

# OBJECT-ORIENTED MULTI-DOMAIN MODELLING OF MACHINE TOOLS: A CASE STUDY

Bernhard Heinzl<sup>(a)</sup>, Michael Landsiedl<sup>(b)</sup>, Niki Popper<sup>(c)</sup>,  
Alexandros-Athanassios Dimitriou<sup>(d)</sup>, Fabian Dür<sup>(e)</sup>, Friedrich Bleicher<sup>(f)</sup>,  
Christian Reinisch<sup>(g)</sup>, Felix Breitenecker<sup>(h)</sup>

<sup>(a) (g)</sup>Institute for Computer Aided Automation, Vienna University of Technology  
<sup>(a) (b) (c)</sup>dwh Simulation Services, Vienna

<sup>(d) (e) (f)</sup>Institute for Production Engineering and Laser Technology, Vienna University of Technology

<sup>(h)</sup>Institute for Analysis and Scientific Computing, Vienna University of Technology

<sup>(a)</sup>[bernhard.heinzl@tuwien.ac.at](mailto:bernhard.heinzl@tuwien.ac.at), <sup>(b)</sup>[michael.landsiedl@drahtwarenhandlung.at](mailto:michael.landsiedl@drahtwarenhandlung.at), <sup>(c)</sup>[niki.popper@drahtwarenhandlung.at](mailto:niki.popper@drahtwarenhandlung.at),  
<sup>(d)</sup>[dimitriou@ift.at](mailto:dimitriou@ift.at), <sup>(e)</sup>[duer@ift.at](mailto:duer@ift.at), <sup>(f)</sup>[bleicher@ift.at](mailto:bleicher@ift.at), <sup>(g)</sup>[christian.reinisch@tuwien.ac.at](mailto:christian.reinisch@tuwien.ac.at), <sup>(h)</sup>[felix.breitenecker@tuwien.ac.at](mailto:felix.breitenecker@tuwien.ac.at)

## ABSTRACT

A number of current research projects aim at increasing energy efficiency in production by using comprehensive simulation models of manufacturing plants. In order to gain knowledge about the optimization potential of machine tools, a simulation model of a turning lathe is developed. Using an object-oriented modelling approach allows combining component models of mechanical, electrical and thermal parts in a structural manner in one multi-domain model. This bottom-up approach is combined with stepwise top-down modelling in three stages in order to identify numerical boundaries of the simulation. Simulation results are validated against measurement data. It is confirmed that object-oriented modelling leads to flexible and modular models, but the automatically generated equations are less efficient during simulation, therefore making it necessary to perform manual adjustments in the model. To increase simulation speed, multirate simulation is performed in Simscape using local implicit fixed-step solvers.

Keywords: object-oriented, machine tool, turning lathe, Simscape

## 1. INTRODUCTION

Rising energy costs and efforts to increase productivity in manufacturing facilities lead to an increased focus on energy efficiency in production. Especially machine tools in metal-cutting manufacturing are among the largest consumers of energy, which have great potential for optimization compared to other energy-intensive manufacturing processes.

For this reason, several current research projects aim at increasing energy efficiency in production by developing comprehensive simulation models of production halls for energy analysis in order to be able to make qualified prediction about the efficiency of different energy saving measures and identify optimization potential (Dorn and Bleicher 2010).

One part of this project investigates the micro-structures of production plants (individual processes and machines) by making extensive energy analysis based on simulation models. Some of these aspects are studied in more detail by developing a multi-domain model of a turning lathe as an example of a machine tool.

A comprehensive approach combines electrical, mechanical as well as thermal aspects of the lathe in one overall model, which afterwards allows for extensive analysis and evaluation regarding energy distribution, comparison of feed and cutting forces as well as dissipated heat.

For modelling we consider a high-level object-oriented approach for physical systems, which provides flexibility and modularity for combining bottom-up modelling with stepwise top-down development in three stages with increasing level of detail. An overview is given in figure 1.

