A Case Study on Object-oriented Modelling and Simulation of Machine Tools

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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 energetic optimization potential of machine tools, a simulation model of a turning lathe is developed. Using an object-oriented modelling approach allows combining mechanical, electrical as well as thermal aspects in a structural manner into one comprehensive multi-domain model. This bottom-up approach is combined with stepwise top-down model refinement in three stages in order to identify numerical boundaries of the simulation. Simulation results are validated against measurement data. Though object-oriented modelling leads to flexible and modular models, the translated 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.

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 [3].

For this reason, several current research projects aim at increasing energy efficiency by developing comprehensive simulation models of production facilities for energy analysis in order to be able to make qualified prediction about the efficiency of different energy saving measures and identify optimization potential [3].

One part of the work presented here investigates the microstructures 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.

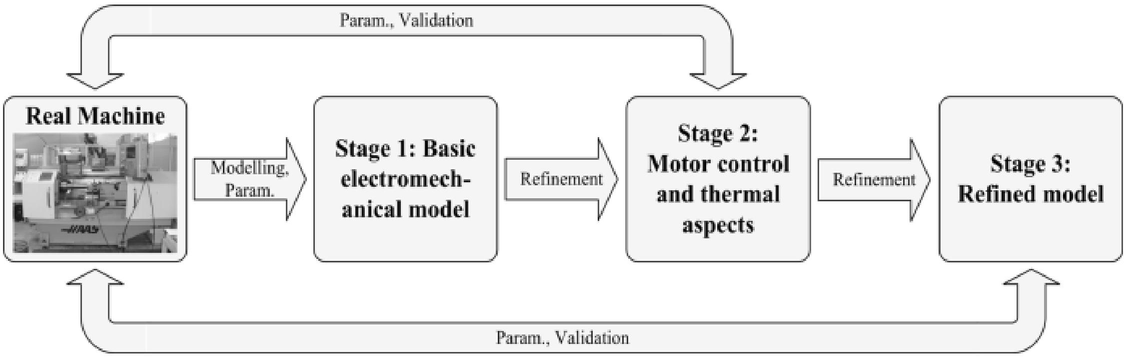

Figure 1: Three stages in the modelling process with increasing level of detail.

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 model refinement in three stages with increasing level of detail, see 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 [5], [6].

1 Stage 1: Basic Electro-mechanical 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, leadscrew drive, linear bearings and slide holding the cross feed.
- Cross feed (x-axis): Servomotor, leadscrew drive, linear bearings and cross-slide with 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.

For implementing the simulation models, Simscape as an extension of MATLAB/Simulink provides an environment for object-oriented multi-domain modelling and simulation of physical systems [5], [6].

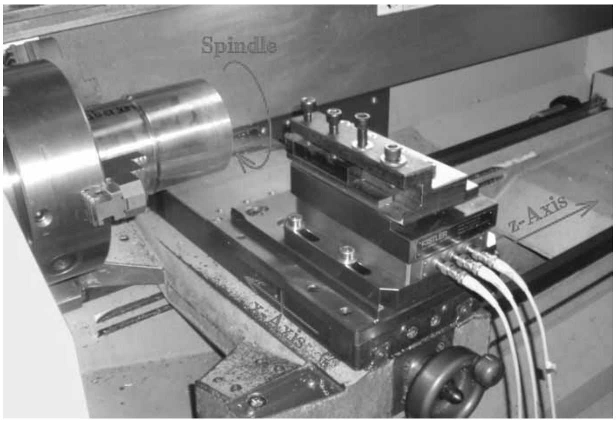

Figure 2: The three axes of the lathe: Spindle for driving the workpiece, longitudinal and cross feed for positioning the tool in the z- and x-direction.

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 cross feed. 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 implemented as custom Simscape components using Simscape Language (see [6]) with parameters extracted from available data sheets. Listing 1 depicts a code fragment of this implementation for the asynchronous machine. It shows common equations in normalized space vector description that can be found in relevant literature (e.g. [7]).

```
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
```

Listing 1: Code fragment of the asynchronous machine model in Simscape Language.

Existing Simscape blocks from the Simscape Foundation library (see [6]) 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 [2]).

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 apects are not yet provided in this model.

2 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:

- 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

2.1 Modelling

The necessity for appropriate motor control for the overall dynamics is also established in [4]. Figure 4 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 using the 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 calibration in order for the system to work properly.

