Aargauerstrasse 1
CH-8048 Zürich
Tel. +41 44 447 20 60
Fax +41 44 447 20 69
info@acel.ch
www.acel.ch

Modeling as a Basis for Efficient Production

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Verfasser: K. Wegener, N. Rüttimann – IWF, ETH Zürich | S. Weikert, M. Ess, J. Mayr, A. Lengwiler – inspire AG, Zürich | J. Burkhalter – Dr. Acél & Partner AG, Zürich

Abstract

Predicting the behavior of manufacturing systems is today a key issue in both industry and science in order to gain a full idea of the achievable performance and to be able to explore the possibilities for efficiency enhancement. Throughout the decades, the measure of efficiency has changed. While the question in the first decades of the last century was on the reliability of processes, the attention then shifted more towards the feasibility of processes then to optimization of quality or cost to quality ratio. Today the efficient use of resources is of major interest. In the beginning, the key issue of scientific manufacturing was to answer the question of what happens. 100 years of modeling has revealed the broad span of tasks: from atoms to the manufacturing network, the question of efficiency needs to be answered. Basic ideas of modeling on different layers are introduced. Besides process and machine models, which form the basis of all, models for process chains as well as for throughput of a factory reveal the capability for efficiency enhancement.

1. Introduction

Today, the prediction of a manufacturing systems' behavior is a key issue in both industry and science in order to gain a full idea of the achievable performance and to be able to explore the possibilities of efficiency enhancement. The earliest modeling of manufacturing processes stems from Tresca in 1864, who tried to predict the feasibility of plastic deformation of ductile materials with his famous yield criterion. Modeling of cutting started in the beginning of the last century with the work of Schlesinger and Taylor, who were interested in the efficiency and output of processes, and in the wear of tools. This rough modeling was later enhanced by Merchant and Kienzle. Their clear focus was to estimate the cutting forces as a basis for the design of processes and machines. These models introduced a theory or rather a coordinate system that is still valid today and is used to a large extent. Since observations can be introduced and compared to others, decisions became possible. However, models cannot be better than the available data of the identified material. Throughout their life time, these simple models, being the only ones available, have received considerable interest and thus many dedicated measurements have been stored in huge databases, hence perpetuating the models applicability and usefulness. But, these models are far away from providing a physical understanding of what really happens at the cutting edge and at the tool's surface. This confines the quantitative predictability to cases in which data have been measured, namely cutting processes. Strictly speaking, physically relevant modeling requires the possibility to perform some material tests such as tensile tests, torsion tests, etc., and derive from those data the materials behavior during cutting, forming and other manufacturing processes. Refined models for manufacturing processes shall be based on continuum mechanical laws. On that level of contemplation, the modeling of all processes more or less resembles, but probably is – depending on the intention of prediction – very inefficient. But since the cutting edge of cutting tools introduces extreme localized disturbances into the material, the idea is to revert to modeling of grains, dislocations and even atoms, and to condense the behavior to macroscopic models as multi-layer models.

Process efficiency cannot be evaluated without taking into account the manufacturing system. This means that modeling of manufacturing processes introduces layers above the continuum mechanics of the process. The machine is part of a playing network, which is the process chain that requires a modeling layer, since increasingly the interdependence of process steps becomes the target of prediction. The process chain may be part of a factory, thus processes and the process chain must be condensed to factory models, which are again part of a manufacturing network. This modeling hierarchy is the essential background of the European vision of convergence of modeling.

The requirements of higher modeling layers need different treatment for process reality than the simulation of the process itself. Therefore a taxonomy of models needs to be outlined as follows for the modeling of chipping, but can be extended with some modifications and extensions to nearly all kind of processes.

1. Experimental models: These models are based on measured data and expressed in mathematical regression algorithms.
2. Analytical models: Physical reality is modeled phenomenologically with analytical functions.
3. Field models: Field models are described by partial differential equations, stemming from continuum mechanical formulation of material behavior. Different numerical methods like FEM, FDM, etc. must be applied in order to evaluate the material's behavior. An integration procedure is needed to compute the overall process parameters like cutting force, etc. from the field solutions for stress, displacement, temperature, etc.
4. Molecular dynamics (MD): MD models describe a number of atoms and their atomic bond. However, even small fields of interaction between tool and workpiece generate immense computation times.
5. Artificial intelligence (AI): Here, models are summarized which are essentially based on decision making processes. The models are trained by real cases and the structure of the database, and their evaluation procedures differ from one model to the other.
6. Multi-layer models: To cover the span over different scales of the problem, multi-layer models and combined models are generated. They use modeling in the micro-scale for a limited geometric size, together with some generalization, averaging or integration methods to condense the information into the higher scale models.