This procedure enables identifying numerical boundaries of the simulation and shows which model complexity can be handled with sufficient performance and which physical components can therefore be taken into account.

Simulation results are validated against real measurement data obtained from an actual turning lathe.

Implementation is done in MATLAB/Simscape as a common simulator for object-oriented modelling of physical systems (MathWorks 2011a; MathWorks 2011b).

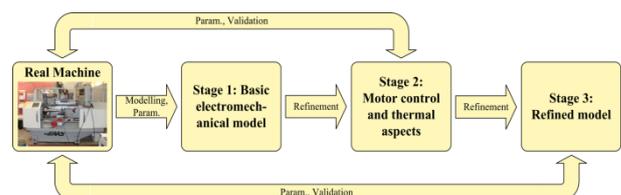


Figure 1: Overview of the Three Stages in the Modelling Process

## 2. STAGE 1: BASIC ELECTROMECHANICAL MODEL

A first step for model development requires investigation of the turning lathe to be modelled and identification of the main electrical and mechanical components. Although the considered machine tool is rather simple compared to others, it provides sufficient possibilities for our investigations. There are three main drivelines:

- Main drive: Main motor, gear belt drive, spindle with chuck and workpiece
- Longitudinal feed (z-axis): Servomotor, lead-screw drive, linear bearings and slide holding the cross feed
- Cross feed (x-axis): Servomotor, leadscrew drive, linear bearings and cross-slide with tool holder and cutting tool

The main drive sets the workpiece into rotation, longitudinal and cross feed drives allow positioning the tool in z- and x-direction (axial and radial to the workpiece), see figure 2. During machining, the cutting tool penetrates the workpiece and removes material in form of a chip during relative motion. The cutting energy is mostly converted into thermal energy. All three drivelines receive their electric power from an inverter, which is simplified in the first step as ideal voltage sources.

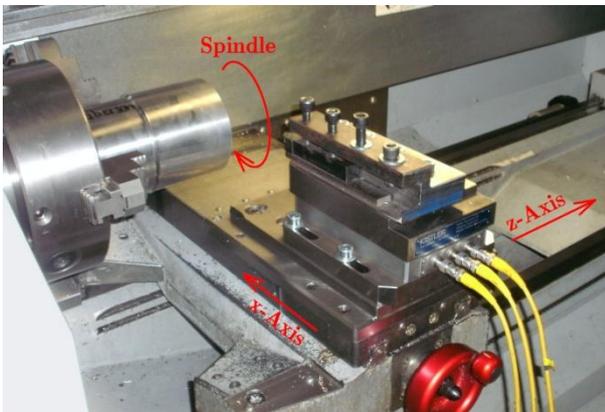


Figure 2: The Three Axes of the Lathe: Spindle for Driving the Workpiece, Longitudinal and Cross Feed for Positioning the Tool in the z- and x-Direction.

For implementing the developed simulation models, we chose Simscape as an extension of MATLAB/Simulink for object-oriented multi-domain modelling and simulation of physical systems (MathWorks 2011a, MathWorks 2011b).

The first overall model is comparatively simple and contains the main mechanical and electrical components of the main drive and the slides for automatic feed and infeed. As part of this first model, figure 3 shows the Simscape model of the main drive with asynchronous engine, voltage supply, gear belt drive, friction components and mechanical loads such as inertias from spindle, chuck and workpiece. The basic structure

of the drive is easy to see which is helpful for further model adjustments and refinements, therefore pointing out one of the big advantages of this object-oriented modelling approach.

