# Advanced Modeling

Research Group TEC | Manufacturing Technology

White Paper

TECHNISCHE UNIVERSITÄT DARMSTADT

PTW TU DARMSTADT

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# 1. The Cluster Advanced Modeling within the TEC research group

## 1.1. What is Advanced Modeling in the production technology?

*„All models are wrong, some are useful“* [1]

With these words, George Box describes both the limits and the potential of modeling.

The modeling of processes or components in production technology can be motivated in different ways and pursue a wide variety of objectives. The spectrum ranges from predicting process behaviour under uncertainty as well as mechanical and thermal tool loading to model-based component design and component monitoring.

Advanced Modeling stands for innovative process models. These can be developed either based on physical relationships or real measurement and process data, or from a combination of these. The process models can be based on classical deterministic modeling, but they can also be defined via novel data-driven models or combined model approaches.

Mathematical models are mainly used for quantified description. Like physical models, they have the development of interrelationships as their overriding goal. Physical models are suitable for conceptual, but also for quantifying description. Mathematical models do not necessarily have to draw on physics. [2] Data-based models draw on process and measurement data and can be generated using a variety of methods, such as the application of machine learning algorithms. These are predestined for quantifying descriptions, for example to carry out predictive maintenance.

The overview of model building shown in Figure 1 represents the status quo. The used models in the TEC research group can be purely mathematical, physical, or data-based, or a combination of these. In the future, these models will be further developed and linked. From a methodological point of view, the modeling approach is described in a generally valid way, so that the transfer to possible other applications can be adaptable. In the future, the cluster will contribute to a clear understanding and a uniform view of models in the TEC research group and the production engineering disciplines located therein. Corresponding overviews are to be derived and used for guidelines, white papers, or publications. The models should be able to be further developed in the long term according to new research findings and thus enable sustainable benefits and knowledge gains. In particular, the transfer of existing models to ever new use cases will be investigated. In addition to a clean, structured, and documented storage of the models, the aspect of early identification of interfaces is of particular importance. The storage of simplified basic models should facilitate the introduction of more complex models in the TEC research group for students and scientific staff.

[1] Box, G.E.P. (1979): Robustness in the Strategy of Scientific Model Building.

[2] http://www.mathematik.tu-dortmund.de/ieem/bzmu2011/_BzMU11_2_Einzelbeitraege/BzMU11_NEUMANN_I_Modell.pdf