The basic issue to be evaluated on the basis of process modeling with respect to efficiency is the efficient use of energy, since it is not only a waste but has far-reaching consequences of subsequent squander like energy for cooling and wear of tools. All layers and thus all models contribute to the efficiency of manufacturing, which will be outlined in the following. Efficiency corresponds to the best performance of the system together with minimum utilization of resources. It must be noted that energy efficiency or abatement of CO2 emissions is too limited in perspective. This is because the waste of energy can be reduced by wasting material, which is not the desired solution. The ongoing discussion on the installation of frameworks for the evaluation of processes' efficiencies therefore seems to reinvent the cost calculation. All efforts for the process that have to be taken into account are already reflected in terms of cost, and thus the only necessary change is – according to general opinion – that energy is weighted too low in present calculations.

Models are also classified in terms of their results. Normally, wear models are distinguished from models of forces and temperature. But, because wear depends on field variables such as stress, temperature and velocity according to 2, it is always only a module of a process model.

2 Modeling of Cutting Processes

2.1 Chipping

As mentioned previously, there are numerous possible modeling techniques. Efficient cutting increases the material removal rate and thus accelerates feed and cutting, tool wear, as well as consumption of fluid and energy for the process itself. Tool wear and cutting speed are correlated by means of Taylor's equation:

$$T_C = k \cdot V_C^n \tag{1}$$

where T_C is the tool's life time and V_C is the cutting speed. Life time and manufacturing time are negatively correlated and need to be balanced against each other. But since tool wear is localized, the risk factors for wear, which include temperature, normal force on the tool surface, relative velocity between material and tool as well as increase of the surface area. This means that virgin metal without oxidation layer comes into contact with the tool and thus it is essential to start with field modeling. In forming technology, process simulation is far more mature than cutting simulation. This is because the urgency of obtaining a solution was of high importance and the cutting problem is far more complicated since material separation, shear localization and damage, thermomechanical coupling, friction and immense gradients of the field variables must be taken into account. In 2005, Klocke et al. 1 were able to achieve a breakthrough in the enhancement of tools for hard turning for the first time by means of field models and numerical solutions using FEM. This is depicted in Figure 1 where the nose of the tool is shown. By changing the nose's radius and by varying the rake angle around the tool's nose, the hot areas can be reduced and removed from the endangered cutting edge. Figure 2 shows one of the rare simulation results of wear by Altan et al. 2. The governing equation is the wear equation by Usui 3, which correlates the wear rate to the risk factors.

$$\frac{dW}{dt} = A\sigma_n v_t \exp\left(-\frac{B}{T}\right) \tag{2}$$

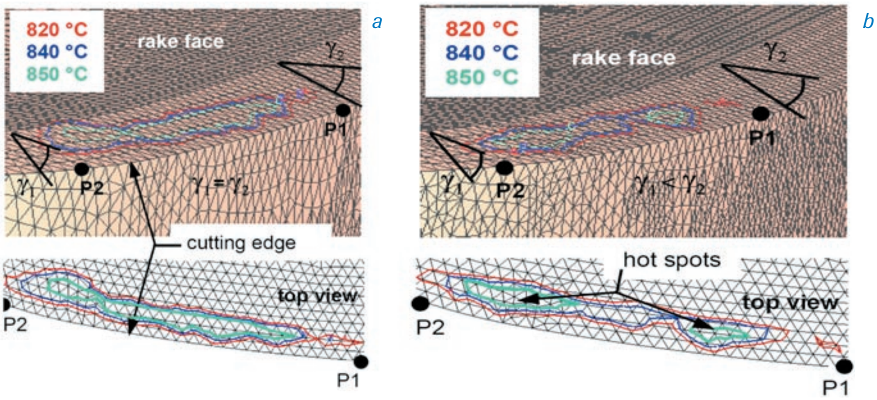

Figure 1 *Hot areas on the cutting edge of a hard cutting tool: (a) constant rake angle, (b) varying rake angle 1*

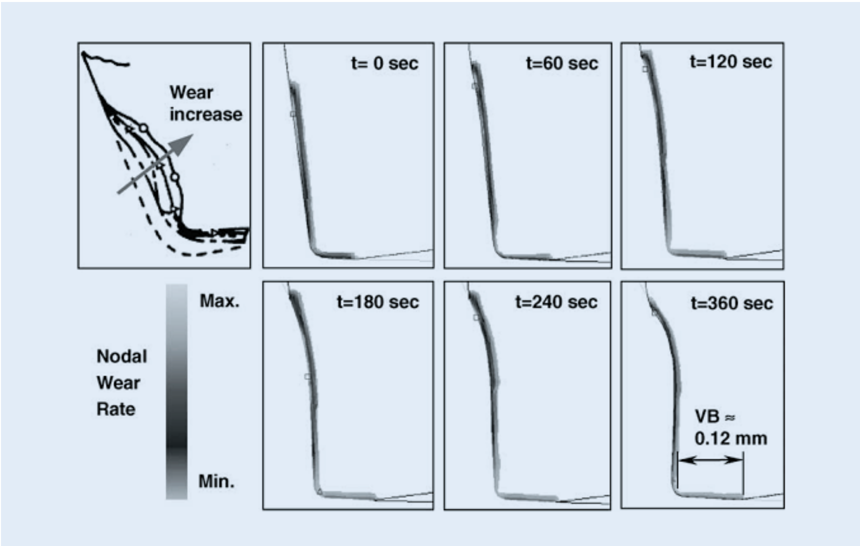

Figure 2 *Wear and wear progress by Altan et al. 2: Top left: wear profiles; rest: wear rates on wear profiles.*

Wear W , describes the depth of a tool's material removal. Here, represents the relative velocity, T is the surface temperature and is the normal stress on the tool's surface.