The asynchronous motor as well as the servo motors for the remaining drives of the lathe and certain basic mechanical components like gear belt drive, lead screw and linear bearings are modelled as Simscape components using Simscape Language (see MathWorks 2011a) with parameters extracted from available data sheets. A code fragment of this implementation for the asynchronous machine is depicted in figure 4. It shows common equations in normalized space vector description that can be found in relevant literature (e.g. Schröder 2009).

```

component AsynchronousMachine
(...)
parameters (Access = public, Hidden = true)
    M = 2/3*[1,-1/2,-1/2;0,sqrt(3)/2,-sqrt(3)/2];
end
equations
    (...)
    us' == M*[u1;u2;u3]; is' == M*[i1;i2;i3];
    i1 + i2 + i3 == 0;
    %Standardized equations for ASM
    us == is*rs + psis.der/Omegaref_el;
    ur == ir*rr + psir.der/Omegaref_el...
        -[-psir(2),psir(1)]*omegam;
    psis == ls*is + ls*(1-sigma)*ir;
    psir == ls*(1-sigma)*(is+ir);
    ur == [0,0];
    %Torque equation
    mr == is(2)*psir(1)-is(1)*psir(2);
end

```

Figure 4: Code Fragment of the Asynchronous Machine Model Using Simscape Language.

Existing Simscape blocks from the Simscape Foundation library (see MathWorks 2011b) complete the model with components for inertia, friction and sensor blocks for measuring state variables. During the machining process, the cutting force generates an additional torque on the motor. This load is modelled as a torque source, where the value of the torque is calculated externally using common formulas and parameters (like shown in Degner et al. 2009).

In order to keep the first model simple and focus on modelling of electrical and mechanical parts, feedback control for the drive motors is not included. This however limits possible simulation scenarios, for example only cases with constant motor speed can be considered. Also, thermal investigations are not yet provided in this model.

## 3. STAGE 2: MOTOR CONTROL AND THERMAL ASPECTS

The first modelling stage showed that the object-oriented modelling approach is indeed suitable for basic modelling tasks regarding machine tools. In this next stage we further develop the model and therefore obtain further possible simulation scenarios for observation.

The basic electromechanical model is extended by a number of components:

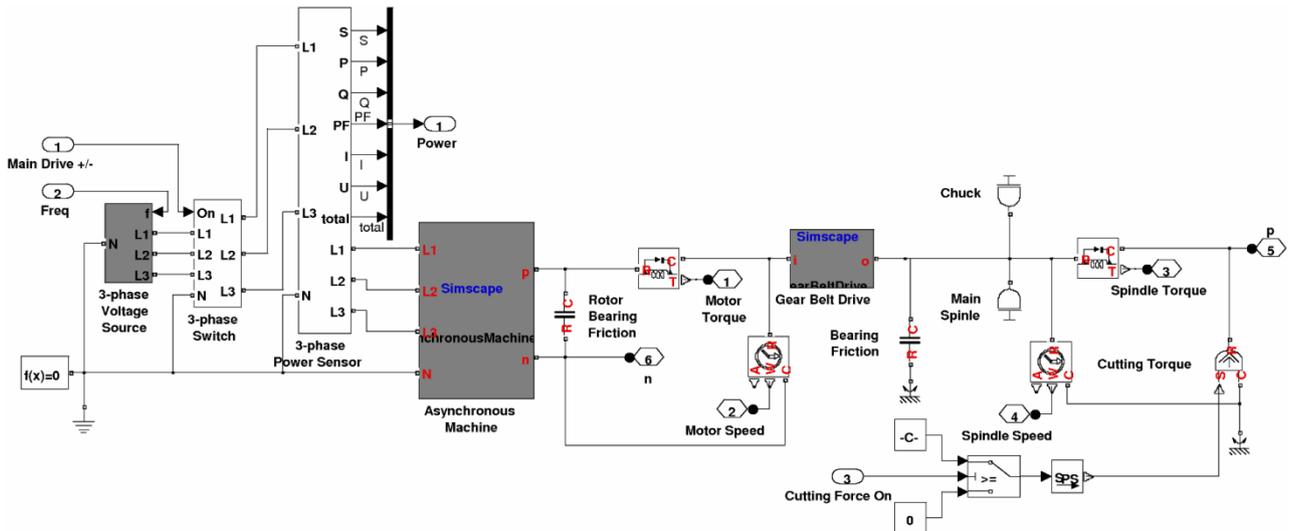


Figure 3: Main Drive of the Turning Lathe Model with Asynchronous Engine, Voltage Supply, Gear Belt Drive and Mechanical Loads.