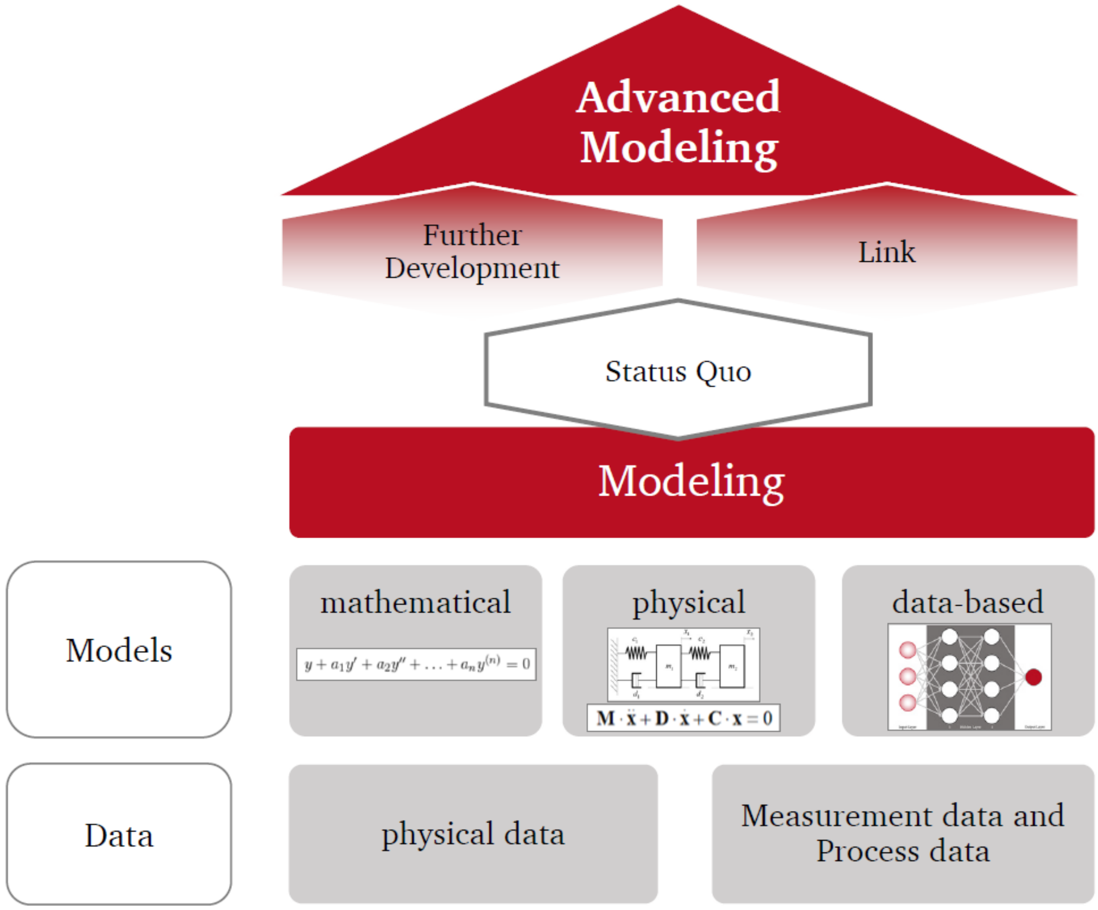


Figure 1: Advanced Modeling within the TEC research group

## 1.2. Research group TEC

Since the beginning of 2021, we have jointly formed the research group TEC | Manufacturing Technology within the Institute for Production Management, Technology and Machine Tools (PTW) at Darmstadt University of Technology. Our vision is to conduct trend-setting research for data-driven, adaptable manufacturing technologies in resource-efficient, responsive production. Enthusiasm for our research, a high level of commitment and initiative, as well as openness and curiosity in breaking new ground are essential characteristics of our TEC team.

The TEC research group has grown together from the three former research groups *Additive Manufacturing*, *Machine Tools and Industrial Robots*, and *Machining Technology*. Thus, we are able to cover a broad field of manufacturing technology. Shortly after the changeover, the closer cooperation in the TEC group became apparent through simpler communication, as well as more agile project application and processing. In order to address specific topics, the research clusters *Smart Components*, *Advanced Modeling*, *Connectivity & Communication* and *Monitoring & Control* were established in the TEC research group. However, these clusters do not represent strictly delimited groups, but are rather to be understood as open spaces for exchange among the colleagues. This enables a differentiated view of the topics from different directions and ensures a targeted exchange of experience and knowledge.

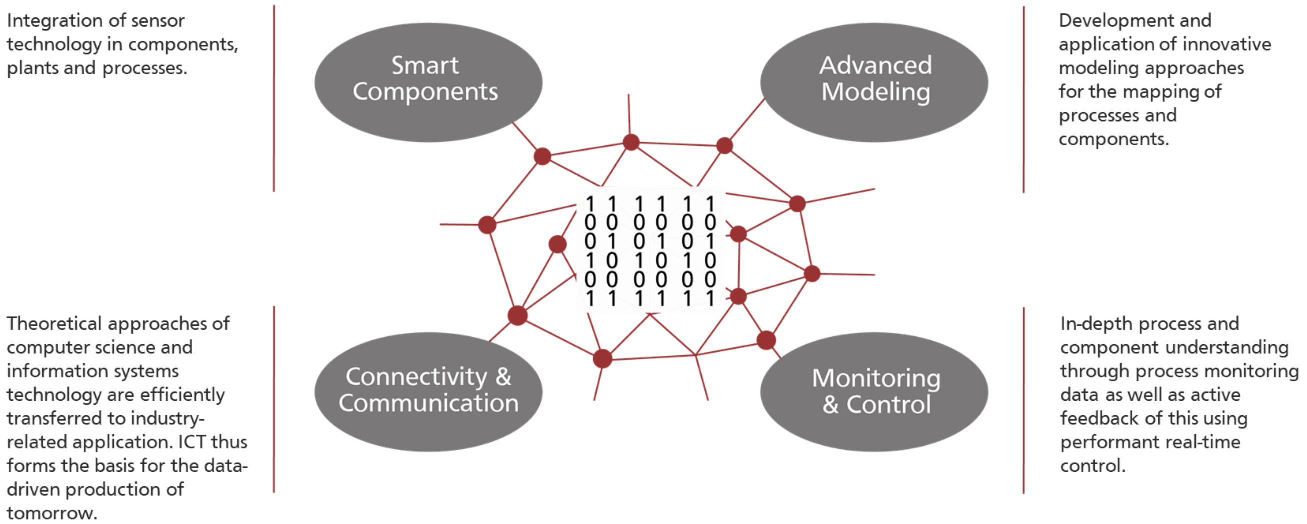


Figure 2: Expertise of the clusters within the TEC group

With the TEC-Lab, PTW has a technical center with a climate-stable measurement and sample preparation room as well as modern machinery. It provides the perfect environment to quickly develop and test new approaches for data-driven manufacturing using agile methods in a solution-oriented manner. With various demonstrators for data-driven manufacturing technologies and networked production solutions, the fun and enthusiasm for data-driven production is also awakened among young scientists.