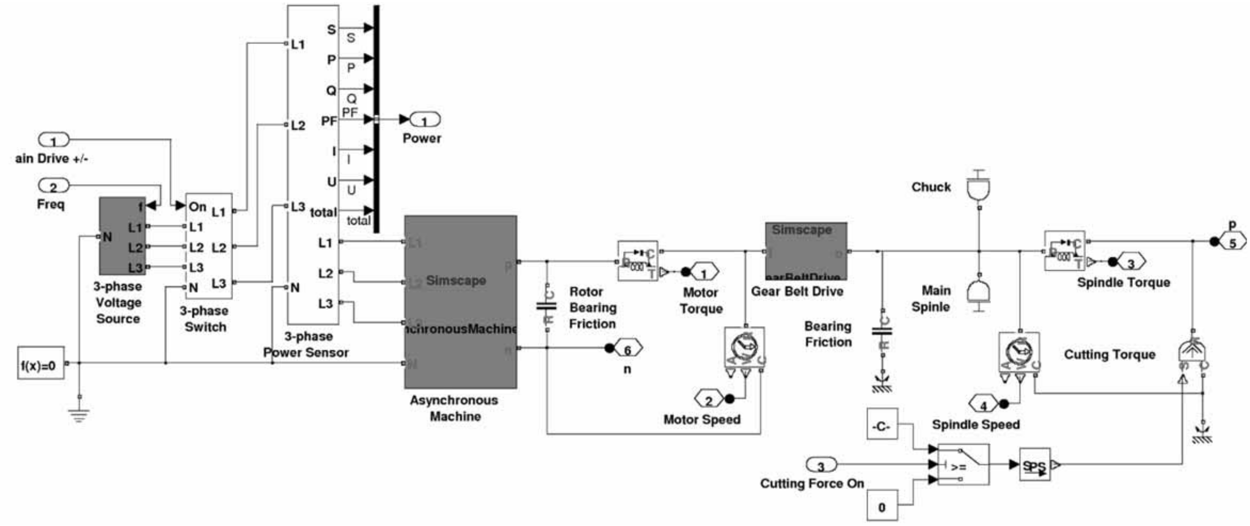

Figure 3: Main drive of the turning lathe model with asynchronous engine, voltage supply, gear belt drive and mechanical loads.

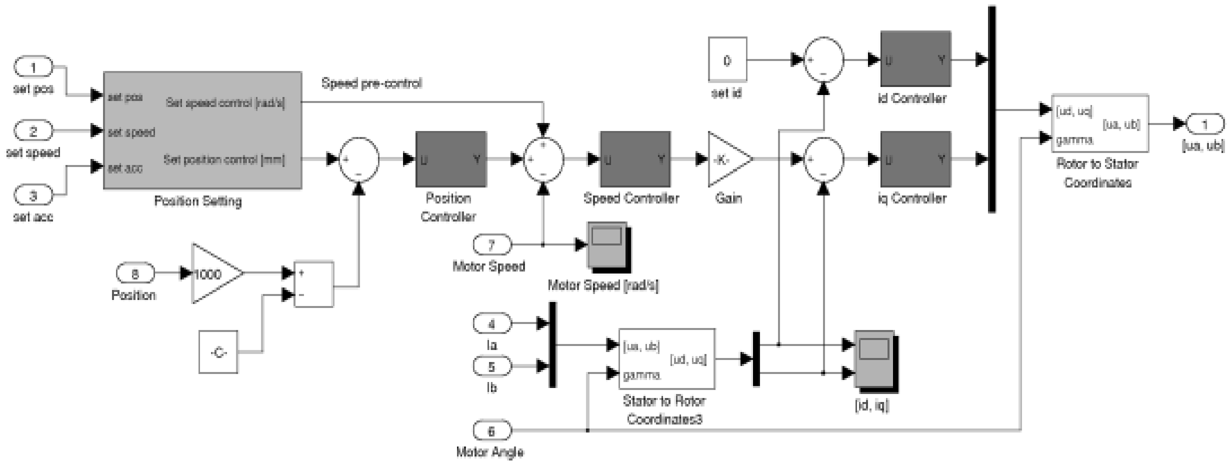

Figure 5: Slide control with position, speed and current controller (red blocks) and space vector output.

