cutting force estimation fit quite well with the measurement. This observation is confirmed, by the correlation coefficients discussed above. Comparing the identified parameter values to literature, one finds for the cutting force the Kienzle parameters $k_{c1,1} = 2178$ N/mm² and $z = 0.26$ [Per06, tab.3.6-2]. The difference is obvious, and shows the importance of the parameter identification instead of using the values from literature. If the literature values would be used, a relative error in the force calculation of about 25% would be introduced.

Energy model validation measurement

The measurement analysis of the model simplification measurement will focus on the power measurement of the reviewed components compared to the total power demand. The results of this analysis must allow a conclusion later in the validation, if the component is negligible or not. The model simplification measurement include measurements focusing on the revolver, the part clamping and the tail-stock. Rotating the revolver by one or multiple positions shows the following power demand: The mean power demand during the rotation is in the same size as the sum of the constant consumers, which is about 500 W. Compared to other electric drives, no power peaks due to high acceleration occur. Continuing the analysis for the part clamping, an average power by compressed air of 0.35 Wh for one clamping procedure and 0.13 Wh for clamp opening is found. It must further be remarked, that during the time where a part is clamped additional 30 Watts power by compressed air are consumed. The last analysis concerning the model simplification measurement is the tail-stock. Using a linear approximation to describe the relation between servo motor power $P_{Z3}$ and clamping force $F_{cl}$, the following description results:
4.3 Simulations

In order to compare the model with the measurements, simulations of the same processes as during the measurement have to be done. In total, two simulation sets are required: One for the electro-mechanical model validation and one of the thermal model validation. The validation of the electromechanical model requires only one simulation case, where the thermal validation requires one for warm-up, process, idle and cool-down, four in total. Each simulation case consists of simulation settings, a machine state sequence and a process file. The simulation settings include thereby the desired step size for the simulation and the required initial states for the thermal model. The step size is for all cases chosen to be one second. Setting the initial conditions requires the use of the measurements. By reading the temperature of the investigated component at the time of the simulation start, the initial conditions is given and shown in table 4.9. For all cases, the cooling coil in the spindle is assumed to have the same temperature as the spindle body.

In the machine state sequence, pairs of machine states and holding times are listed. Starting with the first pair, each machine state will be applied for the corresponding holding time. In the current state of development, the framework does only allow one process definition per simulation case. The single cuts done in the measurement can thereto not be implemented as different processes. Moreover, the time from the first to the last cut during the measurement must be implemented as one single process file. One has now to separate strictly between the machine states defined in section 4.1 and the machine states used in the framework. The first are used for the evaluation, where the later are used for simulation control. Since the process file is only used in the framework when the simulation state is set to PROCESS, this simulation state applies during the whole time between the first and the last cut. Analysing the simulation data with respect to the defined operational states in the context of section 4.1, time spans of Ready and Standby can be identified. Because some components have a state specific power level, all information about components close to the process are included in the process file. This components are the chip conveyor, the cutting fluid pump and the brakes for the axes. This information outsourcing leads to compact machine state series.

Using the information from the measurement protocol, the following machine state sequence can be

<table>
<thead>
<tr>
<th>Simulation case</th>
<th>$\vartheta_{tank}$</th>
<th>$\vartheta_{spindle}$</th>
<th>$\vartheta_{coil}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>El.-mech</td>
<td>301.5 K</td>
<td>301.5 K</td>
<td>301.5 K</td>
</tr>
<tr>
<td>Thermal: warm-up</td>
<td>295.9 K</td>
<td>295.8 K</td>
<td>295.8 K</td>
</tr>
<tr>
<td>Thermal: operation</td>
<td>302.2 K</td>
<td>303.0 K</td>
<td>303.0 K</td>
</tr>
<tr>
<td>Thermal: idle</td>
<td>303.8 K</td>
<td>305.0 K</td>
<td>305.0 K</td>
</tr>
<tr>
<td>Thermal: cool-down</td>
<td>303.5 K</td>
<td>303.5 K</td>
<td>303.5 K</td>
</tr>
</tbody>
</table>

Table 4.9: Initial conditions for all simulation cases. All conditions are for the thermal model of the spindle cooling cycle.

$$P_{el,Z3} = 0.04 \frac{W}{N} \cdot F_{cl}$$ (4.12)
4 Model validation and analysis

derived for the *electro-mechanical model validation simulation*:

1. **# Duration, Machine state**
2. **# [s]**
3. 30, READY;
4. 8950, PROCESS;

Similar for the four simulation cases for the *thermal model validation simulation* can be defined as following. One remark has to be done on the short *Process* state duration at the begin of some measurements: Due to a bug in the actual version of the framework, initialisations of components are not done correctly until the first time the machine goes into *Process*. This short time durations are only a workaround due to the actual circumstances.

**Thermal: warm-up**

1. **# Duration, Machine state**
2. **# [s]**
3. 1, PROCESS;
4. 780, OFF;
5. 9000, READY;

**Thermal: operation**

1. **# Duration, Machine state**
2. **# [s]**
3. 6366, PROCESS;

**Thermal: idle**

1. **# Duration, Machine state**
2. **# [s]**
3. 1, PROCESS;
4. 19660, READY;

**Thermal: cool-down**

1. **# Duration, Machine state**
2. **# [s]**
3. 1, PROCESS;
4. 500, READY;
5. 24130, OFF;

If machine state is *Process*, the process file will be used in order to provide the model with information needed for the process simulation. As mentioned above, the whole time between the first and the last cut is defined as process time. This has to be done, since the framework supplies only one process definition per simulation case. In this case, the process file looks like this:

```xml
<properties>
  <entry key="SamplePeriod">0.2</entry>
  <entry key="X1_d">...</entry>
  <entry key="X1_ap">...</entry>
  <entry key="Z1_y">...</entry>
  <entry key="X1_v">...</entry>
  <entry key="C1_n">...</entry>
  <entry key="AxisBrakeCtrl">...</entry>
  <entry key="LabFlow">...</entry>
  <entry key="ChipConv">...</entry>
</properties>
```

Spaces indicated with dots are filled with the process specific data series of the corresponding signals. The *SamplePeriod* gives thereby the time in seconds between two successive points in the data series, which forces all data series to have the same time vector. Following a short explanation of the signals: Basically, two groups can be made. One containing all process signals, the other the control signals for the auxiliary devices. The process is described by the diameter at the point of cut (*X1_d*), the cutting depth (*X1_ap*), the rotational speed of the spindle (*C1_n*) and the velocities performed by the x and z axis (*X1_v* and *Z1_v*). The signals to the auxiliary devices are the boolean signal of the servo brake control (*AxisBrakeCtrl*), the cutting fluid flow in litres per second (*LabFlow*) and the boolean signal to the chip conveyor (*ChipConv*). The boolean signals indicate if the corresponding component is running (true) or off (false). In the context of the brakes, running means closed brakes.
4.4 Model validation

For all signals, based on the measurement protocol, a value vector and individual time vector has been created. For the sake of completeness, the overturn operations mentioned in the measurement protocols are also included. Using functions implemented in Matlab, a unique time vector with constant sample period based on the signals individual time vectors has been created. Using a simple ZHO element, the value vectors for each signal are interpolated to the new time vector. The result is a series of signal vectors of equal length and sample time.

Given the model and the parametrisation for the Schaublin 42L, together with the simulation configurations, two simulation sets with five simulation cases are implemented in the framework:

- Electro-mechanical model validation simulation
- Thermal model validation simulation
  - Case 1: Warm-up
  - Case 2: Operation
  - Case 3: Idle
  - Case 4: Cool-down

Each simulation set provides data, which is comparable with the two measurement series electro-mechanical model validation measurement and thermal model validation measurement. This data series is used together with the measured, to validate the model and analyse its errors.

4.4 Model validation

The aim of the following section and procedure is to compare the data calculated in the simulation with the data taken by measurements. For a perfect model, which includes ideal system equations and perfect matching parameters, the two data series would match completely. Concerning the models derived during this work, all significant difference compared to the measured data have to be identified. This will be done, by plotting the two data series for all components next to each other. Having located the interesting deviations of the simulated data from the measured data, one has to conclude, if the models sustains the demanded precision and includes all relevant effects. Talking about the demanded precision, we talk about an relative error. If certain modules – especially constant consumers – are not modelled, their contribution to the relative error will strongly depend on the total power demand. Since dependent on the task running and the operational state applying on the machine, the total power can change by a factor seven (see figure 4.6), the contribution of component errors can vary significant. The validation of the model is thereto done, using the concept of the machine states discussed in the begin of this chapter.

4.4.1 Process force model

The drive power required by the machine depends on the process forces. In order to separate errors caused by the force model, from errors introduced by the drive power calculation, the process model will be validated. To calculate the force for a given turning process, a Kienzle approach is used as discussed. The forces are thereby dependent on the feed rate and the cutting depth, which leads to constant forces for a constant process. In reality, vibrations, chips and other influences cause the force to vary during a cut. The question is now, if the force model is able to represent the relevant effect and sizes of the applying forces. Do do so, the relative error distribution as shown in figure 4.2 is used. The simulated
force $F_s(t_i)$ is thereby compared to the measured force $F_m(t_i)$, by building the relative error defined as

$$e(t_i) = \frac{F_s(t_i) - F_m(t_i)}{F_m(t_i)}.$$  (4.13)

Where the set of the $N$ available measurement times is given as $T = \{t_i \mid \forall \ i = 1 \ldots N\}$. Since the time vectors are different for both data series, interpolation of the simulation data to the time vector of the measurement data is required first. After, the error can be calculated by the state formula. Using this error deviation over time, the error distribution is calculated. This distribution gives information about the size of the relative errors and the time during which they occur. For the analysis, one has also to include the absolute values of the forces, in order to estimate the impact on the total power.

Starting with the most dominant force, the cutting force: This force is in the range of $500 - 1200$ N, and has a mean relative error of 8.3%. Looking at the error distribution in figure 4.2(c), one can see, that 90% of the time, the calculated force has a deviation from the measured force of less than $\pm 15\%$. This refers to an absolute error of 180 N. Taking the feed force, which is in the range of $300 - 800$ N, a mean relative error of 1.2% occurs. Where 80% of the time the error is less than $\pm 10\%$ of the measured value. Important is the bulge in the error distribution in the region of $-40\%$ relative error. Looking at the measured feed force, one can see peaks in the force during the acceleration of the axis. This peaks occur due to the inertia of the measurement platform on the revolver. With $180 - 450$ N, the feed force has the smallest contribution to the total force applying on the tool. But, as shown in figure 4.2(a), it has also the most significant relative error. The source for this spreading of relative error is located in the diameter of the wrought part. The cuts, even for the same cutting parameters, have been done at different diameters of the wrought part. In the measurement configuration, the order of the realizations has been chosen such, that the cuts are taken at different diameters. As the diameter of the wrought part affects the passive force, the error distribution of the simulated passive force can be explained. Anyhow, the absolute error is in the worst case still smaller than the absolute error on the cutting force.

From the discussion and validation above, the biggest error source is within the calculation of the cutting force. Even if the passive force shows the larger relative errors, the absolute error occurring at the cutting force is still dominating the one of the passive force. Since the mechanical power is the product of speed and force, the power caused by the cutting force and spindle rotational speed will be dominant. This conclusion can be made by comparing the product of force and speed for all three directions. Based on this estimation, one has to expect relative errors in the process power calculation of 8%.
4.4 Model validation

In order to validate the electro-mechanical model, two points of view are requested. First, the validation of each component, where the consumption and behaviour of the components are compared to the measured one. The second step is the comparison of the total energy demand calculated by the model, compared to the one measured at the line filter of the machine. For both steps, the used tools are relative error calculations and graphical plotting of the data series. The graphical exposition of the data series is used to identify relevant dynamics in the measurement and compare them to the simulated data series, where the relative error calculation is used to check the compliance of the demanded relative error. This procedure has to answer the two questions

1. Does the model represent the relevant physical behaviour of the machine and its components?
2. How good is the behaviour represented?

Starting with the first question, the representation of the relevant dynamics. An cut-out of the measurement and the simulation showing the aggregated power of the machine components is shown in figure 4.3. Components with a constant consumption are shown hat the bottom, where components with variable power level are plotted higher in the stack. For the constant consumers – compressed air and cooler pump – the discussion of the relevant dynamics is obsolete. Components with dynamics exist five in total. Two of them have a discrete number of power levels, namely the chip conveyor and the cutting fluid pump. The correctness of the dynamic of this components depends on the process configuration, which makes a discussion under the current question needless. The spindle cooler compressor has also only two power levels, but its operation state depends on the temperature in the cooling fluid tank. The correctness of the switch time between these two levels depends on the validation results of the thermal model which is done in section 4.4.3.

For the dynamic of the compressor, the difference during start-up stands out: The measured compressor power shows a peak as the compressor is switched on. After, the power approaches from approximately

---

**Figure 4.3**: Power consumption of the components during measurement (left) and simulation (right). The data is taken out from the measurement described in section 4.2.3 and relates to the measurements with IDs 13 and 14 in table C.5

4.4.2 Electromechanical model
eighty percent nominal power the full nominal power. This transient behaviour can be described by a first order element with a time constant of about 25 seconds. The relevance of this difference has to be discussed in the following error calculation and interpretation. Remaining are the control/brake power and Fanuc power to be evaluated. As it can be seen in figure 4.3(a), the control/brake power has three power levels: A first one during Standby, a second one when the state changes to Ready and the axes brakes are opened, and a third one during Process. This state changes can be seen at 4750 seconds and 4775 in the named figure. Identifying this dynamics in the simulation plot figure 4.3(b) fails partly, since one can only identify two power level: One during Standby and the other one during Ready and Process. The relevance of this difference has to be quantified in the error analysis. Looking at the Fanuc power, we are talking about the sum of the spindle and axes consumptions. The measurement shows three power levels superposed by short peaks. The power levels relate to the three situations run trough during a process: First, the axes are controlled, then the spindle is accelerated and turned with no load, followed by the tool being in contact with the wrought material. The named peaks occur during the acceleration of the spindle or the axes. Looking now at the simulation, the same three power levels can be identified, but the peaks are missing. This has been expected due to the model simplifications described in section 3.4.2. Again, the impact of this simplification demands further analysis.

Summarising the first validation part above, three differences in the dynamics of the simulation compared to the one of the measurement can be identified: First, the dynamic of the compressor at switch-on, second a missing power level in the control/brake power and third, the high power peaks due to accelerations in the Fanuc power.

The next step is to validate the precision of the model. As mentioned above, this is done by discussing the relative and absolute error in power demand during the different operational states. To do so, the following definition is used: Given a measurement $P_{meas}[k]$ and a simulated power $P_{sim}[k]$ over $N$ time steps, two key values are used to validate the model. This are the relative error $e[k]$ and the absolute error $\Delta P[k]$, where

$$e[k] = \frac{P_{sim}[k] - P_{meas}[k]}{P_{meas}[k]} \quad \text{and} \quad \Delta P[k] = P_{sim}[k] - P_{meas}[k], \quad k = 1 \ldots N. \quad (4.14)$$

Again, the simulation data series have to be interpolated to the time series of the measurements. The relative error is used to evaluate the size of the error, where the relative error is used to quantify the impact to the total error of the simulation. For each operational state, the relative and absolute error time series can be calculated by (4.14). But instead of the resulting time depended error series, this state specific series are averaged over time resulting in $\bar{e}$ and $\bar{\Delta P}$ for each state. This is done, in order to produce comparable key values for each operational state. Together with the analysis of the relevant dynamics above, the mean error calculation is used to decide whether or not the created model is valid for the desired application and demanded precision.

The total energy demand over time with the corresponding operational states is shown in figure 4.4. As one can see, there exists an error between the sum over all simulated and measured component powers. Further an offset between the measured power at the line filter and the sum over all measured components exists. This is due to components which have not been measured separately. Analysing this offset, the distribution of the absolute error is a helpful tool: During Standby and Ready, more than 75% of the time, the absolute error is in the range of $-320 \pm 10$ W. During Process, still 40% of the time, the absolute error is in the mentioned range. Concluding from this analysis, a constant error of 320 W is identified. This difference comes from constant consumers, which are not measured separately. The caused relative error due to this constant consumers is in the size of $-70\%$ during Standby, $-40\%$ during Ready and less than $-10\%$ during Process. Validating the simulated model by using the total electric energy demand measured at the line filter of the machine, the demanded error bound of $\pm 20\%$ could not be satisfied
4.4 Model validation

![Graph showing power demand over time](image)

**Figure 4.4:** Total power demand for turning with different cutting depths. The sum of the simulated components is shown as solid red line, where the sum over the measured components is shown as dashed line (---). The measured electrical energy demand at the line filter is plotted as a dotted line (⋯). In the lower section of the figure, the operational state – as defined in section 4.1 – is plotted over the time.

In any state, but during *Process*. This error comes not from a misleading model dynamic, but from not modelled components or consumers.