Figure 3: TEC-Lab at PTW

## 2. Advanced Modeling in the Production of the Future

### 2.1. Vision

The Advanced Modeling Cluster sees itself as a platform and network for creating transparent connections and comprehensibility about processes and components in this new complexity. The core objectives are, on the one hand, the consolidation and further development of modeling approaches and simulation models in order to overcome existing application limits and, on the other hand, to ensure the sustainable usability and integrability of models.

Components and processes can be modeled in different approaches. (e.g. analytically, empirically, numerically). The modeling of their cooperation requires an interaction of the models with each other and thus a merging of them. The connection can take place over different physical domains (mechanical, thermal, electrical, ...), over different process steps and chains as well as different scales (macroscopic, microscopic). A key role here is the integrability as well as the sustainable usability of individual models. They allow a fast linkage of the models among each other and guarantee a further use of the models in new research questions.

This opens up new opportunities for gaining knowledge about cause-effect relationships. Furthermore, the continuous combination of versatile models, each of which precisely describes individual aspects, enables a more holistic and realistic view. This enables more accurate predictions and thus also reliable monitoring of processes and components. For further information, please refer to the Monitoring & Control cluster of the TEC research group.

## 2.2. Advanced Modeling

By a model, we understand a simplified representation of the relevant reality, which is delimited by the model horizon. Mathematical models describe a functional relationship between input and output variables, model parameters, and internal variables such as states. The basis for such models can be axiomatic (white-box model), empirical (black-box model) or a combination of both (grey-box model).

A white-box model is derived by deduction from axioms. Simplifications and assumptions are always made, which can influence the result. In black-box models, the model is derived from experimental measurements of a process, i.e. data-driven, or from the user's experience as part of an expert system. A grey-box model combines axiomatic and empirically derived relationships with user experience.

In the research group TEC of PTW, we understand advanced modeling as models that go beyond the known state of the art. These models are created by the continuous development of individual models, or by the linking of different models. The linked models can also be based on different modeling approaches. Special consideration is given to the interfaces and transfer values between the models. An important basis for advanced modeling is therefore a broad base of existing models with different modeling approaches that represent a wide variety of production engineering issues.

## 2.3. Use Cases

In the Advanced Modeling cluster, models are developed for describing complex interactions in the operation of components, machines or processes. The benefit for industry lies in the continuous gain of knowledge and the resulting new approaches for their improvement. The focus is on use cases from the industrial practice of production technology, which so far represent inadequately solved problems and challenges compared to the state of the art. The following use cases are listed as examples:

- Process-parallel quality determination based on internal machine signals
- Process-parallel tool condition/wear
- Component stress in the machining process (mechanical/thermal), e.g. rolling bearings, spindles, tools; e.g. with regard to reliable remaining service life
- Component design
- Basis for the continuous digital twin in the product life cycle

## 3. Selected projects and services for the industry

Research projects related to the Advanced Modeling cluster are carried out at the PTW of TU Darmstadt. In this section, an overview of current research in production engineering is given, which tests new approaches to modeling and model integration and develops them to the point of application implementation in products.

### 3.1.1. DFG Collaborative Research Center 805: Control of Uncertainties in Load Carrying Systems in Mechanical Engineering

At the Collaborative Research Center (CRC) 805, research was conducted at diverse disciplines of the TU Darmstadt and the Fraunhofer LBF over a period of 12 years, in three funding periods, on topics relating to the control uncertainty in load carrying systems.

The process-reliable, precise machining of functional bores is a decisive as well as elaborate step within the production chain. The fine precision hole finishing is carried out towards the end of the value chain, so that failure to maintain tolerances or even tool failure can result in high costs for rework or even component scrap. A usually used manufacturing process is reaming, which machines a prefabricated hole to the final dimension with a high degree of accuracy. An industrial application example is the machining of valve train components in the cylinder block of an internal combustion engine. The uncertainty that occurs in the form of runout, axis misalignment, inclined surface or inclined predrilled hole affects the dynamic behavior of the reamer and causes significant degradation of the circularity, diameter and straightness.

In the first two funding periods of CRC 805, the understanding of reaming process was significantly increased by building a mechanistic process model.[3] This resulted in a comprehensive knowledge of the effect of disturbances in interlinked machining processes, which could also be extended to the combined machining of valve seat ring and valve guide on the combustion engine.[4]

In a transfer project, a complete approach for the evaluation and optimization of the combined machining of valve seat ring and valve guide was developed. For this purpose, all relevant process elements in the process chain were simulated with a computer-aided model. This simulation model allows also a targeted optimize of the tools and the machining strategy.