Due to the special requirements for modeling the cutting process, other numerical solution methods of the field equations than just updated Lagrangian finite elements came up. The key issue is to model material separation and to avoid severe remeshing and interpolation of the field variables as much as possible. Since all material that is deformed goes through shear zones that stay stable relative to the cutting edge, arbitrary Euler-Lagrange formulations (ALE) are used. In doing so, the Eulerian part of the grid does not undergo deformation and thus remeshing is not required. Even full Eulerian meshes can be used as shown in Figure 3. The material to be cut is modeled similar to a fluid, which means that no remeshing takes place and material separation occurs automatically.

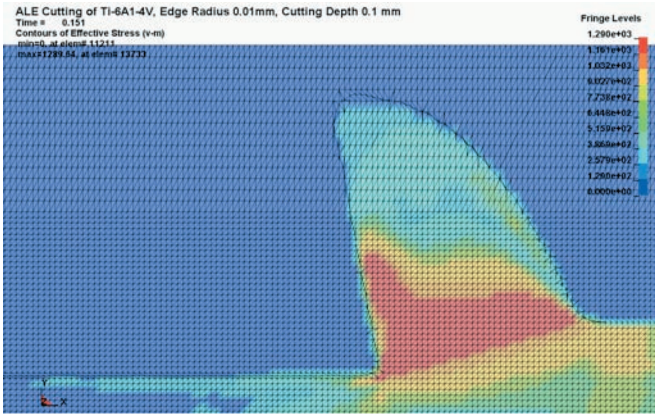

Figure 3 *Eulerian grid for the numerical solution of a cutting problem*

But the mesh smoothing and the solution of the Eulerian timestep is computationally expensive, typically two to five times more expensive than a corresponding Lagrangian timestep, thus increasing the solution time. The Eulerian description also loses the defined surface of a Lagrangian body and needs additional algorithms to interpolate a new surface.

Meshless (or meshfree or particle) methods are a relatively young addition to the methods of continuum mechanical simulations. The foundations were established in 1977 by Gingold & Monaghan 4 and by Lucy 5 in the field of astrophysics.

Meshfree methods are based on the idea that the interpolation function and the metric only depend on the motion of one node. Therefore, distortion does not affect the metric and remeshing is unnecessary. Also, material failures can be easily modeled as a dissolution of the intermodal connection. Thus, it seems to be the ideal scheme to simulate cutting problems. However, obeying essential boundary conditions is not as straightforward as in FEM solution schemes given the field variables are represented by approximat functions. This is because the field value given by the boundary condition necessarily contradicts the approximated field value of the approximation. The most widespread solution to this problem is the usage of a penalty function, introducing an additional term into the system's equations, penalizing the difference between boundary condition and field value. More recent approaches apply a reverse step algorithm, adapting the shape function to equalize the field value and the boundary condition.

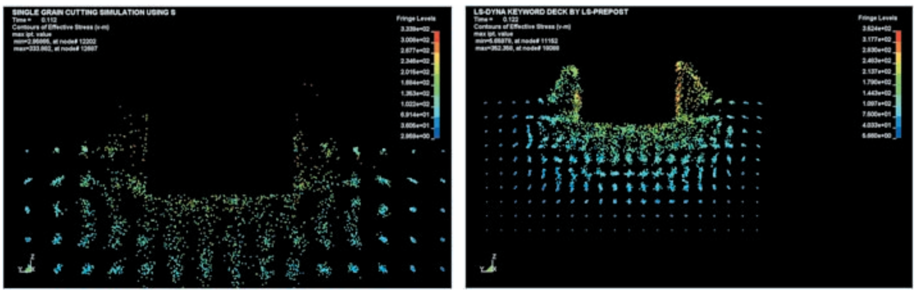

Figure 4 *SPH scheme for the simulation of grinding with different directions of the cutting velocity relative to a cubic grain: Left: cutting velocity parallel to an edge of the cube, right: cutting velocity parallel to a diagonal of the cube*

Several innovative methods were developed between 1990 and 2010, but up to now, no ideal method has emerged, and no commercial implementation apart from the SPH code in LS-Dyna was published. Figure 4 shows a smoothed particle hydrodynamic solution of two different grain orientations in single grain cutting. It can be clearly seen that the cutting result, as expected, depends on the direction of the grains' edges Ploughing prevails if the edge points into the cutting direction, resulting in large walls on either side of the cutting groove.