- Feedback control for all three drive motors
- Calculation of generated heat in lossy components, especially the drive motors
- Heat transition to the environment
- Modelling of energy division in the cutting process

### 3.1. Modelling

The necessity for appropriate motor control for the overall dynamics is also established in (Heinzl et al. 2012). Figure 5 shows the subsystem for the feedback control implemented in Simulink. Cascaded controllers allow control of position, speed and stator current. Since the stator current is typically controlled in the rotor coordinate system, coordinate transformation with the actual rotor angle has to be performed. Nominal values are created including speed and acceleration limits according to target positions which are defined in advance. For controller design, we made use of available data from data sheets as well as manual iterative adjustment in order for the system to work properly.

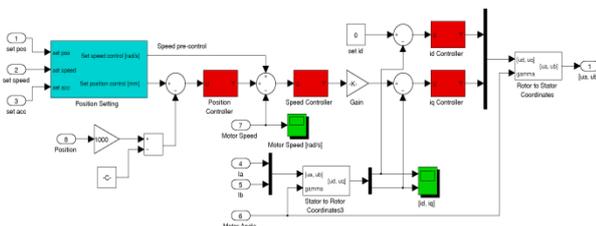


Figure 5: Slide Control with Position, Speed and Current Controller (Red Blocks) and Space Vector Output

The output of the controller subsystem is a vector for the stator voltage, which is then split into phase voltages for an idealized 3-phase converter, which directly supplies the drive motor. The graphical representation of this inverter can be seen in figure 6.

Further model extensions take the waste heat into account that is generated in various components, espe-

cially the drive motors, gear belt drive and friction elements. For that, all necessary components from the model in section 2 are modified with a thermal output port. The waste heat is stored and dissipated into the surrounding environment via convective and radiative heat transfer components, see figure 6. Necessary heat transfer coefficients are taken from available literature (Staton 2008; Boglietti 2003).

In order to increase simulation speed, some adjustments had to be made in the Simscape implementation already in this modelling stage. For that, the three drive trains (main drive, slide and cross-slide) were splint into separate Simscape networks (these are called physical networks or object diagrams), only connected via directed (causal) Simulink signal connections (an overview can be seen in figure 10). This enables more efficient equation generation and handling by the simulator.

### 3.2. Simulation Results

The modifications now allows for more complex simulation scenarios. As an example, we investigate the turning process sketched in figure 7. Used cutting parameters are:

- Cutting speed:  $v_c = 200 \frac{\text{m}}{\text{min}}$ ,
- Feed:  $f = 0.2 \frac{\text{mm}}{\text{U}}$ ,
- Cutting depth:  $a_p = 2 \text{ mm}$ ,
- Material: C45E.

Figure 8 depicts the respective trajectory of the tool tip and time values. All position values are measured with respect to the coordinate system illustrated in figure 7 (green arrows). The simulation starts at an outside position. First, slide and cross-slide are activated with maximum velocity in order to get to the start position for the turning process. After that, the turning process is started with smaller feed velocity. The impact