The knowledge and experience gained in modeling the reaming process were adapted to the drilling/tapping process chain in the third funding period (see Figure 4). Similar as drilling/reaming process chain investigated in the previous funding periods, this is also a two-stage process chain at the end of the value chain that is influenced by various disturbance variables. To avoid component scrap, critical process faults such as tool breakage or out of tolerance must be prevented. For this purpose, passive and active measures have been applied, which are based on continuously developed simulation models of the previous funding periods. These are applied at both tool and machine level in order to ensure the required component quality despite the uncertainty that occurs in the machining process.

[3] Hauer, Thomas (2012): Modellierung der Werkzeugabdrängung beim Reiben – Ableitung von Empfehlungen für die Gestaltung von Mehrschneidenreibahlen. Dissertation. TU Darmstadt, Darmstadt.

[4] Bölling, Christian (2018): Simulationsbasierte Auslegung mehrstufiger Werkzeugsysteme zur Bohrungsfeinbearbeitung am Beispiel der Ventilführungs- und Ventilsitzbearbeitung. Dissertation. TU Darmstadt, Aachen.

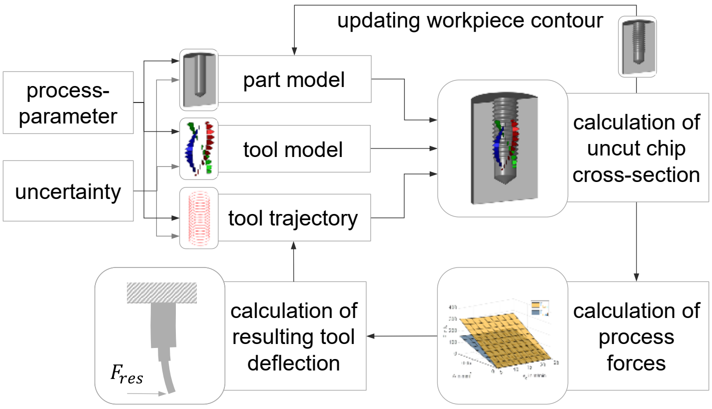


Figure 4: Framework of the mechanistic process model for tapping[5]

### 3.1.2. DFG: Experimental and Numerical Investigation of Low-Frequently Lateral Vibrations in Drilling Considering the Guiding Chamfer Contact

Within this research project, the influence of the guide chamfer on the low-frequency lateral vibrations occurring during deep drilling was investigated (see figure 5).

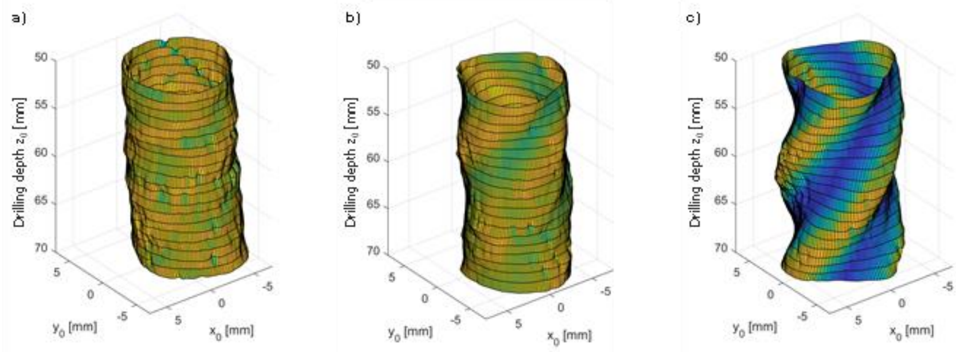


Figure 5: Representation of the experimentally determined bore wall for different guide chamfer widths (deviation from the ideal circular diameter enlarged by a factor of 50) a) 740 µm b) 500 µm c) 300 µm

For this purpose, detailed drilling and cutting force models are being developed which specifically consider the inertial and damping forces of the guide chamfer contact. In cooperation with the Institute for Applied Dynamics (TU Darmstadt), these new models are used to create numerical simulations that represent the relevant effects and are then validated with experimental investigations. In this way, the drilling tool and the associated drilling process can be optimized.

### 3.1.3. AICoM

In AICoM (Artificial Intelligence Controlled Milling), a learning machine tool is being developed for the autonomous milling of customized workpieces. In particular, novel process models for increasing quality and optimizing machine control will be developed. The hybrid process model uses machine learning methods to determine predefined quality characteristics, such as the actual contour of the workpiece based on tool displacement. Machine-internal data, such as axis and spindle current, are used as input variables and fused with external sensor data.

[5] Geßner, Felix; Weigold, Matthias; Abele, Eberhard (2021): Investigation on Tool Deflection During Tapping. In: Peter F. Pelz und Peter Groche (Hg.): Uncertainty in Mechanical Engineering. Proceedings of the 4th International Conference on Uncertainty in Mechanical Engineering (ICUME 2021), June 7–8, 2021. 1st ed. 2021. Cham: Springer International Publishing; Imprint: Springer (Lecture Notes in Mechanical Engineering), S. 104–114.