2.2 Grinding

Grinding is a cutting process which requires a lot of power and consequently a lot of coolant, which should be provided, according to a rule of thumb, with the same speed as the circumferential speed of the grinding wheel. The heat generated in the process requires additional energy to withdraw the excess heat in order to avoid excessive tool wear and to also avoid workpiece damage. Several attempts were made to avoid coolant, from which the most promising ones are the use of structured wheels and engineered grinding tools (EGT). While for structured wheels, the abrasive grain is removed at specified surface regions, for EGT, only those grains that benefit the process are used and thus enhance the efficiency even more. The effect can be described already by the simple Kienzle equation.

$$F_C = k_{C\mu\mu}{}^{1-mc}$$

3

Here, h is the cutting depth, b is the cutting width and F_C is the cutting force. A reduction of h, which occurs in grinding due to high grain density, increases the cutting force and thus the energy required. To improve the process, the abrasive grain must be separated, which is the target for structuring and EGT. EGT are the preferred solution because the consumption of abrasive grains is minimized as much as possible. But sparse grain placement increases the forces on the abrasive grains and increases the wear because fewer grains are active during material removal. To avoid early failure and to optimize the cutting conditions, a process model of grinding is necessary which takes into account the stochastic nature of the grinding wheel with its geometrically undefined cutting edges. Essentially the same modeling types as outlined in section 1 are used, but a further modeling layer is needed because grinding wheel models and their interactions with the material are further differentiated. Either single grains are taken into account for synthesizing the properties of the grinding wheel or the grinding wheel model is phenomenological, which means that its properties are described directly. In the latter, an averaged continuum model of the wheel with attributes for its stiffness and friction coefficient is a possible alternative.

The stochastic model is shown in Figure 5. It consists of probability distributions for each grain on the wheel in terms of its size, position, orientation, morphology, and aspect ratio. It shows the transition from a hexahedron to an octahedron with only one geometric variable, and the further transition to a tetrahedron by once again with only one eccentricity variable. From these distributions, several wheels are generated and the wheel-material interaction is simulated. All process properties of these wheels and their material removal are then calculated by Monte Carlo simulation.

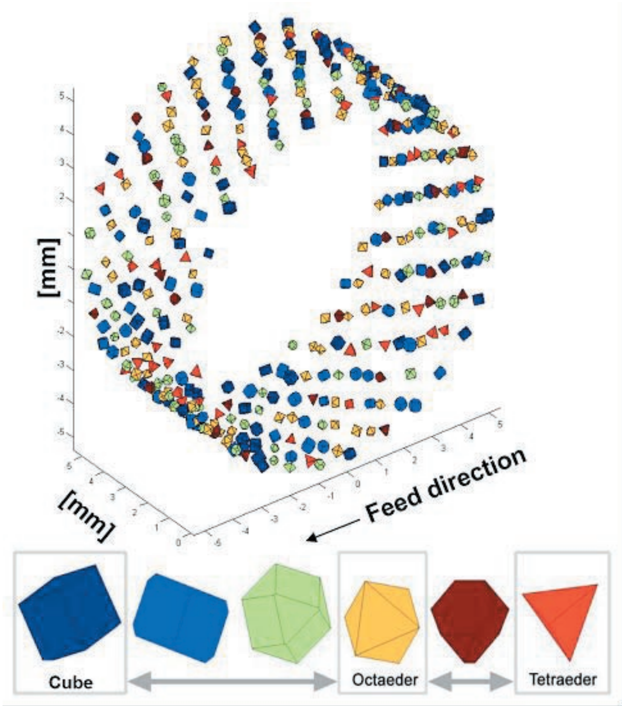

Figure 5 *Grain morphology and simulation model of a stochastic grinding wheel*

While Figure 5 (top) shows the geometry of one representative of a grinding wheel, equations are necessary to describe the material removal and thus the loads on the grain. To reduce computation effort, the grains are represented by their projected area in direction of the cutting speed, while the material removed is the overlap between this projection and the material. Depending on the grain orientation, excessive ploughing occurs as shown in Figure 4, where the ploughed and remaining material is substantially hardened for the removal by subsequent grains. To determine the data for single grains and to receive information on the loads for each of the grains with different orientations, single grain tests are performed and the parameters of the Kienzle equation are identified.