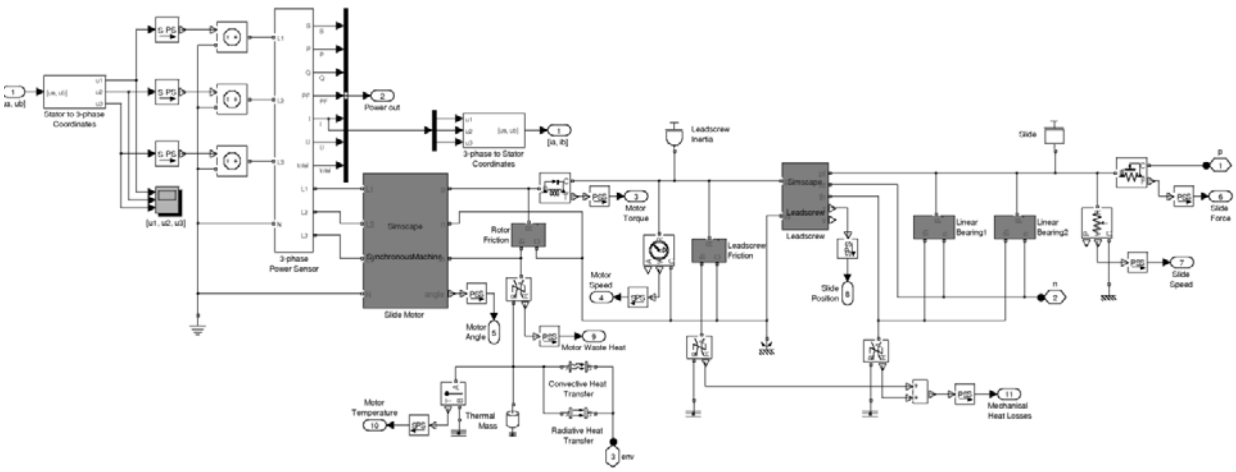

Figure 4: Model of the slide drive for the turning lathe with 3-phase voltage supply, servomotor, leadscrew model, linear bearings and thermal components.

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. Figure 5 shows t he graphical representation o f slide drive model including the inverter.

Further model extensions take into account the diffuse waste heat of various components, especially the drive motors, gear belt drive and friction elements. For that, all necessary components from the model in Section 1 are modified with a thermal output port. The waste heat is stored and dissipated into the surrounding environment via convective and radiative heat transfer, see Figure 5, with necessary heat transfer coefficients taken from available literature [1], [8].

In order to increase simulation speed, some adjustments had to be made in the Simscape implementation. The three drive train models (main drive, slide and cross-slide) were split into separate Simscape networks (object diagrams), only connected via directed (causal) Simulink signal connections (an overview can be seen in Figure 9). This partial decoupling enables more efficient equation handling by the simulator.

2.2 Simulation results

The modifications now allow more complex simulation scenarios. As an example, we investigate a typical turning process sketched in Figure 6. The following cutting parameters were used in the scenario: Cutting speed $v_c = 200\,\mathrm{m/min}$, feed $f = 0.2\,\mathrm{mm/U}$, cutting depth $a_p = 2$ mm, material C45E.

Figure 7 depicts the resulting trajectory of the tool tip and respective time values. All position values are measured with respect to the coordinate system illustrated in Figure 6 (green arrows). The simulation starts at an out-side position. First, slide and cross-slide are accelerated to maximum velocity in order to get to the starting position for the turning process. After that, the turning pro-cess is started with smaller feed velocity. The impact point between tool and workpiece does not leave any noticeable disturbances. The process is finished with negative infeed to the final position.

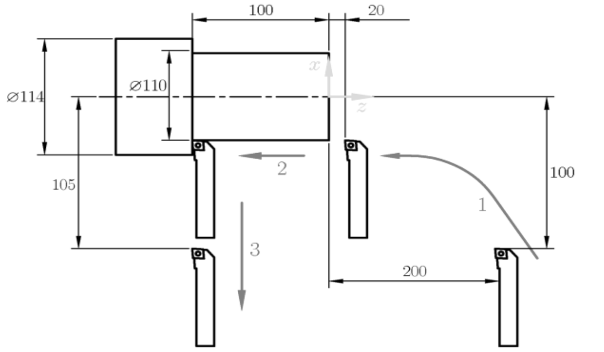

Figure 6: Simulation scenario of a turning process.