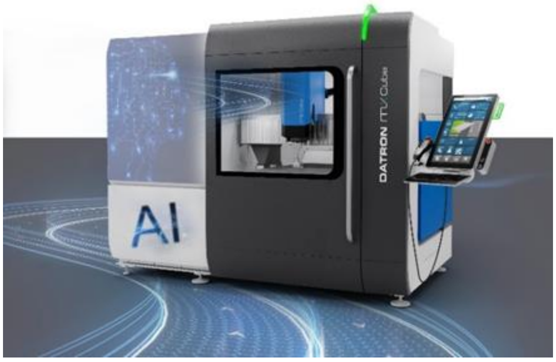

Figure 6: The learning machine tool using the example of a DATRON MX Cube in the AICoM project (image source: DATRON AG and PTW TU Darmstadt).

### 3.1.4. Pay-Per-Stress

Aim of the project pay-per-stress is the development and prototypical implementation of a stress-based payment model for machine tools. A leasing rate depending on the stress of a machine tool has the potential create a more efficient and fairer leasing. Therefore, not only the information about the actual stress of the machine tool and its components is required, but also the cause-effect relation between the stress and wear. To estimate the wear or the remaining useful lifetime different approaches like analytical models from standards or methods from artificial intelligence will tested. The resulting stress factor serves as an indicator for monetary evaluation for the pay-per-stress approach and as a basis for the further development of existing business models to intelligent services.[6]

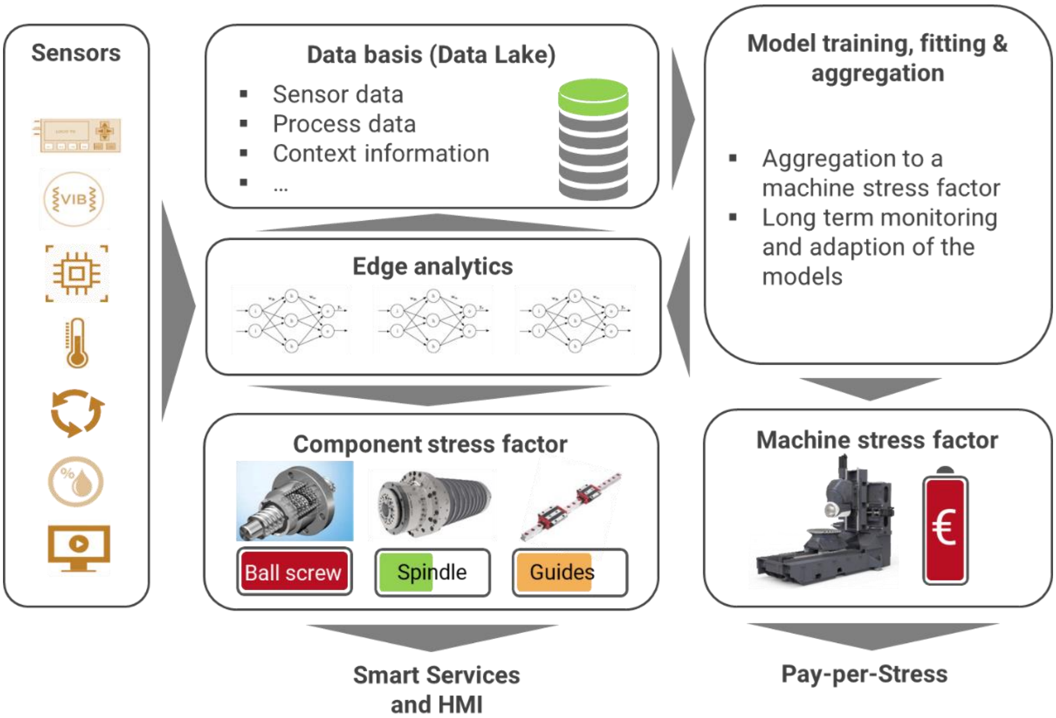


Figure 7: Concept for the development of a stress factor for stress-based payment models in machine tool industry

[6] https://www.ptw.tu-darmstadt.de/forschung_ptw/tec_fertigungstechnologie/aktuelle_forschungsprojekte/pay_per_stress/index.de.jsp

### 3.1.5. Working Group - High Quality Drilling (HQD)

Drilling machining and issues derived from it are the central topics of the High Quality Drilling industry working group. For the processes of deep drilling, reaming, deburring and tapping, the tool- and process-related factors influencing component quality are systematically investigated by means of simulations and specially developed mathematical models. These models are then compared with experiments, thus leading to deeper insights into the respective processes. In collaboration with experts from industry, it is thus possible to increase the productivity of the tools used while at the same time meeting the increasing quality requirements for the component.[7]