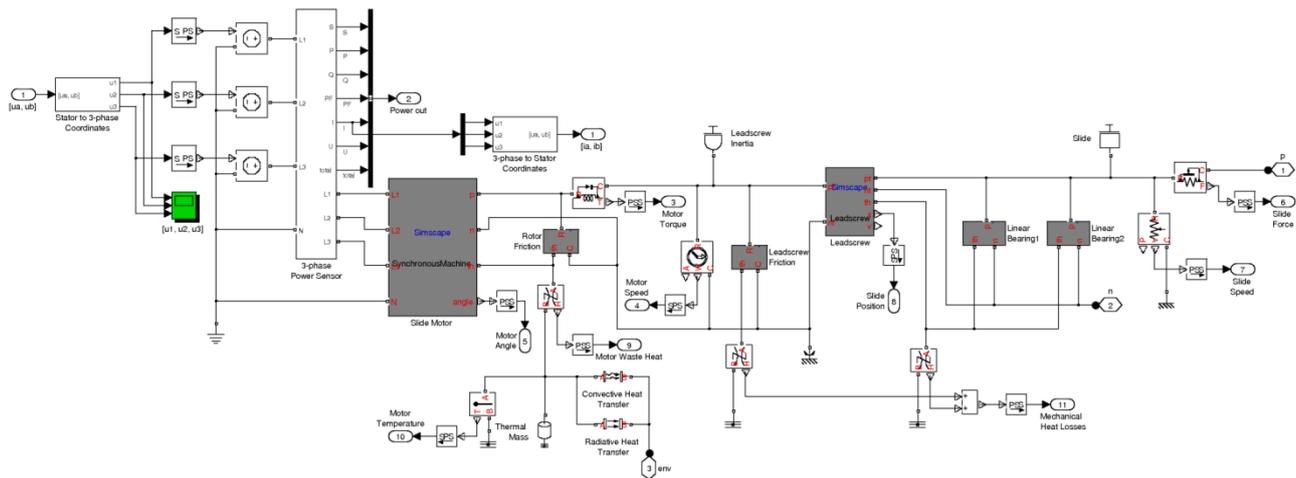


Figure 6: Model of the Slide Drive for the Turning Lathe with 3-phase Voltage Supply, Servomotor, Leadscrew Model, Linear Bearings and Thermal Components.

point between tool and workpiece does not leave any noticeable disturbances. The process is finished with negative infeed to the final position.

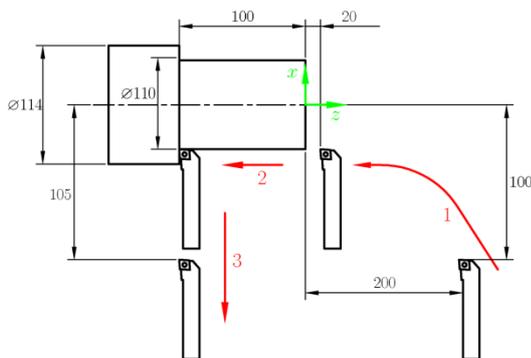


Figure 7: Investigated Simulation Scenario of a Typical Turning Process

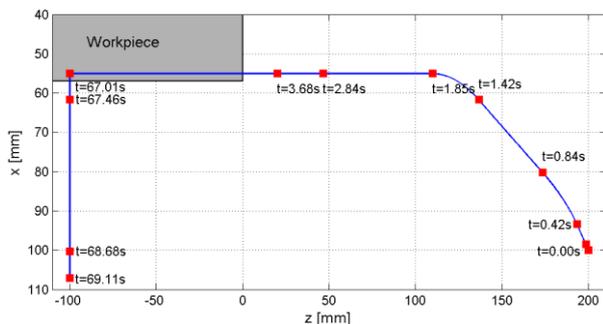


Figure 8: Trajectory of the Tool Tip and Time Values for the Simulation Scenario shown in Figure 7.

For validation, figure 9 compares the calculated total power consumption against measurement data obtained from the turning lathe. Although the cutting parameters were the same for both cases, there is still significant difference in the results, which shows that further model refinement is necessary.

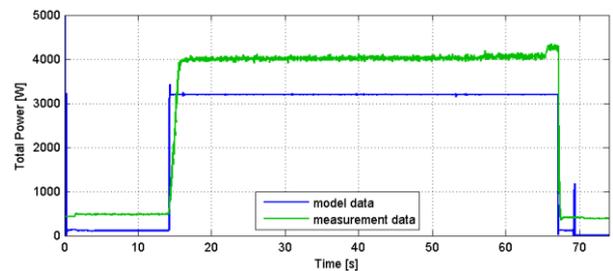


Figure 9: Comparison of Total Power Consumption Between Simulation and Measurement Data.

#### 4. STAGE 3: REFINED MODEL

In the third and final modelling stage, the model is refined by more detailed investigations of the energy supply including power electronic components for a rectifier and inverter.