Going one step deeper than the total electric power demand, one is looking at the components power demands. The goal is now to identify the differences between the measurement and the simulation of single components as relative error, and discuss if the error cause can be assigned to one of the differences in model dynamics identified above. Additionally, parametrization errors have to be respected. To do so, the components will be split into three groups. The first group consists of the components which have a constant consumption over all operational states. The other two groups include the components with varying power levels: The members of the second group have power levels which can not be allocated to an operational state, where members of the third group have a characteristic power level for each operational state. With this arrangement the following group allocation results:

- **Constant consumers:**
  - Compressed air
  - Spindle cooling pump
- **Thermal state dependent consumers:**
  - Spindle cooling compressor
- **Machine state dependent consumers:**
  - Control / break power
  - Chip conveyor
  - Cutting fluid pump
For the first group, the relative error calculation can be done for the whole simulation time in one step, where as the error calculation for the third group is done for each operational state. The second group – components with varying power levels, independent from operational state – special evaluations are requested.

Starting with the evaluation of component group one, the components with constant consumption over all operational stages. The results of the error calculation is show in table 4.10. As one can see, both power consumptions are underestimated, resulting in an error of $-1.5\%$ for the compressed air and $-0.8\%$ for the spindle cooling pump. Both relative error demands are in the same dimension as the expected measurement tolerance. Further analysis of parametrisation errors is thereto not possible. As discussed above, the two components have no significant dynamics over time to be discussed. The error source for the two component can thereto be reduced to errors due to defective model parametrization.

As mentioned, the spindle cooling compressor has a power level dependent on the temperature development of the cooler tank. A state specific error evaluation must be done with caution, because the component might be running over different machine states. Further the switch times are not dependent on the machine states. Looking at the whole simulation time of 2.5 hours, the compressor switches on two times, during the measurement as in the simulation. A comparison of the mean power can therefore be done in this case, without any disturbance due to the thermal model. Doing so, a mean error of 2 W results. This corresponds to a mean relative error of $-16.5\%$. Given the size of the relative error, the difference in dynamics mentioned above can be seen as negligible compared to the errors introduced by misleading switching times.

Doing the same analysis for the components with operational state specific power levels, the errors shown in table 4.10 result. As one can see, the component control/brake power shows a large relative and absolute error. During standby state, this error is in the rage of 30% of the total power demand. As illustrated in figure 4.3 and discussed in the validation of the dynamics, the only difference in the power progression of the simulation compared to the measurement is during the process. Anyhow, this difference is to small to explain the total difference and the constant offset during all operational states. The error in the control/brake power requests further analysis, which will be done in the following section.

Among the remaining three components, the cutting fluid pump and the Fanuc power are interesting due to their high power demand. During Standby and Ready, only the Fanuc is consuming power while supplying the amplifiers and drives. The simulation underestimates the power demand by about 80%. Reasons for this error have to be analysed in the following section. During the Process, the relative error shrinks down to 1%. This error is in the range of the measurement error, and requests no further analysis. During the Process the cutting fluid pump is simulated with an relative error less than 1%. Again, this error requests no further analysis due to the estimated measurement errors.

Summarizing the discussed error calculation results, the error over the sum of all components is in the range of $-1.5\%$ during the Off state, arround 15% during Standby and Ready, and about $-1.5\%$ during the Process state. The model holds thereby the demanded precision of 20% relative error, with respect to the sum of components power demand. Looking at the total energy demand measured at the line filter, the model fails the demanded error tolerance during Standby and Ready.
4.4 Model validation

<table>
<thead>
<tr>
<th>Component</th>
<th>OFF</th>
<th>STANDBY</th>
<th>READY</th>
<th>PROCESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed air</td>
<td>−1.5% (−5 W)</td>
<td>−2.1% (−8 W)</td>
<td>−1.4% (−5 W)</td>
<td>−1.2% (−4 W)</td>
</tr>
<tr>
<td>Spindle cooling pump</td>
<td>−</td>
<td>−0.8% (−1 W)</td>
<td>−0.8% (−1 W)</td>
<td>−0.7% (−1 W)</td>
</tr>
<tr>
<td>Spindle cooling compressor</td>
<td>−</td>
<td>−</td>
<td>overall: −16.5% (−2 W)</td>
<td>−</td>
</tr>
<tr>
<td>Control/break power</td>
<td>−</td>
<td>−29.0% (−86 W)</td>
<td>−25.0% (−83 W)</td>
<td>−27.9% (−100 W)</td>
</tr>
<tr>
<td>Chip conveyor</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>7.4% (16 W)</td>
</tr>
<tr>
<td>Cutting fluid pump</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>1.5% (23 W)</td>
</tr>
<tr>
<td>Fanuc total power</td>
<td>−</td>
<td>−59.9% (−1 W)</td>
<td>−84.0% (−90 W)</td>
<td>−1.2% (−11 W)</td>
</tr>
<tr>
<td>Sum of el. components</td>
<td>−1.5% (−5 W)</td>
<td>−13.2% (−108 W)</td>
<td>−17.0% (−173 W)</td>
<td>−1.6% (−56 W)</td>
</tr>
<tr>
<td>Line filter input</td>
<td>−</td>
<td>−52.3% (−391 W)</td>
<td>−49.0% (−475 W)</td>
<td>−11.1% (−387 W)</td>
</tr>
</tbody>
</table>

Table 4.10: Results of the error calculations for all simulated machine components. Shown are the mean relative error $\bar{e}$ and the mean absolute error $\Delta P$ in brackets. During the Off state, none of the components above has a power consumption, but the compressed air supply. The compressor power is not state specific, but happens to be non-zero mostly during Standby.

4.4.3 Thermal model

As for the electro-mechanical part of the model, the thermal part is validated by using two steps: First the identification of the relevant dynamics, and second the discussion of the precision given by the model. The goal of the validation is, to show if the idea and appliance of a generic thermal model to a machine tool works. As done above, the discussion is done by comparing the simulated data with the measured data. Measurements of temperature have been done at various place in and on the machine as explained in section 4.2.3. Within the model, the cooling system of the spindle is modelled as shown in section 3.7. In total two relevant temperature measurements exist: The spindle and cooling tank temperatures. The simulated temperature of the spindle is thereby the temperature inside the spindle, next to the cooling coil; where the measurement of the spindle temperature is on the other hand taken on the surface of the spindle housing. Because of this difference, the cooling fluid tank temperature is taken for the model validation. Both temperatures – the simulated and the measured – can be assumed to be at the same location. Discussing the temperature development of the spindle cooler tank will include the thermal machine states introduced in the begin of the section. To do so, a simulation scenario has been set up for each thermal state, where the initial temperatures have been set to the same as in the measurement. The measurement and results of the four simulation can bee seen in figure 4.5.

Staring with the most trivial thermal state: Cooldown. During this state, only free heat transfer over the walls of the tank influence the temperature. As it can be seen in figure 4.5, the simulated temperature follows the measured temperature with an offset, but with the same dynamics. The dynamic is given by the implemented physical model of a homogeneous thermal storage combined with the model for a free heat transfer. The offset of the model compared to the measurement can be substantiated by errors in the selected parameters.

Continuing with the cases Warmup and Idle: During both thermal states, the thermal losses of the cooling fluid pump form an additional heat flow. As it can be seen, this heat flow causes the tank content to be heated up. Two main characteristics stand out: First the complete different short time dynamic and second the similar frequency during Idle. The first point is clearly the manifestation of a model error. The difference of the states Warmup and Idle, compared to Cooldown – where the model dynamics matched –
Figure 4.5: Simulated (–) and measured (--) temperature of the spindle cooling fluid in the tank. The time scale is compacted for some thermal states to fit into the graphic.

is the running pump. The heat flow due to pump losses takes place by material transport, which has in this case the faster time constants as the convection and conduction of the free heat transfer. The temperature has been measured at one location in the tank: at the top, where the backlash enters the tank. For the model, a constant temperature over the entire tank is assumed. So the simulation shows the average tank temperature, where the measurement shows the a mixture between tank and backlash temperature. The demanded condition of a homogeneous temperature is not satisfied under these conditions, which leads to the difference in short time dynamic. Where the long time is characterized by the net thermal energy brought to the fluid, leading to the switch times of the compressor due to the temperature of the cooler. As already mentioned, the switch frequency simulated is in the same range as the one measured.

Looking at the Operation state, the same differences in model dynamic occur as already discussed. Investigating at the switch frequency of the measurement, one gets an average of 0.91 mHz compared to a simulated switch frequency of 0.85 mHz. This results a relative switch frequency error of −6.5%. One has to be aware of the feedback cycles in the thermal part of the model. Since the heat flow by the cooler is determined by the tank temperature and vice versa, errors can be amplified. This is manifested in the different time constants mentioned above. Because the model shows large differences in the short time behaviour compared to the measured temperature, a detailed error analysis is obsolete. Summarising the results from the thermal model validation, two main points must be mentioned: First, the model is not able to represent short time thermal dynamics. Second, long time dynamics are modelled within a tolerated error band.

4.4.4 Conclusion of the model validation

In the last three sections, the errors of the process model, the electro-mechanical model and the thermal model of the spindle cooling have been discussed. This results have now to be compared and discussed to decide whether or not the model is valid for the desired approach. As shown above, the mean relative error of the mechanical process power due to the force model is in the range of 8%. Since the Fanuc power shows a relative error of −1.6% during Process, the total relative error introduced by the motor and amplifier models is in the range of −10% during Process. For the component point of view, the demanded precision could not be satisfied for the control/brake power during all states and for the Fanuc
4.5 Model analysis
during *Standby* and *Ready*. The total power demand as sum of components fulfills the desired maximum relative error limit. But only during *Process* the criterion is met when looking at the total machine power at the line filter. Regarding the temperature development of the spindle cooler tank, the following conclusion is made: The thermal subsystem model is only capable of representing the long time thermal behaviour. For conclusions about the component temperature at arbitrary instants of time, the model is not qualified for.

Concluding on the validation of the model, the desired precision is only met under certain circumstances. The errors and problems just described have to be investigated in the following section, to conclude if the errors are caused by parametrization or by model errors. Further information for the conclusion about portability of the model has to be provided.

4.5 Model analysis

Continuing from the validation results, additional information about the model will be derived during the analysis. The focus is thereby on the parameter influence and the identification of errors. The gained inside will be used to evaluate the use of the simulation framework with respect to the criterion formed in the requirements [Lan12]. As it has been shown in the past section, the simulation results show certain deflections compared to the measurement results. With respect to the specification on the precision of the simulation results, the model for the turning machine is valid for certain situations only. The question is now, how the generalisation of this results to other machines or component combinations is limited. The three main error sources have already been discussed during the validation: Errors due to non ideal parameters, due to simplifications in the modelled physics and due to feedback in the model leading to deviations in the time constants. The first error type occurs in all components, where the second type is characteristic for the drives. The third error type can bee seen in the thermal model. It has to be investigated how this three effects influence the simulation result.

In order to answer the question above, three steps are used. First a parameter sensitivity analysis to evaluate the influence of the components parameters to the simulation results. Doing so, the determination of parameter errors can be focused on parameters which errors have a significant influence to the total results. The second step consists of an error analysis. During this analysis, the contribution of the different error sources to the absolute errors identified during the validation shall be determined. The last step includes an analysis of the model topology. Thereby, feedback loops inside the model will be investigated and analysed. Beside the analysis, the methodologies applied to the model ans simulation results are explained. The results gained during the analysis together with the validation conclusion will form the base for discussion of the results in the following chapter.

4.5.1 Parameter sensitivity

The selection of parameters for the model can influence the simulation result significant. In order to quantify the errors due to parameter errors, the influence of each parameter to the total result is required. During this process, the *elementary effects method* (EE) [SRA±08, Fra76, Dei86] is used. This sensitivity analysis describes the influence of changes on a single parameter $\pi \in \Pi$ to the total power $P$. The total power $P$ is thereby a function of the parameter-set $\Pi$. This evaluation is done at a nominal set of parameter values $\Pi_{ref}$. The non-normalized sensitivity for a given function $P(\Pi)$ and parameter $\pi \in \Pi$ at the point $\Pi_{ref}$ is given by the partial derivative by the parameter [SRA±08, p14f]:

\[
\frac{\partial P}{\partial \pi} \bigg|_{\Pi_{ref}}
\]
To compare sensitivities of different parameters, the sensitivity $S_p^P$ has to be normalized. This is done here by the sensitivity function after Horowitz [Fra76, p47]. The weighting factor is thereby the parameter value dividend by the function value $P(\Pi_{ref})$. The resulting sensitivity function is

$$S_\pi(\pi) = \left. \frac{\partial P}{\partial \pi} \right|_{\Pi_{ref}} \cdot \frac{\pi_{ref}}{P(\Pi_{ref})}.$$  \hspace{1cm} (4.16)

As one can see, the sensitivity is described by the local gradient of the $|\Pi|$-dimensional hyperplane $P(\Pi)$, where $|\Pi|$ is the cardinality of $\Pi$. Normalization is done by the fraction between the local parameter value and the local value of $P$. The sensitivity term describes the degree of changes in the power demand $P$, for relative changes in the parameters from $\Pi$. The parameter sensitivity analysis, as defined in (4.16), shall investigate the influence of the component parameters to the calculated power. From figure 4.6, one sees, that during the different operational states the mean power varies significant. Further, the relative contribution of each component to the total power demand varies over the states. The analysis of the parameter sensitivity will thereto flow the classification of the operational states and evaluate the parameters of the components with the largest contribution to the total power demand. The trivial state Airoff is not shown in figure 4.6. During this state no power or resource is consumed either in the measurement nor in the simulation, which makes an analysis obsolete.

Starting with the most energy demanding state, the Process, where all components, but the spindle cooler compressor are force to operate. Of course, the operation of this compressor is partly dependent on the machine state due to the different heat releases. Nevertheless, the contribution to the total energy demand is marginal, which makes the negligence of the component reasonable during this analysis. The components with the most power demand are the cutting fluid pump, the Fanuc, the compressed air and the transformer for control/brake power. This sum of component powers can be described by

Figure 4.6: Average power during the different operational states. The measurement is shown on the left, the simulation results on the right. The trivial case Airoff, where the average power is zero, is not shown.

$$S_p^P(\pi) = \left. \frac{\partial P}{\partial \pi} \right|_{\Pi_{ref}}$$  \hspace{1cm} (4.15)
4.5 Model analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sensitivity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal cutting fluid pump power</td>
<td>$P_{cfpump,nom}$</td>
<td>0.38 1.5 kW</td>
</tr>
<tr>
<td>Spindle efficiency</td>
<td>$\eta_{C1}$</td>
<td>-0.36 0.75</td>
</tr>
<tr>
<td>Spindle amplifier efficiency</td>
<td>$\eta_{amp,C1}$</td>
<td>-0.36 0.9</td>
</tr>
</tbody>
</table>

Table 4.11: Results of the parameter sensitivity analysis after (4.16), with the given parameters for the process state. The table is not complete, only the three parameters with the most significant sensitivity are shown.

$$P_{process} = P_{cfpump} + P_{fanuc} + P_{ctrlbrk} + P_{cair} + P_{var},$$

(4.17)

where the component power demand are given by the models:

$$P_{cfpump} = P_{cfpump,nom}$$

(4.18)

$$P_{fanuc} = \frac{T_{C1} \cdot \omega_{C1}}{\eta_{amp,C1} \cdot \eta_{C1}} + P_{ax}$$

(4.19)

$$P_{cair} = c_{p,\text{air}} \cdot \vartheta_{\text{amb}} \cdot \left[ \left( \frac{p_{\text{supply}}}{p_{\text{amb}}} \right)^{\gamma - 1} - 1 \right] \cdot \rho_{1} \cdot v_{cair}^{*}$$

(4.20)

$$P_{ctrlbrk} = P_{brk,X1} + P_{brk,Z1} + 2 \cdot P_{fan} +$$

$$+ P_{ctrl,amp,C1} + P_{ctrl,amp,ax} + P_{ctrl,amp,Z3} + P_{ctrl,amp,B1}$$

(4.21)

Power used to drive the axes over the Fanuc are summarized in the term $P_{ax}$. Using the axis, servo motor and amplifier models, one could derive the whole term. But as seen above and in other measurements, the contribution of the axes are minimal. In figure 4.4, one has seen a constant difference between the sum of all measured components and the power measured at the line filter. This difference is included here by a constant consumption $P_{var}$. The parameter set $\Pi$ contains all parameters used in the equations above, plus $P_{var}$. For the operational point $\Pi_{ref,process}$, the following process specific parameters have been chosen:

$$T_{C1} = 15 \text{Nm}, \quad F_{Z1} = 500 \text{N}, \quad F_{X1} = 250 \text{N}, \quad \omega_{C1} = 800 \text{rpm}, \quad v_{Z1} = 2 \text{mm/s}$$

(4.22)

Using this values and the component specific parameters defined in section 3.7.3 and the nominal values defined above, the sensitivity $S_{\pi}$ can be calculated for all $\pi$ from $\Pi_{process}$. The result of the sensitivity calculation of the most significant parameters during the Process state is shown in table 4.11. Parameters shown in (4.22) are not drawn here, if they are process specific. It can be seen, that the nominal power of the cutting fluid pump shows the highest parameter sensitivity, followed by the power supply chain of the spindle. To improve the model during the Process state by reducing the parameter errors, one should focus on the cutting fluid pump nominal power and the spindle/amplifier efficiency maps.