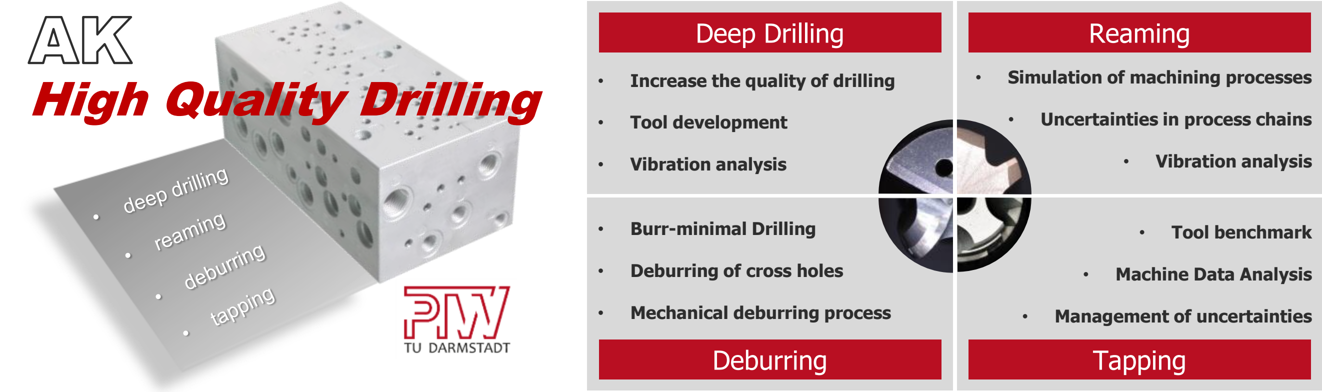


Figure 8: Schematic presentation of the topics of the High Quality Drilling working group

### 3.1.6. Working Group - Motor Spindles

As a core component of the machine tool, motor spindles have a decisive influence on the achievable machining speed and workpiece quality and thus on the productivity and economic efficiency of metal-cutting manufacturing processes. For more than 20 years, the topic of motor spindles has been anchored as a research focus at the Institute for Production Management, Technology and Machine Tools. It is driven forward in close cooperation with industrial partners. Today's trend topics of production technology development, such as Industry 4.0, sensor data fusion, edge computing and predictive maintenance, find their way into the working group. Innovative approaches and synergy effects in the area of additive technologies and lightweight construction are also being pursued in order to develop motor spindle systems for constantly increasing challenges. The modeling of motor spindle systems (mechanical, thermal, electrical and multi-physical in combination) plays a crucial role here. Currently, two topics with a strong connection to the Advanced Modeling Cluster are being worked on in the Motor Spindles working group.

In the sub-project entitled "Model-based spindle monitoring", a meta-model of a motor spindle is being developed as a grey-box model with a combination of physical FEM & MBS spindle modelling and statistical modelling of the relationship between experimentally recorded process parameters as input variables and numerically calculated output variables. The benefit of this metamodel lies in the time-efficient online calculation of the target variables, such as bearing forces and stresses, displacements of bearing rings and sliding bushes, contact forces and moments, without having to integrate additional sensory components into the spindle-bearing system. This represents an innovative approach to the implementation of Industry 4.0 applications in the machine tool sector. The approach is shown in Figure 9.

[7] https://www.ptw.tu-darmstadt.de/industrie/arbeitskreise_ptw/ak_hqd/index.en.jsp