##### 4.1. Modelling

Since the high-frequency switching operations of an inverter are difficult to realize with sufficient accuracy and simulation speed in a mainly continuous model, the switching inverter is replaced by an idealized version which only implements energy conservation and directly sets desired phase voltages.

Also, additional electrical loads like the control computer or lighting are considered because of their influence on the total power consumption.

For better simulation performance, the division of different drivelines into isolated Simscape networks (which are only connected to each other via directed (causal) Simulink signal connections), which was also mentioned in section 3, is continued and expanded on the new model of rectifier and inverter. Figure 10 given an overview of these Simscape networks. In the top part, the three blocks in the middle represent the subsystems for the drivelines shown in figure 3 and 6, resp., which each belong to a separate Simscape network.

In addition, Simscape allows combining the global solver algorithm with local implicit fixed-step solvers, which can handle isolated Simscape networks and

therefore allow performing multirate simulations for better performance (see also MathWorks 2011b). In the given model, this method is employed for the rectifier subsystem, which made it necessary to isolate the respective part from other Simscape networks based on assumptions for signal causality between these networks (see figure 10 bottom).

The local system appears as a discrete subsystem to the global solver, which triggers an event at each local step. A comparison of solver steps between global and local solver is given in figure 11.

On the one hand this results in loss of accuracy for the specified local part, but on the other hand the global solver does not have to resolve high-frequency oscillations in the inverter, since this part only appears as a discrete subsystem in the global model.

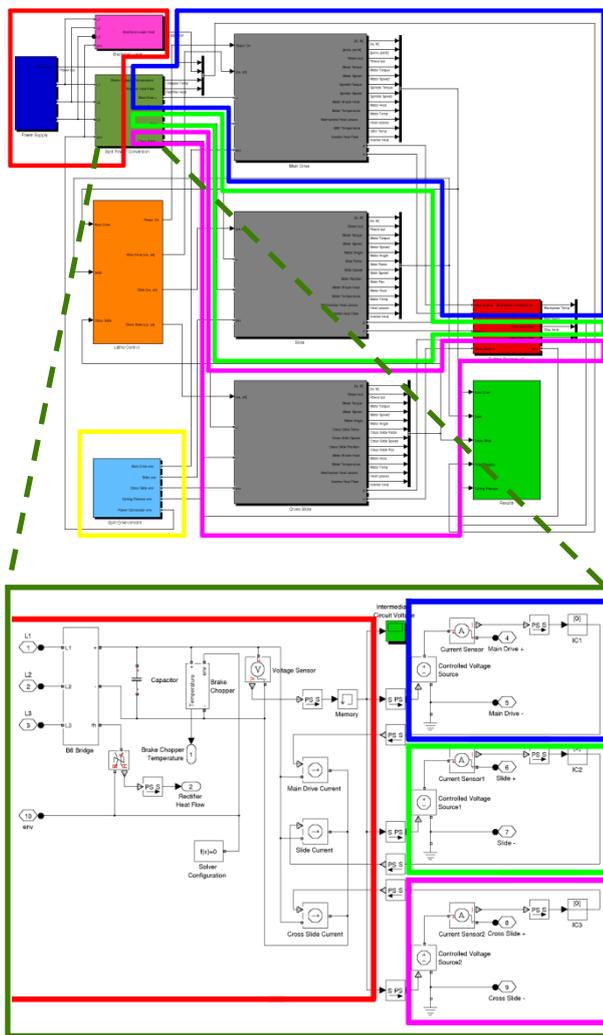


Figure 10: Top: Overview of the Total Simulation Model in Simulink/Simscape. Marked are the Separate Simscape Networks, Which are Only Connected to Each Other via Directed Simulink Signal Connections. Bottom: Detail of the Subsystem for the Electric 3-phase Converter, where the Three Inverters on the Right are Isolated from the Rectifier on the Left. The Left Part (Red) is Handled by a Local Solver Using Backward Euler Method.