Continuing the analysis for the Ready state, where the compressed air, the brake/control power, the spindle cooler pump and the Fanuc have the most significant power demand. The total power demand can be described by the sum of the components above, plus the constant consumption $P_{var}$ representing the various constant consumers which are not modelled or measured separately. This results in the following power balance:
4 Model validation and analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sensitivity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed air flow</td>
<td>( \dot{V}_{\text{cair}} )</td>
<td>0.31 ( \text{l/s} )</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>( \vartheta_{\text{amb}} )</td>
<td>0.31 ( \text{K} )</td>
</tr>
<tr>
<td>Various constant consumers</td>
<td>( P_{\text{var}} )</td>
<td>0.29 ( \text{W} )</td>
</tr>
<tr>
<td>Compressed air pressure</td>
<td>( P_{\text{supply}} )</td>
<td>0.22 ( \text{bar} )</td>
</tr>
</tbody>
</table>

Table 4.12: Results of the parameter sensitivity analysis after (4.16), with the given parameters for the ready state. The table is not complete, only the four parameters with the most significant sensitivity are shown.

\( P_{\text{ready}} = P_{\text{cair}} + P_{\text{ctrlbrk}} + P_{\text{ctrlbrk}} + P_{\text{coolerpump}} + P_{\text{fanuc}} + P_{\text{var}} \). \hspace{1cm} (4.23)

Where the component power demand are given by the models (4.20), (4.21) and the following equations:

\[
P_{\text{coolerpump}} = P_{\text{cfpump,nom}} \hspace{1cm} (4.24)
\]

\[
P_{\text{fanuc}} = P_{X1} (k_{X1} \cdot g \cdot \sin (\alpha_{X1}) \cdot m_{X1}) \hspace{1cm} (4.25)
\]

The power demand of the Fanuc is described by the therm \( P_{X1}(T) \), by witch the power to realize the torque \( T \) by the x-axis servo is calculated. This torque is here the one used to compensate the remaining gravitational forces. For the ready state, no process definition is required. Following the calculation of the sensitivity, table 4.12 results. Leaders of the list are the compressed air volumetric flow \( \dot{V}_{\text{cair}} \) and the ambient temperature \( \vartheta_{\text{amb}} \). The next in line is the constant consumption \( P_{\text{var}} \) of various small components. Also included in the line are the compressed air supply pressure \( P_{\text{supply}} \). Improvements of the parametrization during the Ready state should be made by analysing the compressed air path and optimizing the constant consumption.

Next in line is the Standby state. In difference with the previous state, the axes are not any more in control. The most significant contribution to the total power demand comes now from the compressed air demand, the spindle cooler pump and the control/brake power. Again, the total power demand is estimated by summing the named components power demands up:

\( P_{\text{standby}} = P_{\text{cair}} + P_{\text{coolerpump}} + P_{\text{ctrlbrk}} + P_{\text{var}} \). \hspace{1cm} (4.26)

Where the component specific power demands are given in (4.20), (4.21) and (4.24). Performing the sensitivity analysis on \( P_{\text{standby}} \) for all parameters included in the formulas, the values in table 4.13 can be calculated. The results are very similar to those of the sensibility analysis performed during the Ready state. As for this state, the compressed air path includes the parameters with the highest sensibility. Further the influence of constant consumers is significant.

The sensitivity analysis for the last case is trivial: Because the compressed air power is the only component running during the Off state, the power demand can be described by

\( P_{\text{off}} = P_{\text{cair}} \). \hspace{1cm} (4.27)

where \( P_{\text{cair}} \) is calculated as in (4.20). The sensitivity analysis on the three controllable parameters gives the results shown in table 4.14. Of course, the compressed air path parameters are dominating, since the only power demand is by compressed air flow.
### 4.5 Model analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sensitivity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed air flow</td>
<td>$V_{cair}$</td>
<td>0.39</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>$\vartheta_{amb}$</td>
<td>0.39</td>
</tr>
<tr>
<td>Various constant consumers</td>
<td>$P_{var}$</td>
<td>0.36</td>
</tr>
<tr>
<td>Compressed air pressure</td>
<td>$P_{Supply}$</td>
<td>0.27</td>
</tr>
</tbody>
</table>

**Table 4.13:** Results of the parameter sensitivity analysis after (4.16), with the given parameters for the standby state. The table is not complete, only the four parameters with the most significant sensitivity are shown.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sensitivity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed air flow</td>
<td>$V_{cair}$</td>
<td>1.00</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>$\vartheta_{amb}$</td>
<td>1.00</td>
</tr>
<tr>
<td>Compressed air pressure</td>
<td>$P_{Supply}$</td>
<td>0.71</td>
</tr>
</tbody>
</table>

**Table 4.14:** Results of the parameter sensitivity analysis after (4.16), with the given parameters for the Off state.

Summarizing the results of the sensitivity analysis for all machine states above, the following critical parameters can be identified. The labeling *critical* refers thereby to the influence of potential parameter errors to the simulation results. In the case of the machine model of the *Schablin 42L* with the given parametrization and process parameters, the critical parameters are the volumetric flow of compressed air $V_{cair}$ and the ambient temperature $\vartheta_{amb}$ over all states. During the states where the electric part of the machine is running, the sum of the various constant consumer $P_{var}$ is also critical, as the efficiencies $\eta_{C1}$ and $\eta_{amp,C1}$ in the spindle supply chain become relevant in the *Process* state.

#### 4.5.2 Error sources identification

During the validation, different error types have been characterized. Two of them are: Errors in dynamics due to model errors and offsets between the simulation and the measurement due to non-ideal component parameters. The aim is now, to assign the absolute error, calculated during the model validation, to the discussed error types. Single component errors may therefore be divided into multiple parts, if they are caused by multiple error types. During the investigation of the parameter errors, the results from the section above – the sensibility analysis – will be used. The results of this identification and analysis shall be used to qualify the components and the machine models for further application. Additionally, a guideline for the further used of the model, in order to minimize models errors, shall be created. To keep the analysis within a meaningful range and focus thereby on the main errors, a selection of components and parameters to focus on is done first. Taking the validation and parameter sensitivity analysis from above, the following selection is made:

**Fanuc** During the *Process* state, the power demand of the *Fanuc* is one of the most significant. Further, the efficiencies $\eta_{C1}$ and $\eta_{amp,C1}$ which influence the power demand of the *Fanuc* are identified as parameter with a high sensitivity.

**Control / brake power** The biggest absolute error over all active machine states occurs at this model part. Since the absolute error is in the same range over all states, an additional investigation is mandatory.
**Various consumptions** As discussed in the validation, the various consumptions, which are not measured separately and not modelled, sum up to 320 Watts. Under certain machine states, this contribution to the total energy demand becomes crucial in order to satisfy the ±20% relative error limitation.

**Process model** The identification of the Kienzle parameters has been done using a separate set of measurements, that has been used for the model validation. As the process model is at the begin of the component models chain, errors have an impact on all downstream calculations.

Staring with the component *Fanuc*: As identified during the validation, special model dynamics occur during the acceleration and deceleration of the controlled drives. The resulting peaks in the power demand are not modelled and cause thereto a difference between the measured and simulated *Fanuc* power demand. The component has the highest average power level during the *Process* state. As show by the sensitivity analysis, the parameters $\eta_{C1}$ and $\eta_{\text{amp},C1}$ – representing the spindle drive and amplifier efficiencies – show high sensitivities. Both parameters belong to component models, which are part of chain resulting in the *Fanuc* power demand. The following analysis will thereto focus on the investigation of the influences of the non-modelled power peaks dynamics and the two efficiencies $\eta_{C1}$ and $\eta_{\text{amp},C1}$.

Analysing first the influences of the power peaks to the total energy demand. To estimate the energy consumed due to the power peaks, the measurement with peaks shall be compared to the measurement where the peaks have been removed. To do so, the measured signal is compared to a filtered version of the same signal. The average error during a state $S$ is given as

$$
\bar{e}_S = \frac{1}{N_S} \cdot \sum_{i \in K_S} \frac{P_{\text{filt}}[k_i] - P[k_i]}{P[k_i]},
$$

where $P$ and $P_{\text{filt}}$ are the measured and filtered power data series. This is done over all time steps with the state $S$, such that $N_S = |K_S|$ and $K_S = \{k | \text{state}[k] = S\}$. Performing this calculation for all states where peaks occur, the following values are retrieved:

$$
\bar{e}_\text{standby} = -18\%, \quad \bar{e}_\text{ready} = -78\%, \quad \bar{e}_\text{process} = -3\%
$$

Comparing this values to the values shown in table 4.10, the following observations can be made. First, the component error of $-84\%$ during calculated during the *Ready* state fits on the error of $-78\%$ due to peaks during *Ready*. Second, the relative error of the component *Fanuc* for the state *Standby* is one dimension bigger than the calculated errors due to peaks. Third, the errors during *Process* state are for the component error and the peak errors in the same region. But one has to include the error of the process model, which causes errors in the size of $8\%$ on the cutting force. For the state *Ready*, most of the model error can be explained by the neglected peak dynamics. The situation is different fot the *Standby* and *Process* state, where additional explanations are required.

The *Fanuc* model consist of the axes, drives and amplifier models. Since the axes contribution is marginal, the axis model is not included in the following discussion. For a constant operational point, the motor and amplifier models are both linear. An error in the calculated process force causes thereto a proportional error in the calculated power demand. With the estimated mean error for the *Fanuc* model during *Process*, an error in the range of $-10\%$ caused by the *Fanuc* model has to be explained. Including the errors due to the neglected peak dynamic, still $-7\%$ relative error remain. Analysing therefore the second error source: miss-fitting parameters. As mentioned above, the focus will be on the motor and amplifier efficiencies due to the results of the parameter sensitivity analysis. Given a mechanical spindle power $P_{\text{mech}}$, the resulting *Fanuc* power can be approximated by

$$
P_{\text{Fanuc}} \approx \frac{P_{\text{mech}}}{\eta_{C1} \cdot \eta_{\text{amp},C1}}.
$$
This approach neglects the power demand for the x and z-axes, which are anyway one dimension smaller than the spindle power. During the measurement, only the process forces and the Fanuc power demand have been measured. Without the measurement of the spindle electrical power demand, it can not be differed whether an error occurs in the spindle or amplifier efficiency maps. For the following analysis, a combined efficiency map will thereto be used. This efficiency map can be estimated by combining the maps for the spindle and for the amplifier available in the model. Since the mechanical power can be calculated from the force measurement, the real efficiency can be calculated by dividing the mechanical power by the measured Fanuc power. Plotting both values, the estimated and the real one, the distribution shown in figure 4.7 results. Using the power demand as weights, a mean relative error of about 6% exists. Errors in the efficiency maps are inverse proportional to the resulting errors in power demand. Thereto an error of about $-6\%$ in the Fanuc power demand due to miss-parametrized efficiency maps is expected.

Summing the results from above up, the following conclusions are made: First, the errors of the Fanuc model during Ready can be explained by the model error of the missing peaks. Second, the most significant errors during the Process state are primary caused by parametrisation errors in the Kienzle model and the efficiency maps, and secondary by the neglected peak dynamics. And third, the error during Standby can not fully be explained by model and parametrisation errors. With an absolute mean error of $-1$ W the priority in the error analysis is not given.

Continuing the analysis with the two remaining electrical components: Control/brake power and various consumers. The transformer for the control and brake power which is measured here, does also supply the DC converter of the machine. Similar as for the line filter, more modules are supplied with electrical power than are actually measured separately. Both components show a static error over all operational machine states. This errors can easy be corrected, by adding the constant consumers which are not modelled yet. For the control/brake power component, this consumer is called DC consumption $P_{DC}$, due to the connected and not modelled AC/DC converter. A similar constant consumer named various consumption $P_{var}$ is introduced to represent the various small constant consumers at the line filter, which are not modelled now. The derivation of this values has already been discussed in section 4.4.2, which
4 Model validation and analysis

has resulted in the following values:

\[ P_{DC} = 83 \text{ W} \quad \text{and} \quad P_{var} = 320 \text{ W} \quad (4.31) \]

Using this values for the constant consumers, an reduction of the relative error for the component control/brake power and the line filter is expected. For the first component, this reduction is expected to be in the size of 25%. For the second component, a reduction between 9% and 40% dependent on the machine state can be estimated.

As already mentioned during the analysis of the Fanuc model, errors are introduced by the process model. For the dominant cutting force, the mean relative error is about 8%, which can not be neglected. Again, two error sources exist: Model and parameter errors. Model errors might be non-linearities and secondary effects as vibrations, which are not covered in by the Kienzle approach. Repeating the parameter identification of section 4.2.4, but including the force measurements of the electro-mechanical validation measurement leads to the following parameters:

\[ k_{c1.1} = 1648 \frac{N}{mm^2} \quad \quad z_c = 0.32 \]
\[ k_{f1.1} = 618 \frac{N}{mm^2} \quad \quad z_f = 0.63 \]
\[ k_{p1.1} = 330 \frac{N}{mm^2} \quad \quad z_p = 0.60 \]

Comparing this results to the parameters shown in table 4.8, differences in the cutting and passive force parameters can be seen. Repeating the simulation with the new parameters, the mean errors in the cutting and feed force are reduced to less than 3%, where the passive force mean error is now 8%. Comparing this values to the errors before the optimization, the improvement in relative error is about 60%. This result has to be read carefully, since the parameter identification has been done with the same measurement set as the error calculation. Under real circumstances, the identification of parameters for the test case is only conditionally possible.

Summary of the error identification  During the identification of the error sources, the four components listed in the begin of this section have been analysed. By using the information given by the validation and the sensitivity analysis, the analysis has been focused on the model parts and parameters which have a significant influence on the final calculated power demand. Including the gathered parameters and constant consumers improvements in a new simulation, the mean errors as shown in table 4.15 result. The changes compared to the validated model are the following:

1. Kienzle parameters optimized on the reference measurement
2. Spindle-amplifier combined efficiency map corrected by 6% as calculated above
3. Constant DC consumer added for the control/brake power model.
4. Introduction of a constant consumer \( P_{var} \), representing the sum of all minor constant consumer on the machine connected to the line filter.

As one can see in table 4.15, certain parts of the model have been improved by the additional parameter information. The reduction of the relative error at the line filter below ±20% for all machine states, can only be achieved by the introduction of the constant consumer \( P_{var} \). Similar for the component control/brake power, where the additional consumer \( P_{DC} \) has been introduced. The relative mean error is know below 4% for all machine states. The combination of Kienzle parameter improvement and efficiency map optimization shows only a small improvement in the relative error during Process. But,
4.5 Model analysis

<table>
<thead>
<tr>
<th>Component</th>
<th>OFF</th>
<th>STANDBY</th>
<th>READY</th>
<th>PROCESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed air</td>
<td>−1.4%</td>
<td>−2.1%</td>
<td>−1.4%</td>
<td>−1.2%</td>
</tr>
<tr>
<td>Spindel cooling pump</td>
<td>−0.8%</td>
<td>−0.8%</td>
<td>−0.7%</td>
<td></td>
</tr>
<tr>
<td>Spindel cooling compressor</td>
<td>−</td>
<td>−0.4%</td>
<td>0.3%</td>
<td>−4.0%</td>
</tr>
<tr>
<td>Control/break power</td>
<td>−</td>
<td>−0.4%</td>
<td>0.3%</td>
<td></td>
</tr>
<tr>
<td>Chip conveyor</td>
<td>−</td>
<td>−</td>
<td></td>
<td>7.6%</td>
</tr>
<tr>
<td>Cutting fluid pump</td>
<td>−</td>
<td>−</td>
<td></td>
<td>1.5%</td>
</tr>
<tr>
<td>Fanuc total power</td>
<td>−</td>
<td>−97.8%</td>
<td>−84.5%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Sum of components</td>
<td>−1.4%</td>
<td>−2.4%</td>
<td>−9.5%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Line filter input</td>
<td>−</td>
<td>2.4%</td>
<td>−8.7%</td>
<td>1.2%</td>
</tr>
</tbody>
</table>

Table 4.15: Results of the error calculations for all simulated machine components with optimized parameters. Shown are the mean relative error $\bar{e}$ and the mean absolute error $\Delta P$ in brackets.

including the error of the force calculation, which is about 2.5% for the cutting force, an error of about −3% remains for the spindle and amplifier model, compared to the −9% of above. This error is below the measurement tolerance, and requests no further analysis.