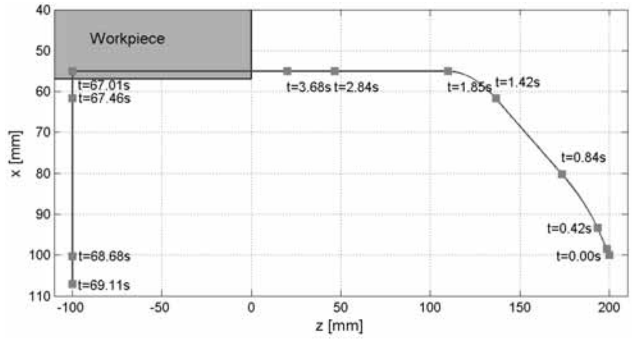

Figure 7: Resulting trajectory of the tool tip and time values for the simulation scenario shown in Figure 6.

For validation, Figure 8 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.

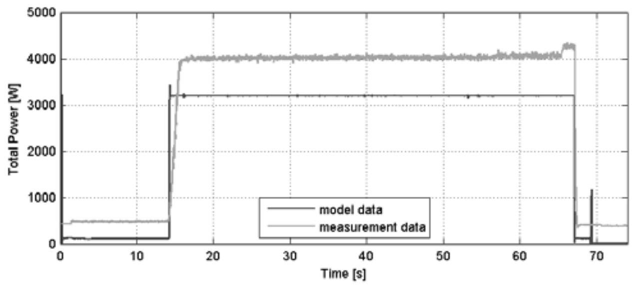

Figure 8: Comparison of total power consumption between simulation and measurement data.

3 Stage 3: Refined Model

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

3.1 Modelling

Since the high frequency switching operations of an inverter are difficult to realize with sufficient simulation speed in a mainly continuous model, the switching inverter is replaced by an idealized version which only implements direct energy conservation. Additional electrical loads are also 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 2, is continued and expanded on the new model of rectifier and inverter. Figure 9 gives 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 Figure 5, 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 [6]. In the given model, this method is employed for the rectifier subsystem, therefore making it necessary to isolate the respective part from all other Simscape networks based on assumptions for signal causality between these networks (see Figure 9 bottom).

The local system acts like 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 10.

On the one hand, this method 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.

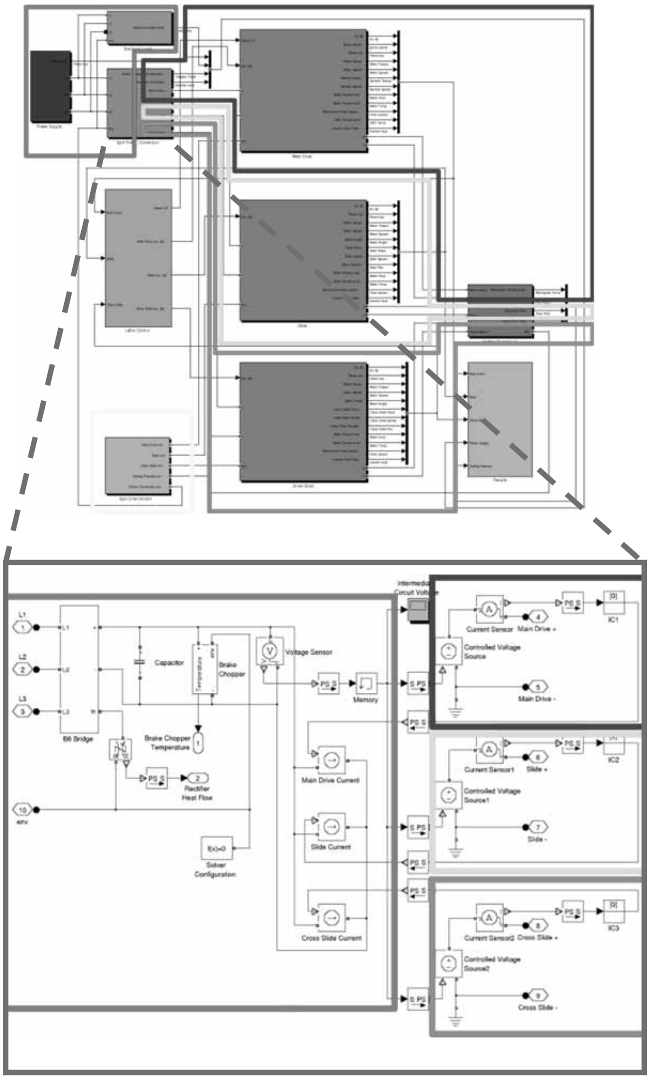

Figure 9: Top: Overview of the total simulation model in Simulink/Simscape. Marked are the separate Simscape networks. Bottom: Detail of the subsystem for the electric 3-phase converter with the three inverters and the rectifier in separate Simscape networks.