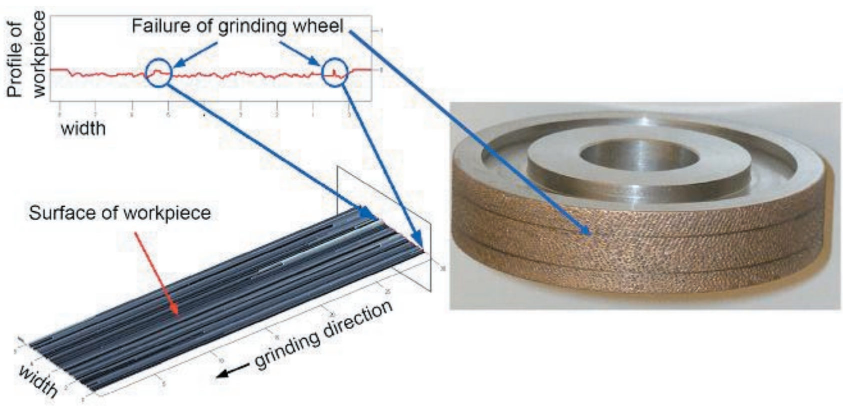

Figure 6 *Test results and identified parameters of the Kienzle equation*

The reason for failure of grains is very complex since a number of different effects may occur, e.g. load on the wheel, attrition wear, grain cracking, grain breakout, and abrasion of the bond. A simple approach is to remove grains that have been loaded above a threshold as described by Pinto 6. With such a model, Figure 6 was derived which depicts the change in roughness due to grain breakout. Two regions of catastrophic wear can be observed which corresponds to a complete loss of grains in one circumferential track. Further enhancement (Wegener et al. 7) considers attrition wear of the grains, which depends on the accumulated contact length and the cutting forces.

$$\ln\left(k_{c\mu\mu} / k_{c0\mu\mu}\right) = c \int A^{(1-m_c)}(s) \cdot ds \quad (4)$$

Here, s is the cutting length, $k_{c\mu\mu}$ is the proportionality factor of the Kienzle equation written as:

$$F_c = k_{c\mu\mu} \cdot A^{(1-m_c)} \quad (5)$$

and $k_{c0\mu\mu}$ is the initial value for unworn grains.

Due to the fact that attrition wear increases the cutting force, this model can be combined with a load limit for grain removal and is able to predict a delayed breakout.

3 Modeling of Machine Tools

3.1 Thermal Modeling

As a rule of thumb, the ongoing discussion on energy efficiency of machine tools can be reduced to the following statement which is valid for cutting machines such as milling, turning and grinding: 75 to more than 80% of the total energy consumed is due to standby, cooling, heating, lubrication, and control. Before considering saving energy through optimized cutting or optimized path planning, it is necessary to discuss the thermal management of machine tools, which has also the ability to increase quality and reduce scrap. While thermally fast machines are disturbed by each irregularity, thermally slow machines need long and energy consuming startup phases or are otherwise always switched on. The thermal behavior of a machine tool increasingly evolves to a quality criterion that can mostly be influenced by the manufacturer. Therefore, thermal simulation and design optimization becomes indispensable, but is not sufficient. Thermal compensation without further energy consumption for cooling is the target for the future. A step into the right direction is the model-based compensation of the machine's axes. This requires an appropriate thermal model implemented on the machine, but also requires temperature measurements to avoid excessive integration errors. Though thermal movements are slow, model-based compensation requires extensive computation because field equations for the temperature and deformation problem need to be solved. Hence, simplifications are essential. Brecher et al. 8 introduced a phenomenological model based on PT1 and PT2 functions for the compensation of the axes, depending on thermal loads from the drives, guideways and threads, for which the parameters must be identified by experimentation. This procedure is shown in Figure 7 and may be termed as phenomenological integration.