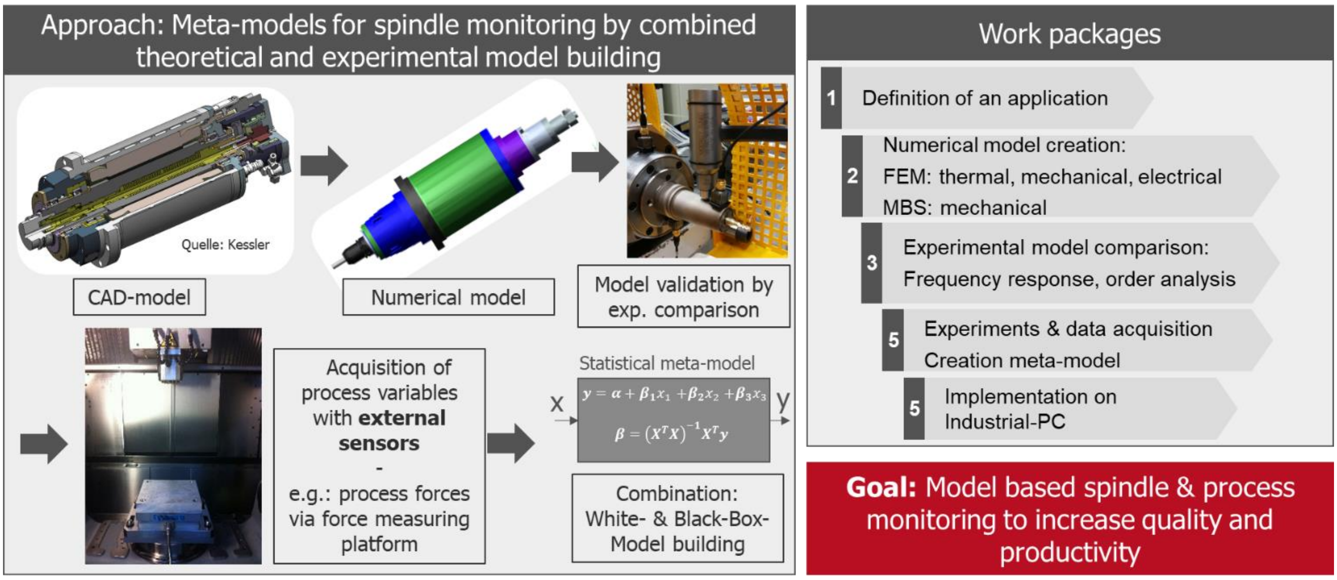


Figure 9: Procedure for model-based spindle monitoring

In the subproject "Experimental analysis of the movement behaviour of spindle bearings", the aim is to investigate the cage movement behaviour during rattling regarding industrially usable approaches to rattle prevention. The focus is on the frictional contact of the spindle bearing between the guiding skirt of the outer ring and the cage. Furthermore, the interaction of rolling elements and cage within the scope of the pocket clearance under radial force load is to be analysed. For this purpose, a highly dynamic force unit using a piezo actuator is set up on the test bench and is bring into service.[8] In Figure 10 on the left shows a camera recording at a discrete point in time as well as the automatic edge detection of the rolling element centers in the cage pockets in order to investigate the ball forward and backward motion under radial load of the rolling bearing. A derived multi-body simulation model is suitable for further numerical investigations.

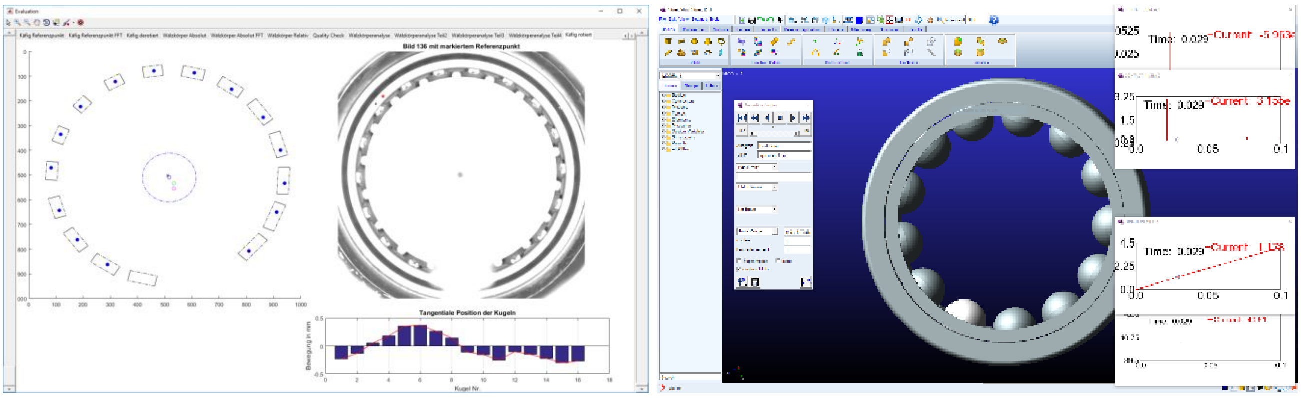

Figure 10: Optical measurement and modeling of unstable rolling bearing motion behaviour

[8] https://www.ptw.tu-darmstadt.de/industrie/arbeitskreise_ptw/ak_motorspindel/index.de.jsp

### 3.1.7. ETA in existing facilities

Within the framework of the joint project "ETA in existing facilities" (original project title: “ETA im Bestand”), solutions are being developed to increase energy efficiency in existing industrial facilities. In addition to research into higher-level methods for increasing energy efficiency, the focus is also on improvements through technology optimization. To this end, investigations are being carried out on the main spindle and the clamping devices in two subprojects.

On the one hand, the focus is on a rotary chuck including an actuating mechanism. The aim is to make a significant contribution to increasing energy efficiency by combining lightweight construction, process monitoring through sensor integration and, substitution of the clamping mechanism. The lightweight construction approach is characterized by a hybrid approach of orthotropic and isotropic materials. Topology optimization methods and FE methods are used to design this multi-material approach. Finally, the metrological investigation of the demonstrator serves to validate the developed models.