As already mentioned, the huge mean error during the Ready state of the Fanuc is explained by the neglected peak dynamic. In difference with the Process state, where huge forces occur and the contribution of the peak energy becomes secondary, the peak energy during the Ready state has a dominant characteristic compared to the energy demand for the axes control. The precision of the model components depends there-to significant on the application.

4.5.3 Model topology

As in a real machine tool, the components used to model the test-bench machine are affected by other components, while taking influence on downstream components. Dependent on the model topology, couplings in series or even circles can be produced. Within this circuit, errors are transmitted from one component model to an other. Dependent on the model, these errors are amplified by the following components in the line. In order to analyse this phenomena over the model, the influence and the interference of the components in the model have to be quantified. In the past analysis of the parameter sensitivity on the total power, it has already be seen, that the results are machine specific. In the following lines, a method will be presented and used to analyse the connections between the components. The goal is thereby to introduce a methodology of model topology analysis, which can be used on further implementations on the framework; and use the results of the methodology applied on the current model to complete the analysis of this work.

The requirements on the methodology is the capability of a qualitative description of the interaction between the model’s components. A methodology which fulfils this requirement, is the Papiercomputer developed by Gomez and Probst [GP87]. The task is thereby to identify relevant states of the model, and there influences to the other states. The influences are mapped on a scale from zero to three, where zero means no influence and three means a big influence. The authors further define the terms active sum and passive sum; the active sum $AS$ of a component is the sum of all quantified influences the component takes on others, while the passive sum $PS$ is the sum of all quantified influence of other
components affecting the current one. It must be remarked, that no feedback of a component to him self is considered in this method. In [GP87] further terminology is used, which includes characteristic factors resulting from a combination of the active and passive sum. Doing so, the information of influence and interference is mixed, which is not useful for the current application. Thereto, the modification of the method described in [ZS03] will be used. This modification starts with with the active and passive sum, and introduces the limit $L$

$$L = \frac{AS}{N} = \frac{PS}{N},$$

(4.32)

where $N$ is the number of components. With this limit, a classification of the components is possible. To do so, the terms active, passive, critical and dull are defined, where each of them defines a set of components. Each component $C_j$ belongs thereby to one and only one of this sets. The sets $S_i$ are further defined as:

$$S_{\text{active}} = \{ C_j \mid AS_j \geq L \land PS_j < L \}$$

$$S_{\text{passive}} = \{ C_j \mid AS_j < L \land PS_j \geq L \}$$

$$S_{\text{dull}} = \{ C_j \mid AS_j < L \land PS_j < L \}$$

$$S_{\text{critical}} = \{ C_j \mid AS_j \geq L \land PS_j \geq L \}$$

(4.33)

Active components have a big influence, and are affected only a little by other components, where passive components are the opposite. Critical components have both, big influences to others and big interference from other components. The danger of an unstable feedback cycle is high, thereto the name critical. Dull components have whether big influence nor are affected much by the other components. The values $AS$ and $PS$ are now used to express the influence and interference.

Applying this methodology to the current model, an identification of the states is required first. As known, the model consists of two parts with two state sets: The thermal part and the electro-mechanical part. The state set includes here all electro-mechanical components and the three temperatures of the ambient: The cooler tank and the spindle. As additional influences, the machine state and the process are added. The complete list is shown in table 4.16. The connections between the component are now quantified, where the display of [GP87, p.24] is used. This notation expresses the influence of each state to the others by $I \in \{0, 1, 2, 3\}$, where zero stands for no and three for a most significant influence. To do so, the results from the simulation and the sensitivity analysis are used. It is further assumed, that all electric components with losses have an influence on the ambient air. Completing the analysis with the calculation of $AS$ and $PS$, table 4.16 results. Building the four introduce component sets, the categorisation as illustrated in figure 4.8 is gained.

Analysing the results in figure 4.8 leads to the following conclusion: The set of active components are the machine state and the process. Since this are the control inputs, it obvious that this states have a big influence on the other system parts. Auxiliary devices with small or constant consumption are classified as dull. This components have no significant influence nor are effect by other components, why no further analysis is requested. Compressed air demand and the drive power by the Fanuc are both components which are moderate affected by other components. Anyway, the compressed air power is classified as a passive component, where the classification of the Fanuc is not ambiguous. Looking at the three temperatures: All have a large passive sum value, which indicates a big interference compared to other components. The ambient temperature is even a critical component and the cooler tank temperature is on the border from passive to critical. As discussed in the validation, the thermal model shows significant difference in the temperature development of the cooler tank compared to the measurement. As it can be seen by this analysis, the temperatures are states with high interference. Small errors in the parametrisation can have a big influence, and can even be amplified in the thermal model over the time.
4.5 Model analysis

<table>
<thead>
<tr>
<th>Influence of ↓ on →</th>
<th>Machine state</th>
<th>Process</th>
<th>Process energy</th>
<th>Fanuc power</th>
<th>Cooling pump energy</th>
<th>Spindle temperature</th>
<th>Cooler tank temperature</th>
<th>Ambient temperature</th>
<th>Cutting fluid pump</th>
<th>Chip conveyor</th>
<th>Control/brake power</th>
<th>Compressed air</th>
<th>Total electric power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine state</td>
<td>MS</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Process</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Process energy</td>
<td>PE</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fanuc power</td>
<td>FP</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Cooling pump energy</td>
<td>CP</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Cooling compressor energy</td>
<td>CC</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Spindle temperature</td>
<td>TS</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cooler tank temperature</td>
<td>TC</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>TA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Cutting fluid pump</td>
<td>CF</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Chip conveyor</td>
<td>CV</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Control/brake power</td>
<td>CB</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Compressed air</td>
<td>CA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total electric power</td>
<td>TOT</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Interference</td>
<td>PS</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Influence</td>
<td>AS</td>
<td>16</td>
<td>14</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 4.16:** Appliance of the paper computer methodology of [GP87] on the model. The state set and the introduced acronyms are explained on the left. Further the resulting limit $L$ as defined in [ZS03] is shown.
Figure 4.8: Result of the component categorisation by the method described in [ZS03]. The acronyms and set limit of $L = 5.9$ are taken from table 4.16.
Results and Discussion

In the past two chapters, specifications and model implementations for the EMod framework have been derived and used to model the test-bench machine. This models have been validated and analysed using measurements taken on the test-bench machine. In the following chapter, the created results will be summarized and discussed. Further, the results are compared to the goal of this work, especial to the list of requirements by M. Lang [Lan12].

5.1 System modelling and implementation

Regarding the results of the system modelling first. Those are the implemented physical component models, the created parameter files and the machine model of the test-bench machine in the framework. In the following discussion, this results are compared to the requirements by Michael Lang. The requirements are tested to be satisfied. If not so, the reasons and possible solutions are discussed. To do so, the requirements are split into two parts: First the required set of machine components, second the ideal model specification. Additional, the possibility of adding information to an existing model during the development process, as animated by Professor Wegener, has to be discussed.

For the system modelling, a specification has been derived. This specification represents the list of requirements on the level of the model. A very important specification is the design of generic elements, in order to guarantee the desired flexibility and modularity. To do so, a generic component is defined as a unique combination of input and output ports. Each port has thereby a name and a unit. All components with the same set of inputs and outputs are of the same generic type. New components must be assigned to a generic type. If not possible, the creation of a new generic type has to be discussed. Comparing the derived list of generic components to the list of required components by Lang [Lan12, chp.4], most of the components are congruent. Differences, as the missing hydraulic or pneumatic aggregate, are due to the definition of generic components. Characterizing the components by their interfaces, both have to supply other modules with a mass flow at a certain pressure, while consuming energy. From this point of view, these components are of the generic type pump. Of course, the physical component models
### Table 5.1: List of the required machine components by [Lan12] and the generic components by which they are realized.

<table>
<thead>
<tr>
<th>Required component</th>
<th>Generic component</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle Control</td>
<td>Motor</td>
<td>various can be realized by an amplifier or over simulation settings, constant components or control elements</td>
</tr>
<tr>
<td>Axe</td>
<td>Linear axis</td>
<td>only translational</td>
</tr>
<tr>
<td>Cooling</td>
<td>Heat exchanger</td>
<td></td>
</tr>
<tr>
<td>Filtration</td>
<td>Constant consumer</td>
<td></td>
</tr>
<tr>
<td>Chip conveyor</td>
<td>Constant consumer</td>
<td></td>
</tr>
<tr>
<td>Compressed air</td>
<td>Compressed air</td>
<td></td>
</tr>
<tr>
<td>Dust collection system</td>
<td>Fan</td>
<td></td>
</tr>
<tr>
<td>Hydraulic aggregate</td>
<td>Pump</td>
<td>consisting of a pump, hysteresis controller and tank</td>
</tr>
<tr>
<td>Pneumatic aggregate</td>
<td>Pump</td>
<td>same as hydraulic</td>
</tr>
<tr>
<td>Pump</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hyd./Pneum. components</td>
<td>Hydraulic</td>
<td>only translational</td>
</tr>
<tr>
<td>Transmission</td>
<td>Transmission</td>
<td></td>
</tr>
</tbody>
</table>

will be different. Other components with discrete power levels, such as chip conveyors, can be modelled by a constant consumption. The complete comparison of the generic types and the required component models can be seen in table 5.1. Given by the defined set of generic components, the required set of components is covered. For all types, except for the hydraulic/pneumatic elements, at least one physical model has been derived. Further the idea of models adaptable with new informations and system models can be realized by using the concept of generic components. Since by following the guide line of generic components, a certain machine component in the model can be exchanged by a component of the same generic type. The new type could for example be a more detailed physical model.

Continuing with the accord of the system modelling and the ideal specification by M. Lang. Some points of the specification are already fulfilled or not part of this thesis. This concerns the following points: The concept of machine configuration and IO-connections is already implemented in the framework and does not require any further discussion. As well as the demand of an implementation in an open-source platform is already guaranteed. Analysis of the simulation data within the framework is not part of this work, and will thereto not further be discussed. The topic is arranged and discussed in the semester thesis of M. Elbe [Elb12].

For the present work, the following requirements on the parametrisation remain: Reference process definition, general information database and machine component database. Creating physical component models and implementing them as Java classes into the existing framework, builds the required model database. Parallel, the machine component database is built by the parameter files for the machine components. Do overcome the problem of machine and component specific parametrisation, different locations to store the parameter files have been defined. Component specific parameters are stored in the machine component database, where machine specific parameters are stored in the machine configuration. Both databases do of course not include a complete set of all thinkable machine parts and vendor components parametrization. This does not infringe the requirement, where only the basic structure is demanded. After the requirements, the model shall base upon a reference process. For this work, the
required *xml* file with time series of the process parameters – such as rotational speed – has been done in Matlab. For further purpose of the framework, a NC parser is required. Given NC code from CAM, this parser must create the required *xml* file. Since this parser does not exist, and the requirement can not be satisfied.

The next set of requirements regards the simulation. Which also includes the energetic and thermal behaviour, as the requirements on the model simplifications. As demanded, QSS is used, since the discussion in the specification of the system modelling has resulted in the same conclusion. For the simulation of the energetic and thermal behaviour, no additional requirements are state. The energetic behaviour is represented by the electro-mechanical component models, where the thermal behaviour can be modelled by the generic thermal components. Interconnection between the two models are created trough heat losses and temperature dependent component control. For all models, certain simplifications are requested. Doing so, the number of parameters and uncertainties shall be reduced, while the signification dynamics are still represented. As mentioned at multiple points during the system modelling, the recommended simplifications have been applied. There influence on the final result has been analysed and will be discussed in the following section.

### 5.2 Analysis and validation of the model

In order to quantify and analyse the simulation results, data series from measurements have been used. This measurements have been taken on the test-bench machine and included electrical power, force and temperature. The measurements have shown, that certain dynamics of the machine are negligible. This are the part clamping with compressed air, the movement of the revolver and movements of the axis without acceleration. Since the tail-stock consumes power proportional to the applied clamping forces, the neglecting in the model can not be justified for all operational situations. For high clamping forces – above 3000 N for the test-bench machine – the including of the tail-stock force should be considered.

Validating the model precision included three steps: The process model, the electro- mechanical model and the thermal model. Concerning the process model, the calculated force has been compared to the average measured force for each cut. The resulting error distribution over the time for the test case has shown mean relative errors of 8%, 1% and 27% for the cutting, feed and passive force. Accounting for the absolute force values, the cutting force error is dominant, where the other two errors are negligible. Since the mechanical process power depends linear on the cutting force, an relative error in power consumption of 8% is introduced on the level of the process.

The validation of the electro-mechanical components has shown three types of errors: Not modelled constant consumers, physical component model errors and parameter errors. For different operational scenarios, some machine components show different power levels, which influences the relative error. Due to the different operations of machine tools in the industry, a general validation without machine states is not suitable. For the error calculation the concept on machine state has been introduced: *Airoff, Off, Standby, Ready* and *Process*. Each state describes a characteristic power level of the machine. From the validation, the following observations are worth mentioning: The transformer for the *control/brake power* has a static consumer of about 85 Watts which is not modelled. This causes a relative error of −25% over all machine states. Looking at the *Fanuc* power during the states *Standby* and *Ready*, a large error of −90% occurs, where during the process the error is about −1%. All other components show relative errors in all operational states within the demanded tolerance of ±20%. Building the sum of all modelled components electrical consumption, the relative error is −2% during *Process*, −17% during *Ready* and −13% during *Standby*; this corresponds to absolute errors of −55, −170 and −110 Watts. When looking at the power measured at the line filter of the machine compared to the sum of
the simulated power consumptions, an offset of 320 Watts can be identified. This relates to a sum of not modelled, constant consumers in the machine. Dependent on the power level of the operational state, the influence on the relative error turns out: −11% error during Process and −50% during Ready and Standby. It's obvious, that the error tolerance of ±20% is violated during Ready and Standby. Part of the discussed phenomena can also be seen in figure 5.1, where the measurement and the simulation of component power series are shown.

The last step contained the validation of the thermal model. To do so, the temperatures measured are compared to the one calculated by the framework. Again, states are introduced to characterize situations of different thermal behaviour: Warmup, Operation, Idle, and Cooldown. Comparing the temperature development of the cooler tank in measurement and simulation for all different thermal states, the following validation result was obtained: The model built by the generic thermal elements is able to represent the long time temperature development. Long time behaviour is characterized by a periodic temperature evolution. For simulations of the short time development, i.e. exact temperature at a time instant, the model is not applicable.

Deviations and errors identified during the validation have been analysed in order to locate the error source and avoid problems for future applications. As mentioned, the three error types are named to be: Missing constant consumers, component model errors and parameter errors. In order to analyse the influence of model parameters during different operational states, a sensitivity analysis has been used. By using the model equations and parameters the influence of each model parameter to the total power demand can be estimated. Since a substantial constant contribution of various small components is identified during the validation, they have also be included. Again, this analysis has been done for each operational state separately. During the Process the nominal power of the cutting fluid pump and the efficiency maps of the main drive power line have the highest sensitivity. At the other states, the compressed air demand and the ambient temperature have a high influence on the result. Also to be mentioned is the contribution of the various constant consumers, except during Process. This has already be visible during the validation by the huge error introduced by the constant difference at the line filter.

Using the information of the validation and the sensitive parameters, the analysis on the influence of component model and parameter errors has been done. The focus was set on the process model parameters, the spindle power line efficiency maps and missing constant consumer connected to the control/brake power and the line filter. By correcting this parameters, the remaining errors are due to component model errors. Summarising the result: The error on the control/brake power is reduced to a maximum of −4%, where the Fanuc power during process has now −0.7% error. The errors of −90% during Ready and Standby still remain. Comparing the line filter to the sum of components, the error is now in the same size for process and ready: 1.3% during process and −9% during ready. Except for the Fanuc during ready and standby, the error margin of ±20% is always satisfied. The Fanuc error during stand-by has an absolute error of −2 Watts, which is negligible compared to the total consumption of 800 Watts. The error during ready has requested further analysis. Summing the contribution of the power peaks of the fast axis acceleration during ready up and comparing them to the total measured energy during ready, this value is about 80% of the total energy. As mentioned, accelerations of the drives are not modelled, which explains the huge difference between the model and the measurement. Concluding from this results, the negligence of dynamics can not be done in general, but must be decided from case to case.