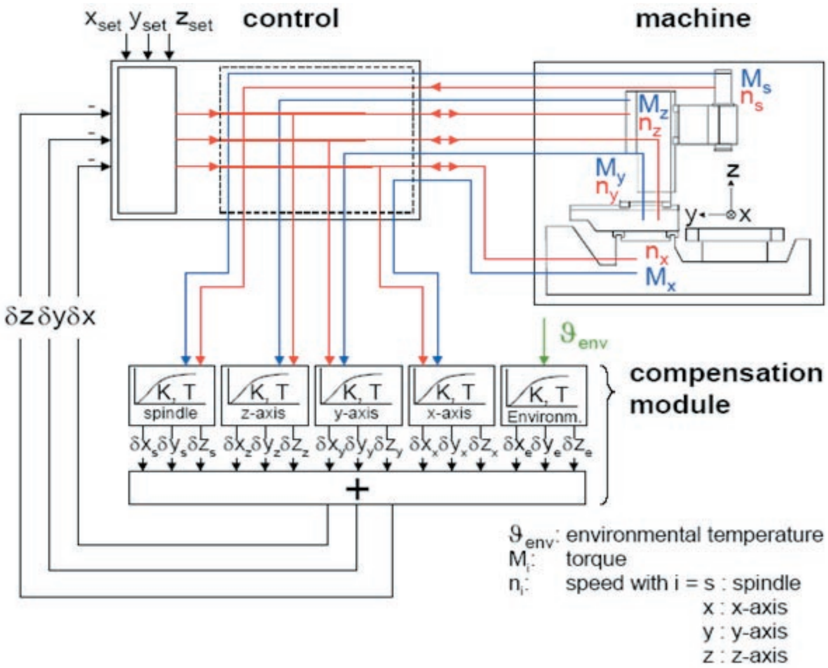

Figure 7 *Phenomenological thermal compensation model (Brecher et al 8)*

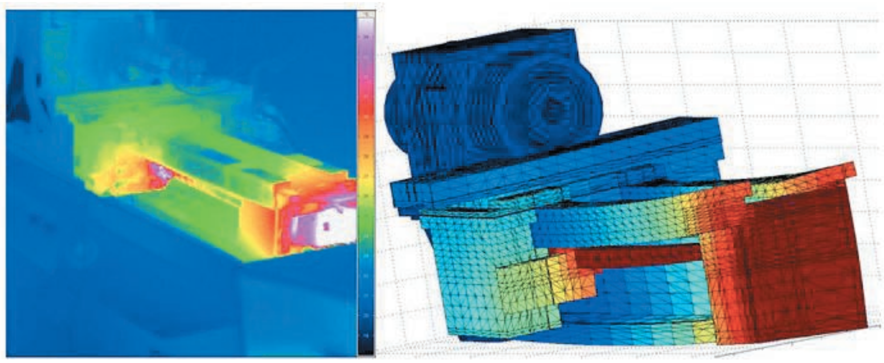

Figure 8 *Thermal analysis of a lathe, left: infrared picture, right: simulated temperature field and distortion for movement in the z-axis*

Mayr 9, 10 proposes to solve this problem with a FDEM solution scheme as a staggered algorithm. The scheme is designated to perform a time step for the heat equation with finite differences and then a time step for the elastic deformation problem with finite elements, for which the temperatures appear as right hand sides, as the loads of the resulting equations.

Figure 8 shows the temperature field of a lathe in a thermally deformed state after several hours of back and forth movement along the z-axis in the steady state. It was computed with the aid of a FDEM scheme and viewed by an infrared camera.

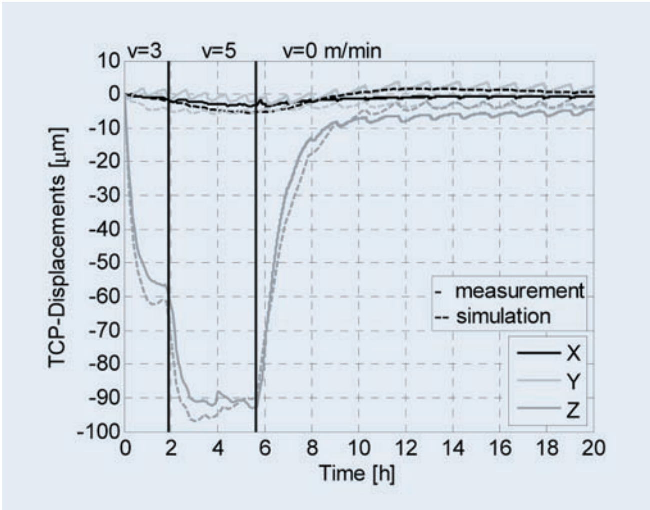

Figure 9 *Thermoelastic TCP displacement for the movement of the lathe from Figure 8*

Figure 9 shows displacements with the same movement but different speeds and subsequent cooling. As only the relative movement between a table mounted frame and a frame mounted to the TCP is relevant, the system of linear equations can be reduced to only those relative movements, displacements and rotations between the tool and the machine bed, which can be defined by the movement of three different points on each side. The reduction of the system of equations can be performed in advance for each of the TCP positions as they influence the stiffness of the machine. This significantly reduces the effort in the time step computations and enables a model-based compensation.

Future developments include the enhancement of models for closed or partially open air enclosures, the distribution of heat due to the coolant and chips, and methods for the choice of thermal calibration points.

3.2 Dynamic Modeling

In the meantime, dynamic modeling of machine tools is also widespread in industry, although its contribution to efficient manufacturing is not as large as assumed. Dynamic modeling during the design phase allows for the reduction of mass, the layout of lightweight components, or even to apply bionic design principles. This is all in an effort to increase damping and dynamic stiffness, and to evaluate machine concepts. In (11), a system of redundant axes is introduced, in which small and lightweight axes take over the task of manufacturing small geometric elements, while large axes span the entire working space. This can save a considerable amount of energy and also manufacturing time, reduce wear and thus save spare parts. Although these axes increase the costs and thus require simulation and subsequent evaluation, the total balance of efforts is positive. Also, during the realization phase, dynamic modeling can contribute to efficiency by introducing a model-based set point generation, which can reduce loads, vibrations and thus wear. Self-learning algorithms will then be necessary to cope with the changing properties due to wear, different tools and clamping, and different workpieces (see for instance 12). Different modeling strategies are available. For utilization within a control system, real time properties must be retained. Therefore, multi-body simulation is the correct choice. During the design phase, an efficient scheme must complement the design process, signifying that rigid body models are used for the concept phase which can be altered to finite element representations as the design proceeds and more detailed information becomes available. Given this point of view, and because lightweight concepts balance the compliance between the machine bodies and its joints, hybrid models become a good choice. Rigid body models can be made compliant by dividing them into smaller rigid elements with concentrated springs and dampers between elements. Instead, hybrid models use a rigid body environment in which dimensionally reduced FEM models for machine bodies are introduced only when necessary as outlined for example in 13.