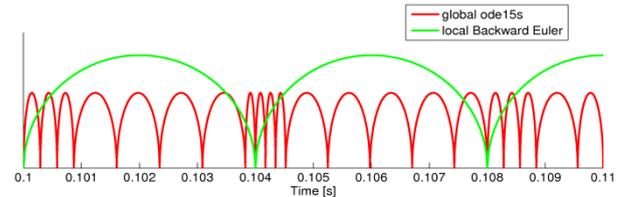


Figure 11: Comparison of Steps Between Local Solver (Backward Euler) and Global Solver (Simulink ode15s).

#### 4.2. Simulation Results

For comparison of simulation results, we again consider the scenario shown in figure 7. The results of a simulation run with the refined model are shown in Figure 12.

Figure 13 visualizes the energy distribution in the system for the given scenario. The input energy is converted into heat mainly in power electronics components, mechanical friction components and in the cutting process. A small part remains as latent energy in the system.

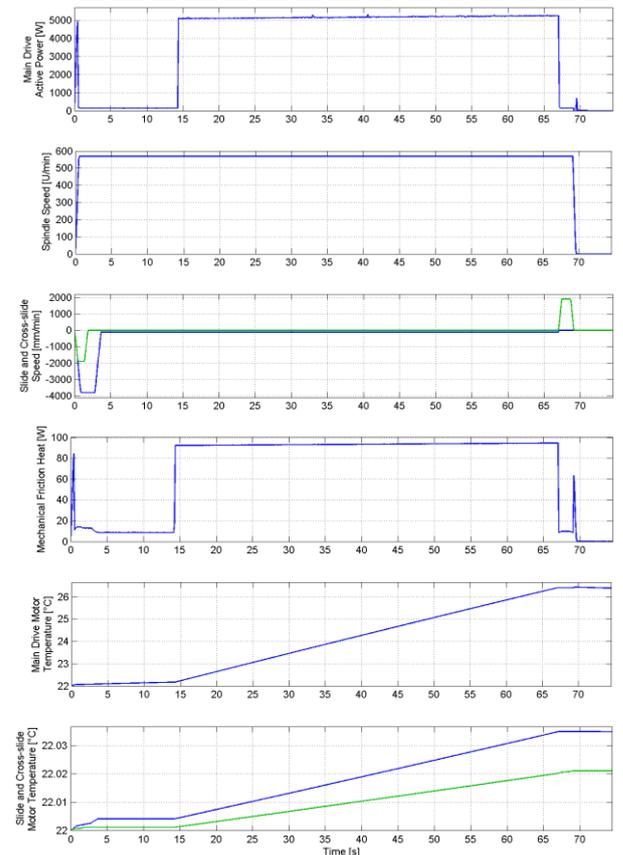


Figure 12: Results of a Simulation Run with the Refined Model. The Plots Show (from Top to Bottom) Main Drive Active Power, Spindle Speed, Slide and Cross-Slide Speed, Mechanical Friction Heat and Main Drive, Slide and Cross-Slide Motor Temperature.

For validation, figure 14 again shows the results for total power consumption compared to respective measurement data. Comparison with figure 9 shows significant better agreement for the refined model. The bottom part of figure 14 compares calculated feed and cutting forces with measurement data.

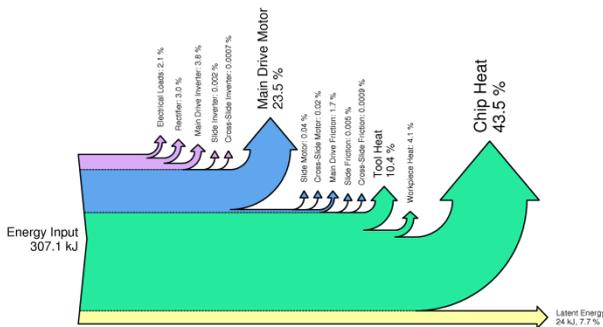


Figure 13: Energy Distribution in the System, Grouped by Parts where Input Energy is Converted into Heat (Power Electronics, Mechanical Friction, Cutting Process, Latent Energy)