Error analysis of the thermal model required additional methods. Since the temperature of the cooler is influenced by the heat exchanger, which on the other side has an operational level dependent on the cooler temperature. To analyse the model topology and the mentioned cycle in especially, a influence/interference analysis has been performed. During this qualitative analysis, the components and states of the machine have been categorized according to their connections to other components. Resulting was the ambient and cooler temperature temperature as critical states. Critical means at this points, the states
5.2 Analysis and validation of the model

![Graph](image)

(a) Measurement

(b) Simulation

**Figure 5.1:** Example for the simulation result taken out of the component model validation measurement. As reference, the measured energy is shown too. Cut number three to six refer to measurements with IDs 11 to 14 in table C.5, the others result from overturining.
have big influence to other states, by are also influenced significant by others. Given an error in one of
this states, it has a significant influence to other components. This errors can even be fed back to the
origin and amplified. Additional information by this analysis is also given on the other machine com-
ponents. The machine state for example, allows big influence, while having only small interference by
other components.

5.3 Summary

In the past sections the system modelling, implementation, validation and analysis results have been
discussed. Further, differences between the requirements for this work and the current results have been
showed. Bringing all the discussed results from above together, leads to the following summarized
information:

- The concept of generic components is compatible with the list of required component list by Lang,
  and enable the desired flexibility in the framework. It is recommended to use the principal of
generic components are programming guideline for future implementations.

- For the simulation, an NC Parser to generate configuration files from CAM software is mandatory
  for the industry. This parser is not implemented and therefore missing. This parser would have to
  be able to deal with different machine configurations.

- Desired model and machine component databases are implemented. There use has been success-
  fully tested with the example of the test-bench machine. Not for all defined generic components a
  model has been implemented.

- The electro-mechanical part of the model depends strongly on the available parameter quality.
  Having enough parameter information, the demanded precision can be satisfied. Impacts of model
  simplification to the final result depend strongly on the application.

- For the desired precision, the summed contribution of small constant consumers have to be in-
  cluded. Knowledge and experience are requested to estimate the sum of various small constant
  consumers on the machine. Further expertise is required to estimate the material consumption,
  such as compressed air. This can be done by using existing machines as reference.

- Neglecting the acceleration of drives is not a generalizable simplification as shown by the results
  above. For certain parts and operational states it is useful, where in other case the contribution of
  the peak powers is significant.

- Modelling the thermal behaviour, especially the heat release to the environment, is possible for
  long time behaviour only. Problematic are the interferences and influences of the temperatures by
  other components and errors.

- Model topology analysis can be used to receive a qualitative description of the component inter-
  connections. In the test-case, the fragility of the thermal model has been demonstrated. Further,
  the method can be used to chose action variables for changes on the machine.

The list above is the result of a system modelling and implementation according to the requirements by
M. Lang in [Lan12]. All component models, implementations and parametrizations are deposited in the
EMod framework by inspire. Same is valid for the simulation and process definition used for the test
cases. The quantification of the simulation results has been done by comparing them to measurement
data. The methods used to achieve the stated results on model precision, error sources and model topol-
ogy are stated in section 4.5. Agreeability of the results with the stated goals of this work is discussed in the following chapter.
Conclusion and Future Work

In this work, system modelling and implementation of machine tool components in a simulation framework has been done. By comparing the simulation data to measurement data, the precision of the tool has been quantified by the example of the turning machine on the test-bench. Using analysis methodologies introduced in section 4.5, further information has been derived. The results of this steps have been discussed in the last chapter. All this steps have been done, in order to fulfil the goals stated in chapter 2:

A Provide component models to the EMod framework. The components must be suitable to describe the power consumption of a machine tool. First considerations for the thermal modelling have to be made.

B Follow the requirement list of [Lan12] regarding the model configuration and simulation, and discuss failed requirements.

C Ensure the placement of new information into an existing model. This as do be done on the level of component model and machine model.

D Achieve a maximum relative error band of $\pm20\%$ and analyse the simulation results with respect to errors and portability of the model for other applications

At this point, a conclusion about the completeness of the results in relation with the state goals is due. To do so, the requirements on the results given by the goals are discussed first, in order to quantify the gained results. This quantification is done for the results from the system modelling and the analysis of the simulation data. Based on the following conclusion, future tasks and applications for this work are discussed.
6 Conclusion and Future Work

6.1 Conclusion

Looking at the goals, stated in the head of this chapter, the discussion of three points is mandatory: Reliability, portability and the use in industry. The first point will discuss the conclusion made for the model validation done above, especially by comparing the given error limitation to the actual identified errors. This information is important for goals A and D. The second point has to deal with the possible appliance of the framework for other machines than for turning machine. This aspect is important for goals B and C. The last point will show the model properties compared to the industrial requirements. This step has to discuss, whether or not the framework with the implemented model components is applicable in industry for development of machine tools: Especially since this information is mandatory to evaluate goal B. All the information is summarized at the end, together with the argumentations about the achievement of the stated goals.

6.1.1 Reliability

To be used as a tool in the development, the framework has to provide data with a known precision. As shown during the analysis, this precision depends on the component models and the parameters entered by the user. In the case of the tested implementation of the test-bench turning machine, the demanded precision could only be guaranteed with a sufficient knowledge about the components parameters and a guess of the sum of small constant consumers. To estimate this sum, the experience on existing machines has to be used. The same conclusion is valid for the thermal part of the model. Multiple estimations for different parameters lead to bigger errors in the final result. By using heat transfer parameters of existing machines to estimate the thermal model parameters, the quality of the parameters and the final result could be increased. Besides the parameters, the influence and interferences in the thermal model are an additional challenge. Since the temperatures modelled are identified as states with big influence and interferences, errors in the temperature calculation can be amplified and have a big impact to the final result. The thermal model can thereto only be used to estimate the trend and long time behaviour of the thermal effects. Statements about the exact temperature development are not possible. With the results from the sensitivity analysis, the precision and reliability of the machine tool can be improved methodically by focusing on critical parameters. Further, the effects of component parameter errors can be quantified.

The conclusion concerning the reliability is the following: For the successful use of the model, informations of existing machines and experts has to be used. Focusing on the methodically identified critical parameters can reduce the effort to achieve the desired quality. With this steps, the desired precision of ±20% relative error can be satisfied on the test-bench machine implementation for the electric power demand. On the thermal side, the precision limit holds only for the long time heat releases, but not for the detailed temperature development.

6.1.2 Portability

Using the framework and the implemented models for other machines, the portability of the model discussed in this work and the corresponding conclusions on reliability have to be secured. The portability of auxiliary component models is thereby simple: If the parametrisation is the same or can be validated as correct, the use of the component in other models is possible. Critical are the components close to the process. Phenomena, such as the acceleration of drives, must carefully be studied. Where ever a general conclusion is not possible, whether or not to neglect a certain effect in the model must be decided
6.1 Conclusion

for each application separately. At the current stage, the process model limits the portability to turning machines only. To use the model for grinding, cutting or laser machine tools, either new process models would have to be implemented, or the process forces must be known a priori and feed into the model as time series.

All this actions and possible implementations of new components have to be done with respect to the concept of *generic components*. By using this definition as system modelling and programming guideline, the desired flexibility in the model is guaranteed. Further the concept of a growing model during the development can be realized. Concluding, the portability for the auxiliary devices is granted. In general, this components cover a big part of the total energy demand. One has to be careful when using components with fast, not modelled dynamics. For the portability on other machining types, other process models or data sources are required.

6.1.3 Use in industry

The requirement list by M. Lang has been created with respect to a substantial use of the framework for the industry. In order to quantify the current model for industrial used, the model is validated against the mentioned requirement list. Concluding from the validation of this model against the list of requirements by M. Lang, the following statement results: The framework with the implemented models is able to represent the desired components. The interfaces required by specification for the configuration and analysis are possible to be included in the framework, but missing at the moment. For the configuration and simulation, this is mainly a NC parser for the process files. Further, methodologies as parameter sensitivity and model topology analysis have successfully be tested.

6.1.4 Summary

Summarizing the conclusions above: Goal A, concerning the contribution to the existing framework, is achieved by the procedure done in the system modelling. The set of components is of course not complete, since may more additional components or physical model can be implemented. The requirements by Lang about the simulation and the models of the framework are satisfied, where at the configuration part a NC parser is missing. At this state of work, goal B can thereto only partly be fulfilled. The possibility to extend an existing model with new information about the machine tool, demanded by goal C, is given by the concept of *generic machine components*. The use of this categorisation and guideline for component models assures a limited set of component model interfaces. Having components with the same interfaces, one component can be exchanged by an other one. By introducing the concept of *generic components*, the modularity of the model is bestowed. Dependent on the parameter quality, the model sustains the tolerated error of ±20% given by goal D. For the successful use of the model, experience and knowledge of the model and the machine tool is required. The parametrisation of a new model should be supported by measurements of similar existing machines. Further the introduced sensitivity analysis can be used to set a focus in parameter improvement and to estimate impact of a parameter error to the total result. Critical components can further be identified by using appropriate methodologies such as the introduced model topology analysis.

During this work, the stated goals A, C and D could fully be fulfilled. During the result analysis in relation to goal B differences concerning the configuration of the model exist. The main problem is the missing connection to CAD or CAM software. All other requirements by M. Lang concerning the configuration and simulation have been met.
6 Conclusion and Future Work

6.2 Future Work

During this thesis, a contribution in the form of component models and parametrizations to the framework EMod has been made. By the procedure, some points could not be analysed and discussed entirely in this work. Resulting form the analysis and conclusion above, the following steps concerning the models and the framework are requested or advised:

- Extend the model library with more models. Especially additional motor models including acceleration phenomena would be of interest, as well as hydraulic components
- Development of methodologies to estimate and quantify the amount of energy consumed by sealing air and small constant consumers
- Implementation of the desired NC parser. As documented in [Lan12], a parser for process data generated by CAM software is inalienable for a successful use in industry
- Use of the evaluation and analysis methods used in this work – i.e. the sensitivity analysis or retrofit indicator – in the analysis part of the framework.
- Implementation and testing of other machine types in the framework. With the components available, grinding or milling machines are recommended.

Withal, it has to be mentioned, that the EMod framework is still under development. GUI for the configuration will follow, as the analysis of the simulation data is part of a ongoing student work [Elb12].
Component model library

The following chapter summarises the results from the system modelling. All derived models are explained by listing their dynamics and interfaces. While using the framework for machine tool modelling, this chapter can be used as documentation and guideline.

A.1 Notation

In order to show the relation between the notation of this work and the framework code, the framework terminology is shown as typewriter text. The equations shown under system dynamics describe the procedure of the update() function within the framework. At each time step, this calculation is performed. Writing $x[k]$, the value available at the exit of the update() function is meant, where $x[k-1]$ is the state value at the function call.

For the mathematical descriptions of the system dynamics of the following models, certain standardized functions are used. Those are linear interpolation and the unit step function. Given the sets $\mathcal{X}$, $\mathcal{Y}$ and $\mathcal{Z}$. This sets describe the points $(x_i, y_i, z_i)$, where $\mathcal{X}$ and $\mathcal{Y}$ are distinct and $|\mathcal{X}| = |\mathcal{Y}| = |\mathcal{Z}|$. Concluding from a point $(x_j, y_i)$ to the corresponding value $z_i$ by linear interpolation within the sets, the following notation is used. Of course the one dimensional case includes the same procedure:

$$z_j = \text{interpol} \ (\mathcal{Z}, (\mathcal{X}, \mathcal{Y}), (x_j, y_j)) \quad (A.1)$$
$$z_j = \text{interpol} \ (\mathcal{Z}, \mathcal{X}, x_j) \quad (A.2)$$

The unit step function has the following definition for a signal $y$ and the result $x$:

$$x = h(y) = \begin{cases} 1 & \forall \ y > 0 \\ 0 & \text{else} \end{cases} \quad (A.3)$$
A.2 Electro-mechanical components

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic component</td>
<td>constant consumer</td>
</tr>
<tr>
<td>Assumptions</td>
<td>• Finite number of $N$ discrete power levels</td>
</tr>
<tr>
<td></td>
<td>• Intermediate change of power levels</td>
</tr>
<tr>
<td>Inputs</td>
<td>$S_{mech}$ level component power level $[-]$,</td>
</tr>
<tr>
<td></td>
<td>limited to ${1, 2, \ldots, N}$</td>
</tr>
<tr>
<td>Outputs</td>
<td>$P_{tot}$ ptotal component power consumption $[W]$</td>
</tr>
<tr>
<td>Parameters</td>
<td>$\bar{P}$ levels power levels of the component $[W]$, where $\bar{P} = [P_1, P_2, \ldots, P_N]^T$</td>
</tr>
<tr>
<td>States</td>
<td>none</td>
</tr>
<tr>
<td>System Dynamics</td>
<td>$P_{tot} = P_{S_{cmp}}$</td>
</tr>
<tr>
<td>Class name</td>
<td>ConstantComponent</td>
</tr>
</tbody>
</table>

\[ P_{tot} = P_{S_{cmp}} \]  \quad (A.4)
A.2 Electro-mechanical components

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic component</td>
<td>motor</td>
</tr>
<tr>
<td>Assumptions</td>
<td>• Negligible acceleration times and power demand</td>
</tr>
<tr>
<td></td>
<td>• All losses are thermal</td>
</tr>
<tr>
<td></td>
<td>• Temperature independent efficiency</td>
</tr>
<tr>
<td>Inputs</td>
<td>$T$ Torque demanded torque [Nm]</td>
</tr>
<tr>
<td></td>
<td>$\omega$ Rotspeed demanded speed [rpm]</td>
</tr>
<tr>
<td>Outputs</td>
<td>$P_{tot}$ PTotal resulting electric power demand [W]</td>
</tr>
<tr>
<td></td>
<td>$P_{mech}$ PUse requested mechanical power [W]</td>
</tr>
<tr>
<td></td>
<td>$\dot{Q}_{loss}$ PLoss heat loss [W]</td>
</tr>
<tr>
<td></td>
<td>$\eta$ Efficiency current efficiency [-]</td>
</tr>
<tr>
<td>Parameters</td>
<td>$\mathcal{P}_{map}$ PowerSamples power samples of the motor [W]</td>
</tr>
<tr>
<td></td>
<td>$\Omega_{map}$ RotspeedSamples speed smaples of the motor [rpm]</td>
</tr>
<tr>
<td></td>
<td>$\mathcal{H}_{map}$ EfficiencyMatrix efficiency matrix for the given power and speed samples [-]</td>
</tr>
<tr>
<td></td>
<td>$T_{fr}$ FrictionTorque static friction torque for load free operation [Nm]</td>
</tr>
<tr>
<td>States</td>
<td>none</td>
</tr>
<tr>
<td>System Dynamics</td>
<td>$\eta = \text{interp} (\mathcal{H}<em>{map}, (\mathcal{P}</em>{map}, \Omega_{map}), (T, \omega))$ (A.5)</td>
</tr>
<tr>
<td></td>
<td>$P_{mech} = T \cdot \omega$                  (A.6)</td>
</tr>
<tr>
<td></td>
<td>$P_{tot} = \frac{P_{mech}}{\eta}$            (A.7)</td>
</tr>
<tr>
<td></td>
<td>$\dot{Q}<em>{loss} = P</em>{tot} - P_{mech}$         (A.8)</td>
</tr>
<tr>
<td></td>
<td>If no load is applied:</td>
</tr>
<tr>
<td></td>
<td>$P_{tot} = T_{fr} \cdot \omega$               (A.9)</td>
</tr>
</tbody>
</table>

Class name Motor
A Component model library

Servomotor

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic component</td>
<td><em>motor</em></td>
</tr>
<tr>
<td>Assumptions</td>
<td>• Negligible acceleration times and power demand</td>
</tr>
<tr>
<td></td>
<td>• All losses are thermal</td>
</tr>
<tr>
<td></td>
<td>• Constant motor and speed constants</td>
</tr>
<tr>
<td>Inputs</td>
<td>$T$ Torque demanded torque [N\text{m}]</td>
</tr>
<tr>
<td></td>
<td>$\omega$ Rotspeed demanded speed [r\text{pm}]</td>
</tr>
<tr>
<td>Outputs</td>
<td>$P_{\text{tot}}$ FTotal resulting electric power demand [W]</td>
</tr>
<tr>
<td></td>
<td>$P_{\text{mech}}$ FUse requested mechanical power [W]</td>
</tr>
<tr>
<td></td>
<td>$Q_{\text{loss}}$ FLoss heat loss [W]</td>
</tr>
<tr>
<td></td>
<td>$\eta$ Efficiency current efficiency [-]</td>
</tr>
<tr>
<td>Parameters</td>
<td>$\kappa_a$ KappaA torque constant [N\text{m}/A]</td>
</tr>
<tr>
<td></td>
<td>$\kappa_i$ KappaI speed constant [V/r\text{pm}]</td>
</tr>
<tr>
<td></td>
<td>$R_a$ ArmatureResistance efficiency matrix for the given power and speed samples [$\Omega$]</td>
</tr>
<tr>
<td></td>
<td>$p$ PolePairs efficiency matrix for the given power and speed samples [-]</td>
</tr>
<tr>
<td></td>
<td>$T_{fr}$ StaticFriction static friction torque [N\text{m}]</td>
</tr>
<tr>
<td>States</td>
<td>none</td>
</tr>
<tr>
<td>System Dynamics</td>
<td>$P_{\text{mech}} = T \cdot \omega$            (A.10)</td>
</tr>
<tr>
<td></td>
<td>$P_{\text{tot}} = p \cdot \frac{T + T_{fr}}{R_a} \cdot \left( \frac{\kappa_i \cdot \omega + T + T_{fr}}{R_a} \right)$ (A.11)</td>
</tr>
<tr>
<td></td>
<td>$\eta = \frac{P_{\text{mech}}}{P_{\text{tot}}}$ (A.12)</td>
</tr>
<tr>
<td></td>
<td>$Q_{\text{loss}} = P_{\text{tot}} - P_{\text{mech}}$ (A.13)</td>
</tr>
</tbody>
</table>