4 Overarching Models

4.1 Process Chains

Most workpieces require more than one single manufacturing step, and thus more than one single manufacturing process. Efficiency optimization of the manufacturing process needs to take into account the whole sequence of steps. This means that rather than optimization of single processing steps, the sequencing needs to be considered, which nowadays normally has a much greater effect on efficiency. This process chain view is shown in Figure 10 for a simple example with a very beneficial outcome, because a whole process could be eliminated in this case.

Process chain models are currently used for cost optimization which takes place in all types of industrial cost calculations (see 14). A general framework for such modeling consists of two consideration levels. The overview level can be used alone, if similar parts or operations have already been experienced. The lower level is necessary for detailed feasibility studies. All process steps deliver intermediate data that can be used in some quality functions. Optimization can be done by varying the process steps but also the intermediate data, namely the degree of completion of each step as is shown in Figure 10. However, the development state of automatic process chain layout is still very rudimentary 15.

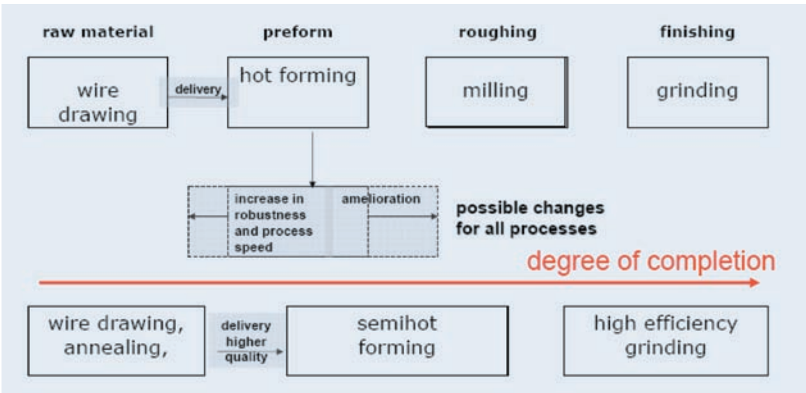

***Figure 10** Model scheme of a manufacturing process chain*

Any change in the cost function allows for optimization in terms of energy consumption or efficient utilization of resources. But for efficiency, a major aspect is the propagation of errors throughout the process chain. This is due to the fact that it determines what kind of correction step needs to be introduced between process steps or at the end of the chain in order to reach the accuracy target. An error model consists of kinematic transfer functions for each process step on each functional element of the workpiece. Such an error propagation model is developed as an example for an assembled cam shaft, where the seats of the camlobes on a tube are widened by knurling, and the camlobes are then pressed onto these widened seats. It has about 50 input and process errors, for which the error distributions must be specified. By using Monte Carlo simulation, the distribution of errors for all functional elements of the camshaft can be determined. In this way, the process capability coefficients can also be predicted. Figure 11 shows the comparison between a measured error distribution and a simulated distribution. Now, the benefit of this error model is that the error sensitivities can be derived from the input distribution, and the most important input errors may be reduced by some technical means in the manufacturing device, in the raw material, or even by additional correction steps. The solution of the inverse problem is even more interesting, namely to compute the most efficient way to reach the required tolerances at the end.

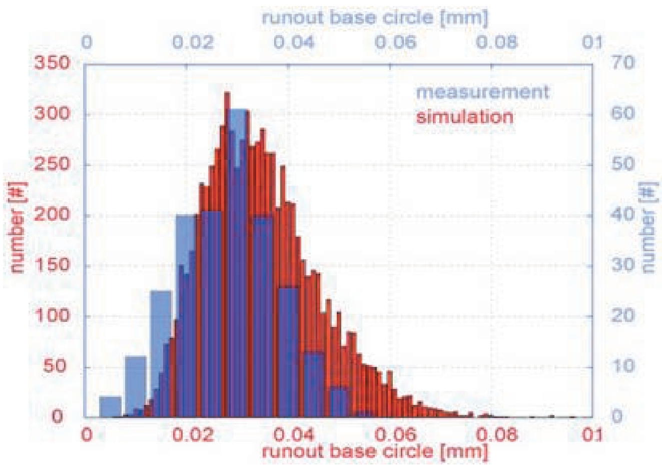

Figure 11 *Model scheme of a manufacturing process chain*

4.2 Manufacturing Sites

Manufacturing companies are often subject to very rapid external changes to which they need to adapt to. As shown for process chains in 4.1, the efficiency of manufacturing sites is strongly determined by the interdependencies between thedifferent manufacturing machines and not by the machines themselves. The organization is carried out by production planning systems (PPS), which is the link between the market requirements and the manufacturing system. From the very beginning, they are based on models of the manufacturing site. But the widespread MRPII system 16, which generates manufacturing orders on the level of manufacturing steps, does not take into account these interdependencies because it assumes rigid processes and transitions between them as stated in 17.