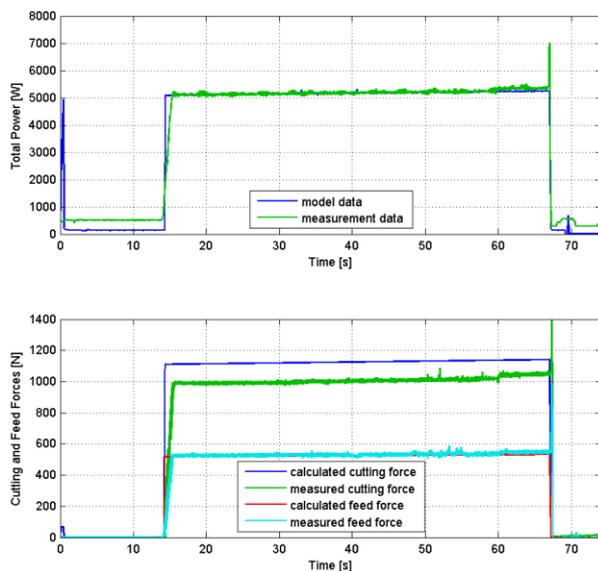


Figure 14: Comparison of Total Power Consumption (Top) as well as Feed and Cutting Forces (Bottom) Between Simulation and Measurement Data.

## 5. CONCLUSION

It can be said that the advantages of object-oriented modelling of physical systems have been confirmed in application. This approach leads to modular models, which preserve the basic structure of the original system and can easily be modified and adapted. However, this approach results in more complex models with a larger systems of equations, which moreover are less efficient for simulation, so that difficulties with insufficient performance are likely to occur even for models of moderate size.

Manual adjustment can help increasing simulation speed significantly, for example by splitting the model in isolated Simscape networks. This also allows performing multirate simulation using local Simscape solvers. However, splitting the model requires assumptions regarding signal causality, which basically is contradictory to the object-oriented modelling approach.

Comparison of the simulation results with measurement data showed sufficient agreement in principle, however some improvements in the models are still

possible, for example in the models for the drive motors or the cutting process.

## REFERENCES

- Boglietti, A., Cavagnino, A. and Staton, D.A., 2003. Thermal analysis of TEFC induction motors. *Industry Applications Conference*, p. 849-856.
- Degner, W., Lutze, H., and Smejkal, E., 2009. *Spanende Formung. Theorie – Berechnung – Richtwerte*. München: Hanser Verlag.
- Dorn, C. and Bleicher, F., 2010. Interdisziplinäre Forschung zur Energieoptimierung in Fertigungsbetrieben. *Junior Science Conference 2010*.
- Heinzl, B., Dorn, C. and Dimitriou, A., 2012. Object-oriented Modelling of Machine Tools for Energy Efficiency Analysis in Production. *In Proceedings of MATHMOD Vienna 2012 – 7th Vienna Conference on Mathematical Modelling*. February 15-17, 2012, Vienna.
- MathWorks 2011a. *Simscape Language Guide*. Available from: [http://www.mathworks.com/help/pdf\\_doc/phymod/simscape/Simscape\\_lang.pdf](http://www.mathworks.com/help/pdf_doc/phymod/simscape/Simscape_lang.pdf). [Accessed May 15, 2012].
- MathWorks 2011b. *Simscape User's Guide*. Available from: [http://www.mathworks.com/help/pdf\\_doc/phymod/simscape/Simscape\\_ug.pdf](http://www.mathworks.com/help/pdf_doc/phymod/simscape/Simscape_ug.pdf). [Accessed May 15, 2012].
- Schröder, D., 2009. *Elektrische Antriebe – Grundlagen*. Berlin Heidelberg: Springer. ISBN 978-3-642-02989-9.
- Staton, D.A. and Cavagnino, A., 2008. Convection heat transfer and flow calculations suitable for electric machines thermal models. *IEEE Transactions on Industrial Electronics*, p. 3509-3516.