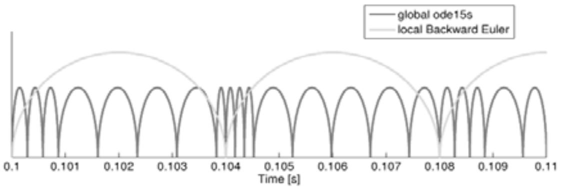

Figure 10: Comparison of steps between local solver (Backward Euler) and global solver (Simulink ode15s).

3.2 Simulation results

For comparison of simulation results, we again consider the scenario shown in Figure 6. The results of a simulation run with the refined model are shown in Figure 11.

Figure 12 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 during the cutting process. A small part remains as latent energy in the system.

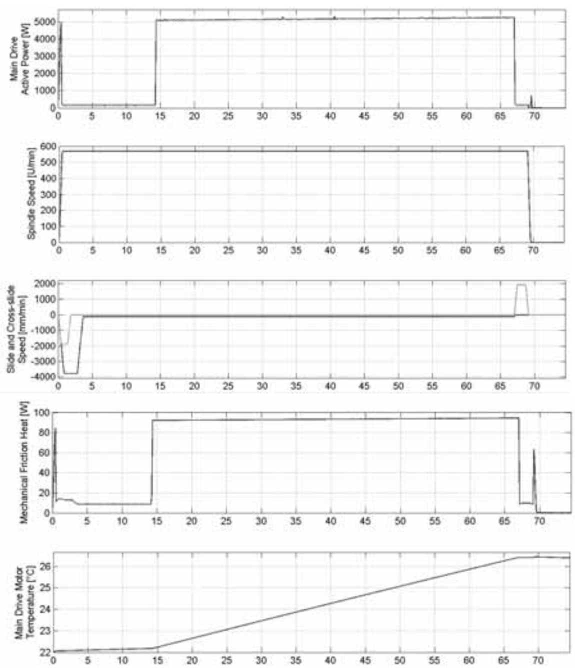

Figure 11: Results of a simulation run with the refined model. The plots show (from top to bottom) main drive active power, spindle speed, slide and cross-slide speed, mechanical friction heat and main drive motor temperature.

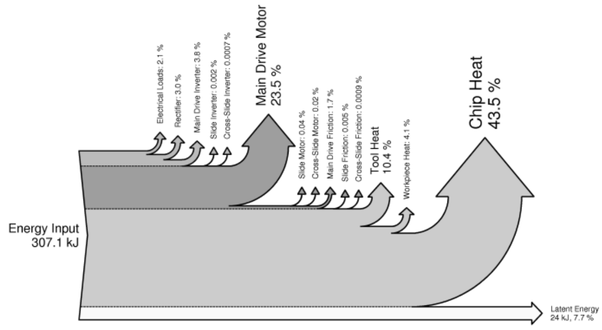

Figure 12: Energy distribution in the system, grouped by parts where input energy is converted into heat (power electronics, mechanical friction, cutting process, latent energy).

4 Conclusion

This case study confirms the advantages of using an object-oriented approach for model development of physical systems. Modular models preserve the basic structure of the original system and can easily be adapted and refined. However, this approach also results in more complex models with larger and less efficient equation systems, so that difficulties with insufficient performance are likely to arise even for models of moderate size.

Manual model adjustments can help increase simulation speed significantly, for example by decoupling the model into isolated networks. This also allows performing multirate or co-simulation by using different and customized solvers. However, splitting the model requires assumptions regarding signal causality, which basically is contradictory to the acausality principle of object-oriented modelling.

Comparison of the simulation results with measurement data showed sufficient agreement in principle; however some improvements are still possible, for example in the models for the drive motors or the cutting process.

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