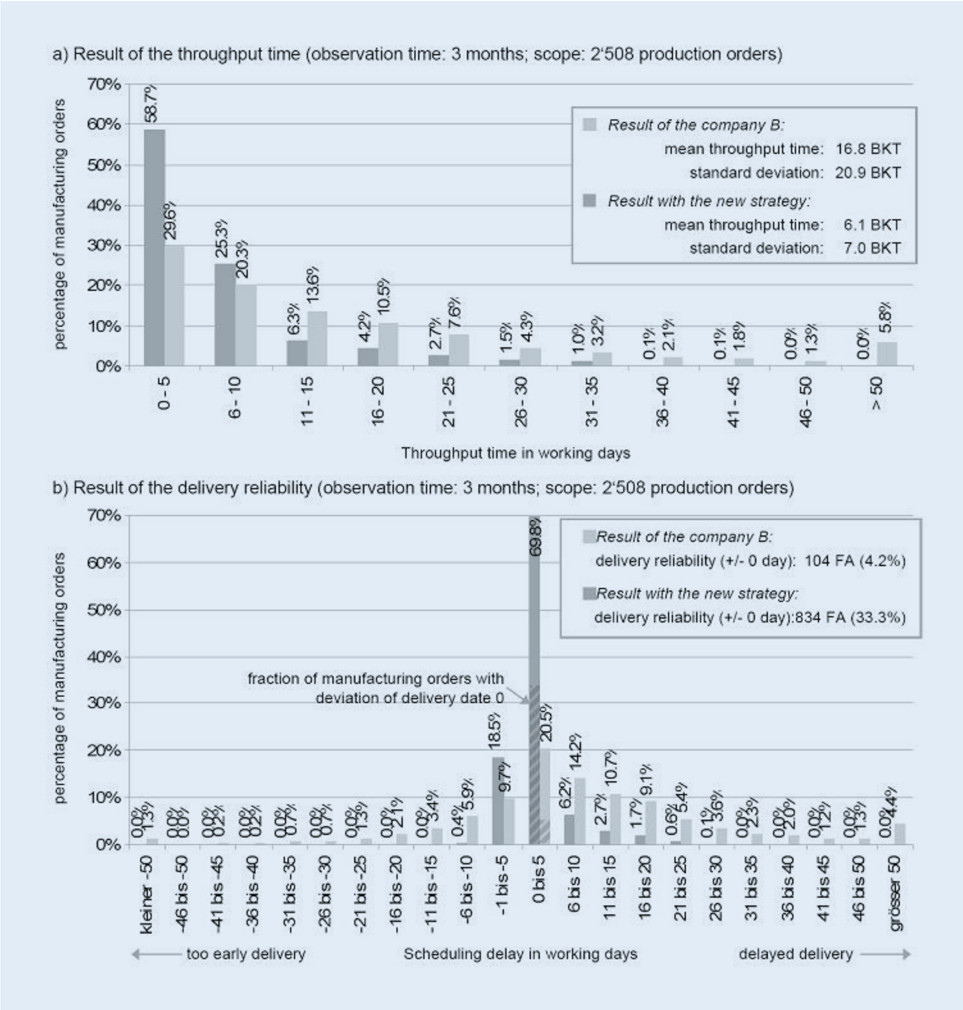

Figure 12 *Results from event oriented simulation on the basis of real factory data and comparison of delivery times using the new scheme and MRPII*

Only rarely does the real production sequence correspond to rigid plans 18. Changes need a complete recalculation of the whole production plan, which is done only during the nighttime or during weekends because of the extensive computational effort. In the meantime, corrections in manufacturing are organized by hand which in turn delays the delivery date. This clearly shows the limits of detailed modeling in a turbulent manufacturing environment. A newly proposed scheme leads to a more efficient planning because it installs modeling rules as closed loop sequences directly on the level of autonomous production machines. The concept of the new strategy is such that only the end date is a mandatory date. This is different from MRPII, in which the start and end dates of all manufacturing steps are planned.

The closed loop control is based on the notion of a Prio-Quotient of a manufacturing order. It is defined as the ratio of the available time span to the end date as defined by the order, and the dynamic run time of the order. Dynamic run time represents the time that will elapse because of the actual queues in the manufacturing systems for which the order at hand must travel through. By taking into account the actual state of the manufacturing systems, the assumption is that the queues can be reduced by using a FIFO strategy.

To prove the efficiency of the control scheme and the new strategy, an event-based simulation is derived from the PPS data of a real company, which are then imported into the system. Afterwards, the simulated delivery times from the new control scheme are compared with the actual times experienced by the company. Figure 12 clearly shows the benefit of implementing such a new control scheme within the company. The upper part a shows a significant reduction of the manufacturing orders' run times, while the lower part b shows that also the punctuality of the orders was drastically enhanced.

5 Summary

In the past decades, modeling has evolved as the most important tool for enhancing efficiency. The current problem is that the metrics of efficiency is changing. But, the utilization of models enables the prediction of process results and to evaluate measures before they become active. Such simulations are the prerequisite for sensitivity analysis and identifying the most effective means for increased efficiency. Consequently, modeling is used on all levels, from process simulation and the machine tool to the entire manufacturing site, or from a product based standpoint of the process chain.

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