Class name ServoMotor
## A.2 Electro-mechanical components

### Amplifier

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic component</td>
<td>amplifier</td>
</tr>
</tbody>
</table>
| Assumptions | • Only thermal losses  
• Temperature independent efficiency  
• Constant control power |
| Inputs | S: level, Operational state [-]  
P\text{dmd}: PDmd, demanded power [W] |
| Outputs | P\text{tot}: PTotal, resulting electric power demand [W]  
P\text{sply}: PSply, resulting supply power [W]  
P\text{ctrl}: PCtrl, resulting control power [W]  
\dot{Q}_{\text{loss}}: PLoss, heat loss [W] |
| Parameters | P\text{dmd}: PowerSamples, power samples [W]  
\mathcal{H}_{amp}: Efficiency, power transmission efficiency samples [-]  
P\text{ctrl}: PowerCtrl, static control power [W] |
| States | none |
| System Dynamics | If component is off S = 0:  
\[ P_{\text{tot}} = \dot{Q}_{\text{loss}} = P_{\text{supply}} = P_{\text{ctrl}} = 0 \]  
Else:  
\[ \eta = \text{interpol}(\mathcal{H}_{amp}, P_{\text{dmd}}, P_{\text{dmd}}) \]  
\[ P_{\text{tot}} = \frac{P_{\text{dmd}}}{\eta} + P_{\text{ctrl}} \]  
\[ \dot{Q}_{\text{loss}} = P_{\text{tot}} - P_{\text{dmd}} \] |

Class name Amplifier
Linear axis

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic component</td>
<td>axis</td>
</tr>
</tbody>
</table>
| Assumptions       | • Slow movements, small inertia effects  
                  | • No frictional forces  
                  | • Ideal power conversion |
| Inputs            | $F_{ax}$ ProcessForce force along the axis [N]  
                  | $v_{ax}$ Speed demanded axis speed [rpm] |
| Outputs           | $T$ Torque resulting torque [W]  
                  | $\omega$ RotSpeed resulting rotational speed [W] |
| Parameters        | $k$ Transmission transmission ratio [mm/rev]  
                  | $m$ Mass mass of the moved part [kg]  
                  | $\kappa$ Alpha angle between the axis and the vertical [°] |
| States            | none |
| System Dynamics   | $T = k \cdot (F_{ax} - m \cdot g \cdot \cos \kappa)$ (A.18)  
                  | $\omega = \frac{v_{ax}}{k}$ (A.19) |
| Class name        | LinAxis |


A Component model library
## Linear transmission

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic component</td>
<td>transmission</td>
</tr>
</tbody>
</table>
| Assumptions | ■ Dominant thermal losses  
■ Perfect liner transmission  
■ Constant efficiency |
| Inputs | |
| $T_{dmd}$ | Torque | demanded torque [Nm] |
| $\omega_{dmd}$ | Rotspeed | demanded speed [rpm] |
| Outputs | |
| $T$ | Torque | resulting torque [Nm] |
| $\omega$ | Rotspeed | resulting speed [rpm] |
| $Q_{loss}$ | PLoss | heat loss [W] |
| Parameters | |
| $k$ | TransmissionRatio | torque constant [-] |
| $\eta$ | Efficiency | speed constant [1] |
| States | none |
| System Dynamics | |
| $T = \frac{k}{\eta} \cdot T_{dmd}$ | (A.20) |
| $\omega = \frac{\omega_{dmd}}{k}$ | (A.21) |
| $Q_{loss} = \omega_{dmd} \cdot T_{dmd} \cdot \frac{1 - \eta}{\eta}$ | (A.22) |
| Class name | Transmission |
A Component model library

---

**Fan**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic component</td>
<td>fan</td>
</tr>
</tbody>
</table>
| Assumptions | • validity of the fan law  
• small deviations from nominal operational point  
• no controlled mass flow required  
• small pressure gradients |
| Inputs |  
| u | level  
operational level [−] |
| Outputs |  
| \( P_{\text{tot}} \) | PTot \( \)  
resulting power demand [W] |
| \( \dot{m} \) | MassFlow \( \)  
resulting mass flow [kg/s] |
| \( Q_{\text{loss}} \) | PLoss \( \)  
heat loss [W] |
| Parameters |  
| \( \rho_{\text{fl}} \) | RhoFluid \( \)  
fluid density \([\text{kg/m}^3]\) |
| \( P_{\text{el,ref}} \) | PelRef \( \)  
reference point power demand \([\text{V/rpm}]\) |
| \( \dot{V}_{\text{ref}} \) | VdotRef \( \)  
reference point volumetric flow \([\Omega]\) |
| \( p_{\text{ref}} \) | pRef \( \)  
reference point pressure drop [−] |
| States | none |
| System Dynamics |  
\[
P_{\text{tot}} = P_{\text{el,ref}} \cdot u^3 \quad (A.23)
\]
\[
\dot{m} = \dot{V}_{\text{ref}} \cdot \rho_{\text{fl}} \cdot u \quad (A.24)
\]
\[
\dot{Q}_{\text{loss}} = P_{\text{tot}} - \dot{V}_{\text{ref}} \cdot p_{\text{ref}} \cdot u^3 \quad (A.25)
\]

Class name | Fan |
## A.2 Electro-mechanical components

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Generic component</strong></td>
<td><strong>pump</strong></td>
</tr>
<tr>
<td><strong>Assumptions</strong></td>
<td>• Only thermal heat losses</td>
</tr>
<tr>
<td></td>
<td>• Available pump map</td>
</tr>
<tr>
<td></td>
<td>• One power level only</td>
</tr>
<tr>
<td><strong>Inputs</strong></td>
<td>$S$ level operational state [-]</td>
</tr>
<tr>
<td></td>
<td>$\dot{m}_{dmd}$ MassFlowOut demanded mass flow [kg/s]</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td>$P_{\text{tot}}$ PTotal resulting electric power demand [W]</td>
</tr>
<tr>
<td></td>
<td>$\dot{m}_{\text{in}}$ MassFlowIn resulting inflow [kg/s]</td>
</tr>
<tr>
<td></td>
<td>$Q_{\text{loss}}$ PLoss heat loss [W]</td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td>$P_{\text{pump}}$ ElectricalPower Nominal pump power [W]</td>
</tr>
<tr>
<td></td>
<td>$P$ PressureSamples pressure samples [Pa]</td>
</tr>
<tr>
<td></td>
<td>$\mathcal{M}$ MassFlowSamples mass flow samples [kg/s]</td>
</tr>
<tr>
<td></td>
<td>$\rho_{fl}$ DensityFluid fluid density [kg/m$^3$]</td>
</tr>
<tr>
<td><strong>States</strong></td>
<td>none</td>
</tr>
<tr>
<td><strong>System Dynamics</strong></td>
<td>If $S = 1$:</td>
</tr>
<tr>
<td></td>
<td>$\dot{m}<em>{\text{in}} = \dot{m}</em>{dmd}$</td>
</tr>
<tr>
<td></td>
<td>$P_{\text{tot}} = P_{\text{pump}}$</td>
</tr>
<tr>
<td></td>
<td>$Q_{\text{loss}} = P_{\text{tot}} - \dot{m}<em>{\text{in}} \cdot \rho</em>{fl} \cdot \text{interpol}(P, \mathcal{M}, \dot{m}_{\text{in}})$</td>
</tr>
<tr>
<td></td>
<td>otherwise, all outputs are zero.</td>
</tr>
<tr>
<td><strong>Class name</strong></td>
<td>Pump</td>
</tr>
</tbody>
</table>

\[ (A.26) \]
\[ (A.27) \]
\[ (A.28) \]
## Pump with reservoir

### Property Value

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic component</td>
<td>pump</td>
</tr>
</tbody>
</table>
| Assumptions | • Only thermal heat losses  
• isentropic gas compression  
• available pump map  
• One power level only |
| Inputs |  

\[
\begin{align*}
S & \quad \text{level} \quad \text{operational state [-]} \\
\dot{m}_{\text{dmd}} & \quad \text{MassFlowOut} \quad \text{demanded mass flow [kg/s]} \\
\end{align*}
\]

| Outputs |  

\[
\begin{align*}
P_{\text{tot}} & \quad \text{PTotal} \quad \text{resulting electric power demand [W]} \\
\dot{m}_{\text{in}} & \quad \text{MassFlowIn} \quad \text{resulting inflow [kg/s]} \\
\dot{Q}_{\text{loss}} & \quad \text{PLoss} \quad \text{heat loss [W]} \\
\end{align*}
\]

| Parameters |  

\[
\begin{align*}
P_{\text{pump}} & \quad \text{ElectricalPower} \quad \text{Nominal pump power W} \\
P & \quad \text{PressureSamples} \quad \text{pressure samples [Pa]} \\
\mathcal{M} & \quad \text{MassFlowSamples} \quad \text{mass flow samples [kg/s]} \\
\rho_{\text{fl}} & \quad \text{DensityFluid} \quad \text{fluid density [kg/m}^3]\text{]} \\
p_{g,\text{init}} & \quad \text{GasPressureInitial} \quad \text{initial gas pressure of the reservoir [Pa]} \\
V_{g,\text{init}} & \quad \text{GasVolumeInitial} \quad \text{initial gas volume [m}^3]\text{]} \\
V_{\text{fli,init}} & \quad \text{FluidVolumeInitial} \quad \text{Initial fluid volume in the reservoir [m}^3]\text{]} \\
p_{\text{fli,max}} & \quad \text{PressureMax} \quad \text{upper threshold for the control [Pa]} \\
p_{\text{fli,min}} & \quad \text{PressureMin} \quad \text{lower threshold for the control [Pa]} \\
\end{align*}
\]

| States |  

\[
\begin{align*}
m_{\text{fl}} & \quad \text{fluid mass in the reservoir [kg]} \\
S_{\text{pump}} & \quad \text{pump state (true if running) [-]} \\
\end{align*}
\]

### System Dynamics

\[
\begin{align*}
S_{\text{pump}}[k] & = S \land ((p_{\text{fli}} < p_{\text{fli, max}} \land S_{\text{pump}}[k - 1]) \lor (p_{\text{fli}} \leq p_{\text{fli, min}} \land \neg S_{\text{pump}}[k - 1])) \quad (A.29) \\
\dot{P}_{\text{tot}} & = \begin{cases} P_{\text{pump}} & \text{if } S_{\text{pump}} \text{ is true} \\ 0 & \text{else} \end{cases} \quad (A.30) \\
p_{\text{fli}} & = p_{g,\text{init}} \cdot \frac{V_{g,\text{init}}}{v_{g,\text{init}} + V_{\text{fli,init}} - m_{\text{fl}}/p_{\text{fli}}} \quad (A.31) \\
\dot{m}_{\text{in}} & = h(P_{\text{tot}}) \cdot \text{interpol}(\mathcal{M}, P, p_{\text{fli}}) \quad (A.32) \\
m_{\text{fli}}[k] & = m_{\text{fli}}[k - 1] + T_S \cdot \left(\dot{m}_{\text{in}} - \dot{m}_{\text{dmd}}\right) \quad (A.33) \\
\dot{Q}_{\text{loss}} & = P_{\text{tot}} - \frac{\dot{m}_{\text{in}}}{p_{\text{fli}}} \cdot p_{\text{fli}} \quad (A.34) \\
\end{align*}
\]

### Initialisation

\[
\begin{align*}
m_{\text{fli}} & = \rho_{\text{fli}} \cdot V_{\text{fli,init}} \quad (A.35) \\
S_{\text{pump}} & = 0 \quad (A.36) \\
\end{align*}
\]

Class name PumpAccumulator
### A.2 Electro-mechanical components

**Heat exchanger**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic component</td>
<td><em>heat exchanger</em></td>
</tr>
</tbody>
</table>
| Assumptions     | • Constant EER  
|                 | • No significant thermal losses |
| Inputs          | $S$ \hspace{1em} level \hspace{1em} operational state [-] |
| Outputs         | $P_{tot}$ \hspace{1em} $P_{total}$ \hspace{1em} resulting electric power demand [W]  
|                 | $Q_{th}$ \hspace{1em} $P_{thermal}$ \hspace{1em} resulting heat flow [W] |
| Parameters      | $P_{he}$ \hspace{1em} CompressorPower \hspace{1em} nominal power [Nm/A]  
|                 | $\varepsilon$ \hspace{1em} EERCooling \hspace{1em} EER of the system [\$/rpm] |
| States          | none |
| System Dynamics | $P_{tot} = \begin{cases} P_{he} & \text{if } S = 1 \\ 0 & \text{else} \end{cases}$ \hspace{1em} (A.38)  
|                 | $Q_{th} = \varepsilon \cdot P_{tot}$ \hspace{1em} (A.39) |
| Class name      | HeatExchanger |


## Compressed air supply

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic component</td>
<td><em>compressed air</em></td>
</tr>
<tr>
<td>Assumptions</td>
<td>see [GWW10]</td>
</tr>
<tr>
<td>Inputs</td>
<td></td>
</tr>
<tr>
<td>$\dot{V}_{dmd}$</td>
<td>Flow</td>
</tr>
<tr>
<td>$p_{amb}$</td>
<td>PressureAmb</td>
</tr>
<tr>
<td>$\vartheta_{amb}$</td>
<td>TemperatureAmb</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
</tr>
<tr>
<td>$P_{tot}$</td>
<td>PTotal</td>
</tr>
<tr>
<td>Parameters</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
</tr>
<tr>
<td>$c_p$</td>
<td>HeatCapacity</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>IsentropicCoefficient</td>
</tr>
<tr>
<td>$p_{supply}$</td>
<td>SupplyPressure</td>
</tr>
<tr>
<td>States</td>
<td>none</td>
</tr>
<tr>
<td>System Dynamics</td>
<td></td>
</tr>
<tr>
<td>$P_{tot} = c_p \cdot \vartheta_{amb} \cdot \left[ \left( \frac{p_{supply}}{p_{amb}} \right)^{\gamma - 1} - 1 \right] \cdot \rho \cdot \dot{V}$</td>
<td>(A.40)</td>
</tr>
<tr>
<td>Class name</td>
<td>CompressedAir</td>
</tr>
</tbody>
</table>
A.3 Thermal components

Free heat flow

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal type</td>
<td>thermal energy flow</td>
</tr>
</tbody>
</table>
| Assumptions   | • convection and conduction are dominant  
|               | • constant heat conduction coefficient  
|               | • constant convection coefficient  
|               | • Focusing on free heat transfer with ambient air  
|               | • Thermal layers separated by $N$ layers  |
| Inputs        | $\theta_1$ Temperature1 
|               | $\theta_1$ Temperature2 
| Outputs       | $\dot{Q}_{12}$ PThermal12 heat flow from level 1 to level 2 [W]  
|               | $\dot{Q}_{21}$ PThermal21 heat flow from level 2 to level 1 [W]  |
| Parameters    | $S$ Surface nominal air density [m$^2$]  
|               | $\bar{\alpha}$ ConvectionConstants convection constants of the two wall surfaces [W/m$^2$K]  
|               | $\bar{\lambda}$ ConductionConstants conduction constants of the wall layers [W/m$^3$K]  
|               | $\bar{d}$ WallThicknesses thickness of the layers [Pa]  |
| States        | none |

System Dynamics

\[
k = \left[ \frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \sum_{i=1}^{N} \frac{d_i}{\lambda_i} \right]^{-1} \quad (A.41)
\]

\[
\dot{Q}_{12} = k \cdot S \cdot (\theta_1 - \theta_2) \quad (A.42)
\]

\[
\dot{Q}_{21} = -\dot{Q}_{12} \quad (A.43)
\]