On the other hand, the use of the synchronous reluctance machine as main spindle drive in machine tools is tested. With the synchronous reluctance motor, the efficiency can be improved compared to the commonly used asynchronous machines and at the same time, the use of rare earth metals as in permanent magnet synchronous machines can be avoided. The modeling and design using FE methods of these machines as well as the validation of the models by comparative measurements on the real setup are considered.

### 3.1.8. AVISPA II

The project Automation of Visual Inspection and Finishing processes for Aero-engines is situated in the field of Condition Monitoring and Quality Inspection. The competitiveness of the European aero-engine industry can be significantly improved by a zero-defect approach for selected components and manufacturing processes. This will be achieved by implementing automated image-based inspection processes, machine learning (AI), process automation and control loops in critical manufacturing processes. This represents the usage of advanced models for monitoring application. Key areas of interest include predictive monitoring of cutting tool wear in machining processes (see Figure 1), closed-loop control of various machining techniques, such as abrasive surface machining of additively manufactured engine parts, and automation of visual inspection of components with honeycomb structures to detect complex assembly issues and defects.[9]

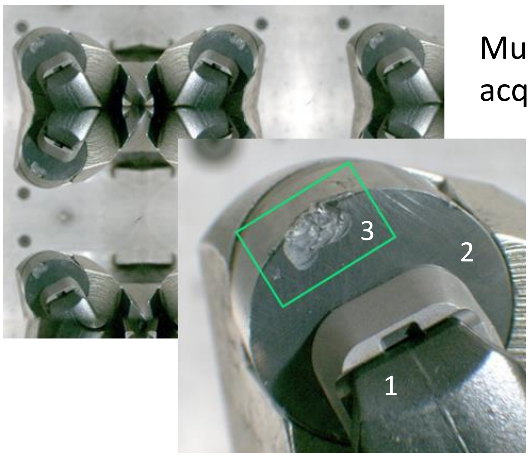


Figure 11: Image-based classification of the state of tool wear for industrial cutting inserts

[9] https://www.ptw.tu-darmstadt.de/forschung_ptw/tec_fertigungstechnologie/aktuelle_forschungsprojekte/avispa_tec/index.en.jsp

### 3.2. Service Offering

The TEC research group of PTW TU Darmstadt offers development and consulting services around the topic of Advanced Modeling. Components such as motor spindles or assemblies of machine tools can be modeled and their operating behavior analyzed. There are also a variety of approaches for describing and simulating manufacturing processes in models. The consulting services include, for example, the further development of methodological approaches to modeling or the design of model interfaces as well as the conversion of models into time-efficient models for process-parallel use.

## 4. Dissemination of knowledge

In addition to lectures for students and industry partners, we implement the knowledge gained in demonstrators that serve to reinforce knowledge and provide training and continuing education. In the Advanced Modeling cluster, there are several demonstrators that are intended to address the target group of industry on the one hand and students of mechanical engineering, mechanics and mechatronics on the other. The demonstrators are intended to demonstrate the models and allow them to be experienced in simplified examples in the TEC-Lab and, on the other hand, to present the direct benefits of the models in production for process description in interaction with processes on the machines in the TEC-Lab and, in connection with the Monitoring & Control research cluster, condition monitoring up to predictive maintenance. The basis for the demonstrators and their continuous further development are the considered use cases of the research projects.

## 5. List of Publications

The publications are listed in the order in which they can be assigned to the listed projects under section 4.


- T. Hauer, „Modellierung der Werkzeugabdrängung beim Reiben – Ableitung von Empfehlungen für die Gestaltung von Mehrschneidenreibahlen“, Dissertation, TU Darmstadt, Aachen, 2012. ISBN: 9783844015492
- C. Bölling, „Simulationsbasierte Auslegung mehrstufiger Werkzeugsysteme zur Bohrungsfeinbearbeitung am Beispiel der Ventilführungs- und Ventilsitzbearbeitung“, Dissertation, TU Darmstadt, Aachen, 2018. ISBN: 9783844063929
- C. Bölling and E. Abele, “Simulation of Multi-Stage Fine Machining Processes at the Example of Valve Guide and Valve Seat”, In: AMM 885, S. 255–266, 2018. DOI: 10.4028/www.scientific.net/AMM.885.255
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- C. Bölling, M. Kuhne and E. Abele, “Modeling of process forces with consideration of tool wear for machining of sintered steel alloy for application to valve seat in a combustion engine”, In: Prod. Eng. Res. Devel. 11 (4-5), S. 477–485, 2017. DOI: https://doi.org/10.1007/s11740-017-0759-y
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- E. Abele and F. Geßner, „Spanungsquerschnittmodell zum Gewindebohren. Modellierung der Auswirkung von Unsicherheit auf den Spanungsquerschnitt beim Gewindebohren“, In: wt

Werkstattstechnik online 108 (H. 1/2), S. 2–6, 2018. DOI: https://doi.org/10.37544/1436-4980-2018-01-02

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