Class name thermal/FreeHeatTransfer
Forced heat flow

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal type</td>
<td>thermal energy flow</td>
</tr>
<tr>
<td>Assumptions</td>
<td>• no heat losses during transport</td>
</tr>
<tr>
<td></td>
<td>• for fast moving fluids</td>
</tr>
<tr>
<td>Inputs</td>
<td>$\dot{\vartheta}_1$ Temperature1 temperature of level 1 [K]</td>
</tr>
<tr>
<td></td>
<td>$\dot{\vartheta}_1$ Temperature2 temperature of level 2 [K]</td>
</tr>
<tr>
<td></td>
<td>$\dot{m}$ MassFlow mass flow between the two levels</td>
</tr>
<tr>
<td>Outputs</td>
<td>$\dot{Q}_{12}$ PThermal12 heat flow from level 1 to level 2 [W]</td>
</tr>
<tr>
<td></td>
<td>$\dot{Q}_{21}$ PThermal21 heat flow from level 2 to level 1 [W]</td>
</tr>
<tr>
<td>Parameters</td>
<td>$c_p$ HeatCapacity heat capacity of the moved fluid [J/kgK]</td>
</tr>
<tr>
<td>States</td>
<td>none</td>
</tr>
<tr>
<td>System Dynamics</td>
<td>$\dot{Q}_{12} = c_p \cdot \dot{m} \cdot (\dot{\vartheta}_1 - \dot{\vartheta}_2)$ \hspace{1cm} (A.44)</td>
</tr>
<tr>
<td></td>
<td>$\dot{Q}<em>{21} = - \dot{Q}</em>{12}$ \hspace{1cm} (A.45)</td>
</tr>
<tr>
<td>Class name</td>
<td>thermal/ForcedHeatTransfera</td>
</tr>
</tbody>
</table>
A.3 Thermal components

### Homogeneous storage

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal type</td>
<td>thermal energy storage</td>
</tr>
</tbody>
</table>
| Assumptions  | • homogeneous internal energy distribution  
                  • perfect mixture  
                  • constant specific heat capacity |
| Inputs       | \( \vec{Q}_{\text{in}} \) In  
                  \( \vec{Q}_{\text{out}} \) Out |
|             | thermal inflows [W]  
                  thermal outflows [W] |
| Outputs      | \( \vartheta \) Temperature |
|             | temperature of the storage [K] |
| Parameters   | \( c_p \) HeatCapacity  
                  \( m \) Mass  
                  \( T_S \) from SimConfig  
                  \( \vartheta_{\text{init}} \) from SimConfig |
|             | heat capacity of the moved fluid [1/kgK]  
                  mass of the storage [kg]  
                  sample time [s]  
                  initial temperature [K] |
| States       | \( \vartheta \) storage temperature [K] |
| System Dynamics | \( \dot{\vartheta}[k] = \dot{\vartheta}[k-1] + \frac{T_S}{m \cdot c_p} \left( \sum_i \vec{Q}_{i,\text{in}} - \sum_j \vec{Q}_{j,\text{out}} \right) \) (A.46) |
| Initialisation | \( \vartheta = \vartheta_{\text{init}} \) (A.47) |
| Class name   | thermal/HomogStorage |
## Layer storage

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal type</td>
<td>thermal energy storage</td>
</tr>
</tbody>
</table>
| Assumptions | • layer internal energy distribution  
|             | • no mixture  
|             | • constant specific heat capacity |
| Inputs     |       |
| $\vartheta_{in}$ | TemperatureIn inflows temperature [K] |
| $\vartheta_{amb}$ | TemperatureAmb outflows temperature [K] |
| $\dot{m}$ | MassFlow mass flow through storage [kg/s] |
| Outputs    |       |
| $\vartheta_{out}$ | TemperatureOut outflow temperature [K] |
| $\dot{Q}$ | PLoss heat flow to ambient [K] |
| Parameters |       |
| $c_p$ | HeatCapacity heat capacity of the moved fluid [J/kgK] |
| $m$ | Mass mass of the storage [kg] |
| $S$ | Surface surface exposed to ambient [m²] |
| $\alpha$ | ConvectionConstant convection constant to ambient [W/km²] |
| $\lambda$ | ConductionConstant conduction constant of the wall [W/km²] |
| $d$ | WallThickness wall thickness [m] |
| $N$ | NumberElements number of elements for approximation [-] |
| $T_s$ | from SimConfig sample time [s] |
| $\vartheta_{init}$ | from SimConfig initial [K] |
| States     |       |
| $\vec{\vartheta}$ | storage elements temperatures [K] |
| System Dynamics |       |
| $k = \left[ \frac{1}{\alpha} + \frac{d}{\lambda} \right]^{-1}$ | (A.48) |
| $\vartheta_0 = \vartheta_{in}$ |       |
| $\vartheta_i[k] = \vartheta[k - 1] + T_s \cdot \frac{N}{m} \cdot \dot{m} \cdot (\vartheta_{i-1} - \vartheta_i) - \frac{S \cdot k}{m \cdot c_p} \cdot (\vartheta_i - \vartheta_{amb})$ | (A.50) |
| for $i = 1, 2, \ldots, N$ |       |
| $\dot{Q} = \frac{S \cdot k}{N} \sum_{i=1}^{N} (\vartheta_i - \vartheta_{amb})$ | (A.51) |
| $\vartheta_{out} = \vartheta_N$ | (A.52) |
| Initialisation |       |
| $\vartheta_i = \vartheta_{init}$ | $i = 1, 2, \ldots, N$ | (A.53) |
| $\dot{Q}$ |       |
| Class name | thermal/LayerStorage |
### A.4 Mathematical operations

#### Sum

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
</table>
| **Information** | - Input signals must all be of the same unit  
- multiple signals can be connected to a single input |
| **Inputs** | $\vec{P}_+$ Plus added signals  
$\vec{P}_-$ Minus subtracted signals |
| **Outputs** | $P_{tot}$ Sum result of the sum |
| **Operation** | $P_{tot} = \sum_i P_{+,i} - \sum_j P_{-,j}$ (A.55) |
| **Class name** | math/Sum |

#### Gain

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Information</strong></td>
<td>- Input and output signal must all be of the same unit</td>
</tr>
<tr>
<td><strong>Inputs</strong></td>
<td>$P_{in}$ Input input signals</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td>$P_{out}$ Output output signal</td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td>$k$ gain predefined gain, from the machine configuration</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>$P_{out} = k \cdot P_{in}$ (A.56)</td>
</tr>
<tr>
<td><strong>Class name</strong></td>
<td>math/Gain</td>
</tr>
</tbody>
</table>
A Component model library

A.5 Basic control elements

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hysteresis</strong></td>
<td></td>
</tr>
<tr>
<td>Information</td>
<td>Intermediate switch when reaching a threshold value</td>
</tr>
<tr>
<td>Inputs</td>
<td></td>
</tr>
<tr>
<td>$P_{in}$</td>
<td>Input</td>
</tr>
<tr>
<td>Outputs</td>
<td></td>
</tr>
<tr>
<td>$P_{out}$</td>
<td>Output</td>
</tr>
<tr>
<td>Parameters</td>
<td></td>
</tr>
<tr>
<td>$P_{out,l}$</td>
<td>OutputLow</td>
</tr>
<tr>
<td>$P_{out,h}$</td>
<td>OutputHigh</td>
</tr>
<tr>
<td>$P_{tr,l}$</td>
<td>ThresholdLow</td>
</tr>
<tr>
<td>$P_{tr,h}$</td>
<td>ThresholdHigh</td>
</tr>
<tr>
<td>States</td>
<td></td>
</tr>
<tr>
<td>$S_{low}$</td>
<td>indicates if the state was low</td>
</tr>
<tr>
<td>Operation</td>
<td></td>
</tr>
<tr>
<td>$S_{low}[k]$</td>
<td>$= \ (S_{low}[k-1] \land (P_{in} &gt; P_{tr,l})) \lor$ (A.57)</td>
</tr>
<tr>
<td></td>
<td>$\ \lor \ \neg S_{low}[k-1] \land P_{in} \geq P_{tr,h}$ (A.58)</td>
</tr>
<tr>
<td>$P_{out}[k]$</td>
<td>$= \begin{cases} P_{out,l} &amp; \text{if } S_{low}[k] \text{ is true} \ P_{out,h} &amp; \text{else} \end{cases}$ (A.59)</td>
</tr>
<tr>
<td>Initialization</td>
<td>$S_{low}$ is true</td>
</tr>
<tr>
<td>Class name</td>
<td>control/HysteresisControl</td>
</tr>
</tbody>
</table>
## A.5 Basic control elements

**Switch**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Information</strong></td>
<td>Input signal is passed if the control signal has a certain value</td>
</tr>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
</tr>
<tr>
<td>$P_{in}$</td>
<td>Signal</td>
</tr>
<tr>
<td>$S_{ctrl}$</td>
<td>Control</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
</tr>
<tr>
<td>$P_{out}$</td>
<td>Output</td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td></td>
</tr>
<tr>
<td>$S_{high}$</td>
<td>passHigh</td>
</tr>
<tr>
<td>$P_{th}$</td>
<td>threshold</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td></td>
</tr>
<tr>
<td>$$ P_{out} = \begin{cases} P_{in} &amp; \text{if } S_{high} \land (P_{in} &gt; P_{th}) \text{ is true} \ P_{in} &amp; \text{if } \neg S_{high} \land (P_{in} &lt; P_{th}) \text{ is true} \ 0 &amp; \text{else} \end{cases} \quad (A.60) $$</td>
<td></td>
</tr>
<tr>
<td><strong>Class name</strong></td>
<td>control/SwitchControl</td>
</tr>
</tbody>
</table>
Test-bench model configuration

A machine configuration within the EMod framework consists of two parts: The component definition and the linking list. In the following appendix, all information required to set up the machine configurations used for this work is provided. In total, two configurations have to be listed. One representing the configuration derived during the system modelling, where the second one represents the optimized version of the later used during the error analysis. Parameter and process files are not discussed here, but the location of the original configuration files used is described in chapter D.

B.1 Machine components

All components used for the model of the test-bench machine are listed in table B.1. Each component has a property name, model type and parameter set. The component name is a unique identifier within the model, where the type describes the implemented model used for this component. Most of the components require a parameter set, which is stored in the machine component database. Additional model specific attributes are shown in the last column. As the machine configurations share the same machine components but one, only one table is used.

Table B.1: Complete list of the components used to model the test-bench machine Schaublin 42L in the EMod framework.

<table>
<thead>
<tr>
<th>Name</th>
<th>Model type</th>
<th>Parameter set</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>motor</td>
<td>Kessler_000101561</td>
<td></td>
</tr>
<tr>
<td>X1</td>
<td>servoMotor</td>
<td>FanucAlphaC6_2000</td>
<td></td>
</tr>
<tr>
<td>Z1</td>
<td>servoMotor</td>
<td>FanucAlphaC12_2000</td>
<td></td>
</tr>
<tr>
<td>Z3</td>
<td>servoMotor</td>
<td>FanucAlphaC12_2000</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>servoMotor</td>
<td>FanucAlphaM9_3000</td>
<td></td>
</tr>
</tbody>
</table>

continued on next page
### Table B.1: (Continued)

<table>
<thead>
<tr>
<th>Name</th>
<th>Model type</th>
<th>Parameter set</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1_ax</td>
<td>linAxis</td>
<td>Schaublin42L_X1</td>
<td></td>
</tr>
<tr>
<td>Z1_ax</td>
<td>linAxis</td>
<td>Schaublin42L_Z1</td>
<td></td>
</tr>
<tr>
<td>X1_Brake</td>
<td>constantComponent</td>
<td>FanucAlphaC6_2000</td>
<td></td>
</tr>
<tr>
<td>Z1_Brake</td>
<td>constantComponent</td>
<td>FanucAlphaC12_2000</td>
<td></td>
</tr>
<tr>
<td>X1_BrakeAction</td>
<td>switchControl</td>
<td>–</td>
<td>signalUnit: NEWTONMETER</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>controlUnit: NONE</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>threshold: 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>passHigh: false</td>
</tr>
<tr>
<td>Z1_BrakeAction</td>
<td>switchControl</td>
<td>–</td>
<td>signalUnit: NEWTONMETER</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>controlUnit: NONE</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>threshold: 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>passHigh: false</td>
</tr>
<tr>
<td>Z3_ax</td>
<td>linAxis</td>
<td>Schaublin42L_Tailstock</td>
<td></td>
</tr>
<tr>
<td>T1_pos</td>
<td>revolver</td>
<td>Schaublin42L</td>
<td></td>
</tr>
<tr>
<td>C1_amp</td>
<td>amplifier</td>
<td>FanucSPM-26</td>
<td></td>
</tr>
<tr>
<td>AxEnergy</td>
<td>sum</td>
<td>–</td>
<td>unit: WATT</td>
</tr>
<tr>
<td>Ax_amp</td>
<td>amplifier</td>
<td>FanucSVM2-20-20</td>
<td></td>
</tr>
<tr>
<td>Z3_amp</td>
<td>amplifier</td>
<td>FanucSVU1-80</td>
<td></td>
</tr>
<tr>
<td>B1_amp</td>
<td>amplifier</td>
<td>FanucSVM1-80</td>
<td></td>
</tr>
<tr>
<td>CuttingFluidPump</td>
<td>pump</td>
<td>SpandauVogel_PV80_180</td>
<td></td>
</tr>
<tr>
<td>SpindleCoolingCompressor</td>
<td>pump</td>
<td>Hyfra_VKW_21_1S</td>
<td></td>
</tr>
<tr>
<td>SpindleCoolingPump</td>
<td>pump</td>
<td>Hyfra_VKW_21_1S</td>
<td></td>
</tr>
<tr>
<td>SpindleCoolingController</td>
<td>hysteresisControl</td>
<td>SpindleCoolingCompressor</td>
<td></td>
</tr>
<tr>
<td>ChipConveyor</td>
<td>constantComponent</td>
<td>Bonfigioli_BN80_4A</td>
<td></td>
</tr>
<tr>
<td>Fan_in</td>
<td>fan</td>
<td>Pfannenberg_PF_3000</td>
<td></td>
</tr>
<tr>
<td>Fan_out</td>
<td>fan</td>
<td>Pfannenberg_PF_3000</td>
<td></td>
</tr>
<tr>
<td>FanucTotalPower</td>
<td>sum</td>
<td>–</td>
<td>unit: WATT</td>
</tr>
<tr>
<td>FanucTotalHeatLoss</td>
<td>sum</td>
<td>–</td>
<td>unit: WATT</td>
</tr>
<tr>
<td>CompressedAir</td>
<td>compressedFluid</td>
<td>Air8bar</td>
<td></td>
</tr>
<tr>
<td>ControlPowerTransformer</td>
<td>sum</td>
<td>–</td>
<td>unit: WATT</td>
</tr>
<tr>
<td>TotalPower</td>
<td>sum</td>
<td>–</td>
<td>unit: WATT</td>
</tr>
<tr>
<td>TotalHeatLoss</td>
<td>sum</td>
<td>–</td>
<td>unit: WATT</td>
</tr>
<tr>
<td>Thermal_SpindleTemperature</td>
<td>homogStorage</td>
<td>Kessler_000101561</td>
<td></td>
</tr>
<tr>
<td>parentType: Motor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal_SpindleFreeFlow</td>
<td>freeHeatTransfere</td>
<td>Kessler_000101561</td>
<td></td>
</tr>
<tr>
<td>parentType: Motor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal_SpindleHeatExchanger</td>
<td>layerStorage</td>
<td>SpindleHeatExchanger</td>
<td></td>
</tr>
<tr>
<td>Thermal_CoolerBackflow</td>
<td>forcedHeatTransform</td>
<td>CoolingFluidSpindle</td>
<td></td>
</tr>
<tr>
<td>Thermal_CoolerTemperature</td>
<td>homogStorage</td>
<td>Hyfra_VKW_21_1S</td>
<td></td>
</tr>
<tr>
<td>parentType: HeatExchanger</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal_PumpLossToFluid</td>
<td>gain</td>
<td>–</td>
<td>unit: WATT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>gain: 0.3</td>
</tr>
<tr>
<td>Thermal_PumpLossToAmbient</td>
<td>sum</td>
<td>–</td>
<td>unit: WATT</td>
</tr>
<tr>
<td>Thermal_CoolerFreeFlow</td>
<td>freeHeatTransfere</td>
<td>Hyfra_VKW_21_1S</td>
<td></td>
</tr>
</tbody>
</table>

continued on next page
B.2 Component linking

How the components described in the last section interact with each other, is defined in the component linking. Since the raw file with the input output connections is hard to read, a graphical illustration is used. The original files of the machine configurations can be found at the place listed in chapter D. Given the files defining the machine components and linking, a flow chart of the model can be draw. To do so, the *dot* language of the *Graphviz* software package is used. The results of this automatically generated flowcharts are shown on the following pages. Since the two machine configurations show more differences in the component linking than in the component definitions, the two configurations are show separate. Additional to the components, simulators are objects used in the model configuration. Simulators are thereby used to inject control or process signals into the model components. To differ between simulators, electro-mechanical components and thermal models different colors are used:

- **blue**: Simulators and simulation control signals
- **red**: Thermal subsystem model
- **black**: Electromechanical components
- **dashed**: Temperature signals

A final remark on the output ports of the components listed in the following charts: The information to draw the following charts is taken from the machine configuration. Thereby only the connected output ports can be seen. This is the reason, why some outputs are not listed in the charts, even if they are defined in the models. Since every input must be connected to a signal, the lists of input ports are complete.

---

1Only used in optimized model
Figure B.1: Test bench machine model linking
B.2.2 Optimized test cases model

Figure B.2: Optimized machine model linking
Measurement configurations and protocols

In total three measurement setting are created for the model validation. The following sections replenish the information given in chapter 4. This complements cover the full measurement configurations and protocols, as the machine programs and cycles used during the measurements. To do so, the following abbreviations are used:

**Abbreviations**

- **ID** identification, consecutively enumeration of the measurements within a configuration
- **SID** system identification number,
- **FID** file identification number, unique number for each measurement referring to the file with the raw data of the measurement
- **NCI** new cutting inlet; indicates, if a new cutting edge has been used. Generally for each cut with material remove, a new cutting edge is used
- **NWP** new wrought part; indicates, if a new wrought part has been installed
- **CF** cutting fluid, is set to yes if cutting fluid has been used
- **X** referring to the programmed x-coordinate for the cutting tool. The x-coordinate is thereby set by the diameter
## C.1 Parameter identification measurement

For the parameter identification measurement, the machine program in section C.4.1 is used, where the parameters are changed according to table C.1. For each cut, a new cutting insert is used. A new wrought part is installed when the remaining diameter did not allow the demanded cutting velocity due to the spindle speed limitation. In order to have known initial conditions, every new wrought part is first reduced to a diameter of 40 mm before taking the measurement.

<table>
<thead>
<tr>
<th>ID</th>
<th>SID</th>
<th>NCI</th>
<th>NWP</th>
<th>( f )</th>
<th>( a_p )</th>
<th>( X )</th>
<th>( v_c )</th>
<th>( L )</th>
<th>CF</th>
<th>Material</th>
<th>FID</th>
<th>start</th>
<th>stop</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>yes</td>
<td>yes</td>
<td>0.10</td>
<td>1.2</td>
<td>37.6</td>
<td>100</td>
<td>50</td>
<td>yes</td>
<td>51CrV4</td>
<td>1</td>
<td>12:22:30</td>
<td>12:23:11</td>
<td>Begin energy measurement, 2× overturn</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>yes</td>
<td>no</td>
<td>0.12</td>
<td>1.2</td>
<td>35.2</td>
<td>100</td>
<td>50</td>
<td>yes</td>
<td>51CrV4</td>
<td>3</td>
<td>12:26:41</td>
<td>12:27:11</td>
<td>Measurement failed</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>yes</td>
<td>no</td>
<td>0.18</td>
<td>1.2</td>
<td>32.8</td>
<td>100</td>
<td>50</td>
<td>yes</td>
<td>51CrV4</td>
<td>4</td>
<td>12:29:12</td>
<td>12:29:30</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>yes</td>
<td>no</td>
<td>0.20</td>
<td>1.2</td>
<td>30.4</td>
<td>100</td>
<td>50</td>
<td>yes</td>
<td>51CrV4</td>
<td>5</td>
<td>12:31:25</td>
<td>12:31:38</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>yes</td>
<td>no</td>
<td>0.12</td>
<td>1.2</td>
<td>28.0</td>
<td>100</td>
<td>50</td>
<td>yes</td>
<td>51CrV4</td>
<td>8</td>
<td>12:34:25</td>
<td>12:34:49</td>
<td>Measurement failed due to CF</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>yes</td>
<td>no</td>
<td>0.18</td>
<td>1.2</td>
<td>25.6</td>
<td>100</td>
<td>50</td>
<td>yes</td>
<td>51CrV4</td>
<td>9</td>
<td>12:38:05</td>
<td>12:38:18</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>yes</td>
<td>no</td>
<td>0.20</td>
<td>1.2</td>
<td>23.2</td>
<td>100</td>
<td>50</td>
<td>yes</td>
<td>51CrV4</td>
<td>12</td>
<td>12:44:26</td>
<td>12:44:38</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>yes</td>
<td>no</td>
<td>0.10</td>
<td>1.2</td>
<td>20.8</td>
<td>100</td>
<td>50</td>
<td>yes</td>
<td>51CrV4</td>
<td>14</td>
<td>12:46:50</td>
<td>12:47:11</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>4</td>
<td>yes</td>
<td>yes</td>
<td>0.20</td>
<td>1.2</td>
<td>38.6</td>
<td>100</td>
<td>50</td>
<td>yes</td>
<td>51CrV4</td>
<td>15</td>
<td>12:52:23</td>
<td>12:52:43</td>
<td>1× overturn</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>yes</td>
<td>no</td>
<td>0.18</td>
<td>1.2</td>
<td>36.2</td>
<td>100</td>
<td>50</td>
<td>yes</td>
<td>51CrV4</td>
<td>16</td>
<td>12:55:07</td>
<td>12:55:27</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>yes</td>
<td>no</td>
<td>0.12</td>
<td>1.2</td>
<td>33.8</td>
<td>100</td>
<td>50</td>
<td>yes</td>
<td>51CrV4</td>
<td>17</td>
<td>12:57:18</td>
<td>12:57:47</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>yes</td>
<td>no</td>
<td>0.10</td>
<td>1.2</td>
<td>31.4</td>
<td>100</td>
<td>50</td>
<td>yes</td>
<td>51CrV4</td>
<td>18</td>
<td>12:59:19</td>
<td>12:59:52</td>
<td></td>
</tr>
</tbody>
</table>

**Table C.1:** Full measurement configuration and documentation taken during the measurement process for the parameter identification measurement. The terms used in the col-headers are the same as defined at the begin of this chapter. [Taken at 09.12.2011]
C.2 Energy model validation measurement

The energy model validation measurement consists of two sets: One to validation the simplifications made and one to validate the implemented components. The first measurement sets did not request a process to be running. While the program in section C.4.1 is used for the component validation measurement.

C.2.1 Model simplification validation

The model simplification validation measurements focus on the use of the revolver, the part clamp and the tail-stock. Following the three measurement configurations with the time protocol.

<table>
<thead>
<tr>
<th>ID</th>
<th>SID</th>
<th>positions</th>
<th>direction</th>
<th>start</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>cw</td>
<td>13:56:00</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>ccw</td>
<td>13:56:15</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>cw</td>
<td>13:56:30</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>1</td>
<td>ccw</td>
<td>13:56:45</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1</td>
<td>cw</td>
<td>13:57:00</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>1</td>
<td>ccw</td>
<td>13:57:15</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>3</td>
<td>cw</td>
<td>14:00:00</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>3</td>
<td>ccw</td>
<td>14:00:30</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>3</td>
<td>cw</td>
<td>14:01:00</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>3</td>
<td>ccw</td>
<td>14:01:30</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>3</td>
<td>cw</td>
<td>14:02:00</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>3</td>
<td>ccw</td>
<td>14:02:30</td>
<td></td>
</tr>
</tbody>
</table>

*Table C.2: Full measurement configuration and protocol for the revolver measurement. Each set names the direction of rotation (clock-wise, counter clock-wise) and the number of positions rotated. [Taken at 07.02.2012]*
### C Measurement configurations and protocols

<table>
<thead>
<tr>
<th>ID</th>
<th>SID</th>
<th>action</th>
<th>start [hh:mm:ss]</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>close clamp</td>
<td>14:24:00</td>
<td>clamp at 5.4 bar = 2750 daN [Sch99a]</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>open clamp</td>
<td>14:24:30</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>close clamp</td>
<td>14:25:00</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>open clamp</td>
<td>14:25:30</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>close clamp</td>
<td>14:26:00</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>open clamp</td>
<td>14:26:30</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>close clamp</td>
<td>14:27:00</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>open clamp</td>
<td>14:27:30</td>
<td></td>
</tr>
</tbody>
</table>

**Table C.3:** Full measurement configuration and protocol for the part clamping measurement. [Taken at 07.02.2012]

<table>
<thead>
<tr>
<th>ID</th>
<th>SID</th>
<th>force [daN]</th>
<th>start [hh:mm:ss]</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>106</td>
<td>15:02:00</td>
<td>door opened one time</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>206</td>
<td>15:04:30</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>307</td>
<td>15:06:30</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>401</td>
<td>15:08:30</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>503</td>
<td>15:10:30</td>
<td>finished at 15:12:30</td>
</tr>
</tbody>
</table>

**Table C.4:** Full measurement configuration and protocol for the tail-stock measurement. [Taken at 07.02.2012]
C.2.2 Component model validation

As for the parameter identification measurement, the machine cycle program in section C.4.1 with a new cutting insert of each measurement is used. Again, the wrought part is changed if a critical diameter is reached, followed by a dress to 40 mm diameter. During the measurement, a registered damage on the cutting fluid pipe occur.

**Table C.5:** Full measurement configuration and documentation taken during the measurement process for the energy model validation measurement. The terms used in the col-headers are the same as defined at the begin of this chapter. [Taken at 05.12.2011]

<table>
<thead>
<tr>
<th>ID</th>
<th>SID</th>
<th>NCI</th>
<th>NWP</th>
<th>( f )</th>
<th>( \alpha_p )</th>
<th>( X )</th>
<th>( v_c )</th>
<th>( L )</th>
<th>CF</th>
<th>Material</th>
<th>FID</th>
<th>start</th>
<th>stop</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>no</td>
<td>yes</td>
<td>0.15</td>
<td>0.0</td>
<td>50.0</td>
<td>100</td>
<td>50</td>
<td>–</td>
<td>51CrV4</td>
<td>15:02:30</td>
<td>15:03:15</td>
<td>Air cut</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>yes</td>
<td>no</td>
<td>0.15</td>
<td>1.0</td>
<td>38.0</td>
<td>100</td>
<td>50</td>
<td>yes</td>
<td>51CrV4</td>
<td>15:07:58</td>
<td>15:08:35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>yes</td>
<td>no</td>
<td>0.15</td>
<td>1.2</td>
<td>35.6</td>
<td>100</td>
<td>50</td>
<td>yes</td>
<td>51CrV4</td>
<td>15:10:45</td>
<td>15:11:20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>yes</td>
<td>no</td>
<td>0.15</td>
<td>1.4</td>
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C.3 Thermal model validation measurement

During the measurement of the thermal behaviour of the machine, the machine cycle of section C.4.2 is used. Since the measurement window is limited in time by the temperature measurement software, restarts have been required. In the second part, with overturning instead of face turning have been done. This measurements are not used for the validation.

Table C.6: Full measurement protocol for the thermal model validation measurement. [Taken at 05.12.2011 to 06.12.2011]

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<td>10:35:25</td>
<td>Begin temperature measurement</td>
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<td>10:45:00</td>
<td>Begin energy measurement N03</td>
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<td>10:47:40</td>
<td>Machine main switch closed</td>
<td>Machine did not start, amplifier error</td>
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<td>10:58:00</td>
<td>Main switch off, on, off, …</td>
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<tr>
<td>11:20:00</td>
<td>Machine ready</td>
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<tr>
<td>13:21:00</td>
<td>Dry run</td>
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<tr>
<td>13:22:00</td>
<td>Dust collection on</td>
<td>Shop floor installation</td>
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<tr>
<td>13:35:46</td>
<td>Begin force measurement FID 01</td>
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<td></td>
<td>Begin face turning</td>
<td></td>
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<td>13:50:30</td>
<td>Stop turning, stop force measurement</td>
<td>Setting max. rot. speed to 2000rpm</td>
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<td>14:01:35</td>
<td>Begin face turning FID 02</td>
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<td>Stop process</td>
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<td>Begin face turning FID 05</td>
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<td>Begin face turning FID 06</td>
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<td>15:37:00</td>
<td>Begin new temperature measurement</td>
<td>Stop process</td>
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<td>14:16:00</td>
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<td>Setup of new machine cycle: Overturning instead of face turning</td>
<td>Not used in the validation</td>
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<td>15:59:30</td>
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<td>Begin overturning</td>
<td>FID 08</td>
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C Measurement configurations and protocols

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<td>Machine to stand-by</td>
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C.4 Machine cycle programs

For the measurements the following two machine cycle programs are used. The information is given by the laboratory engineer and the machine documentation [Sch99a].

C.4.1 Turning, single cut

```
O0324 (TLB D42MM l SCHNITT) ;
M820 G92 S6000 ;
G28 U0 W0 ;
;
T0202 (DREHEN KMP) ;
G0 G95 G96 G54 Z5 X65 ;
X40 F0.15 S100 M104 S100 M104 (PARAMETER) ;
;
M8 (KSS EIN) ;
G04 X2 (WARTEZEIT) ;
M601 ;
G1 Z-55;
M611 M09 ;
G0 X80 ;
X200 Z50 ;
M30 (M30 ODER M99) ;
```

C.4.2 Face turning, roughing cycle

```
O0001 ;
M820 G92 S2000 ;
N5 G28 U0 W0 ;
N10 T0202 ;
N15 G0 G95 G96 G54 Z5 X64 M104 S100 ;
```
C.4 Machine cycle programs

N20 G01 X43 Z0.5 F0.2 ;
N25 M8 ;
N30 G74 U1 R2 ;
N35 G74 P40 Q45 W0 F0.1 S100 T0202 ;
N40 G1 Z-40;
N45 X0 ;
N50 N55 G0 G40 X80 Z100 M5 ;
N55 M30 (M30 ODER M99) ;
CD disk contents

1 Literature ................................. Used literature in digital form
   Energy models .............................. Papers about machine tool energy models
   Kienzle ................................... Parameter identification and design of experiment
   Latex ....................................... Documentation of the packages used for the report
   Measurements ............................ Papers about machine tool energy measurements
   Methodologies ............................ Analysis and validation methods and procedures
   Simulation ................................. Numerical ODE solvers and implementations

2 Test-bench ................................... Test-bench and installed equipment informations
   Machinery materials ........................ Factsheets and informations
   Measurement system ......................... Factsheets for energy, temperature and force measurement
   Schaublin 42L ................................ Type plates, factsheets and correspondence
   Tools ........................................ Used cutting inserts and tool holders

3 Measurements ................................ Planing, raw data and preprocessed data
   2011-11-10 .................................. Basic test measurement, data is not used here
   2011-12-05 .................................. Known as component model validation measurement
   2011-12-09 .................................. Known as parameter identification measurement
   2011-12-15 .................................. Known as thermal model validation measurement
   2011-12-22 .................................. Test measurements on Fanuc output
   2012-02-07 .................................. Known as Model simplification validation measurement

   Messprotokoll_Schaublin_Kienzle_20111205.docx
   Messprotokoll_Schaublin_Kienzle_20111209.docx
   Messprotokoll_Schaublin_Testmessung_20111110.docx
   PlanungMessreiheSchaublin42LTMi3.docx
   PlanungMessreiheSchaublin42LTMi3_20120207_Nachmessungen.docx
   VerkabelungSchaublin.xlsx

continued on next page
4_Simulations

Simulation data and analysis results

- 2011-12-05
- 2011-12-05_OptiParam
- 2011-12-09
- 2011-12-15_Cooldown
- 2011-12-15_Operation
- 2011-12-15_Ready
- 2011-12-15_Warmup

5_Analysis

Used analysis tools and implemented functions

- Matlab
  - Various functions for analysis procedures
- Downloads
  - External packages download from Mathworks
- Figures
  - Plotting and report oriented functions
- KienzeParameters
  - Force measurement preprocessing and parameter identification
- ParameterIdentification
  - Component parameter identification
- ProcessFileGenerator
  - Parser for time series to xml file
- Simulink
  - Heat exchanger simulation experiments
- ThermalMeasurement
  - Thermal measurement preprocessing
- Validerung
  - Validation and simulation analysis orient routines
- supportingFunctions
  - General functions, used for multiple purposes
- Papiercomputer.ods
  - Influence/interference analysis implementation
- Sensitivity_Analysis.nb
  - Mathematica notebook for sensitivity calculations

6_EMod

Standalone version of the framework, rev. 95

- README.TXT
  - Basic information about configuration and execution
- EMod.jar
  - Java archive with the framework classes
- MachineComponentDB
  - Component database
- Machines
  - Machine and simulation configurations
- app.config

7_Report

Latex files, editable figures and final output

- thesis.pdf
  - Final report file

8_Presenations

- EcodesignMethodenToolbox20120118Praesentation_sizuest.pptx
- ZwischenPraesentation_sizuest.pptx
Bibliography


Bibliography


Titel der Arbeit:

Development and verification of an energetic machine tool model on the example of a turning machine

Art der Arbeit und Datum:

Masterarbeit, date

Betreuung:

Andreas Leuenberger
Adam Gontarz
Lukas Weiss

Student:

Name: Simon D. Züst
E-mail: sizuest@ethz.ch
Legi-Nr.: 06-909-923


Zürich, 10. 5. 2012: __________________________