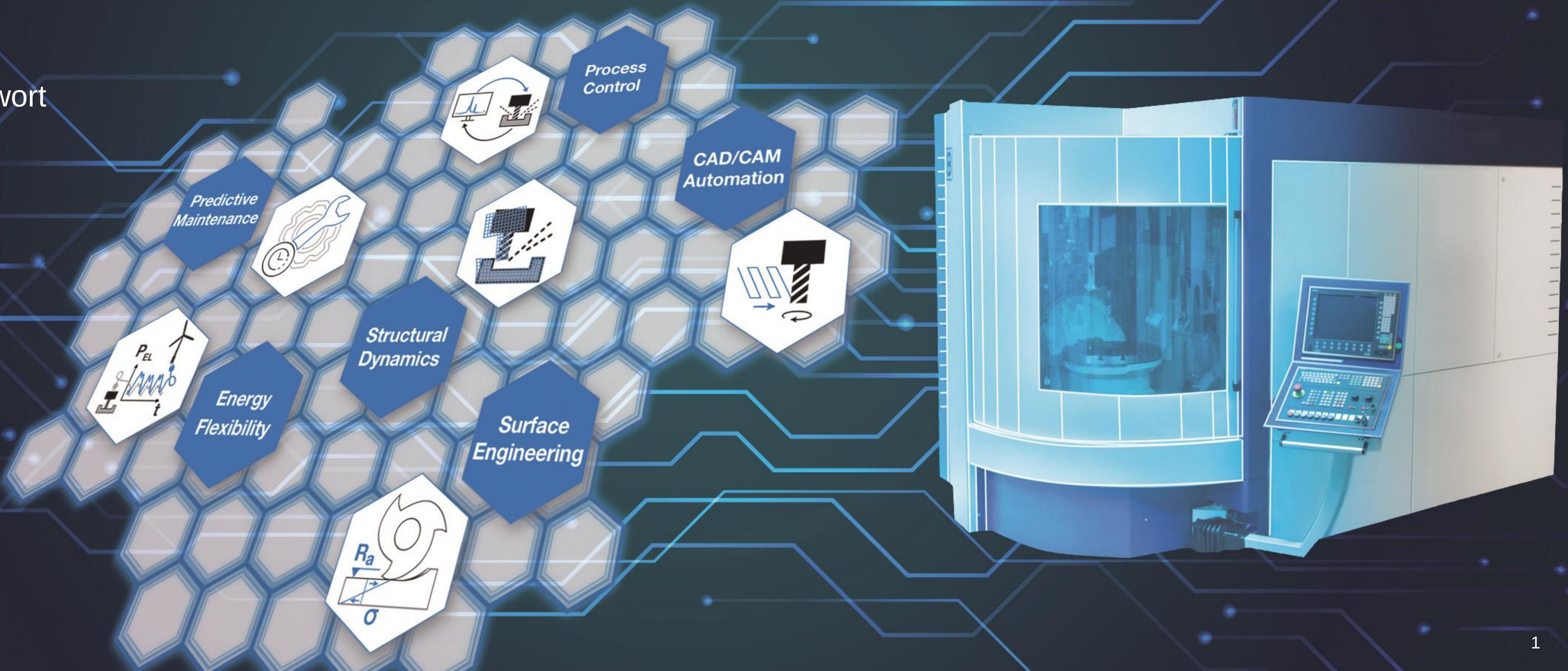
Holistic Approach to Digital Twins for Machine Tools

Connected – Virtual – Online

Robin Kleinwort



Digital Transformation is the Key Enabler for Numerous Business Cases of Future Factories

Overview

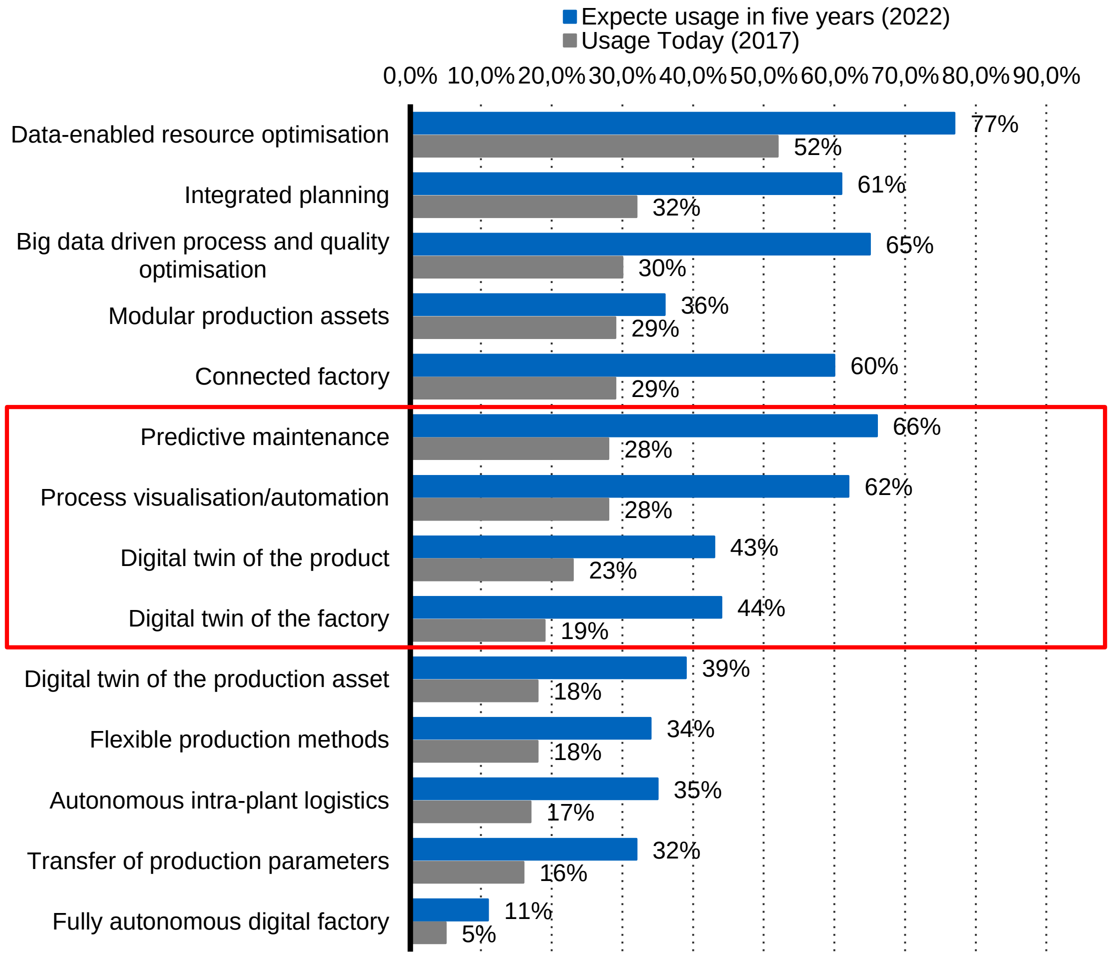
Global Production Networks

Local Production Shop Floors

Machine Tools

Machining Processes

“Hot Topics” in Digitalized Production



Source: Statista/PwC

Digital Transformation is the Key Enabler for Numerous Business Cases of Future Factories

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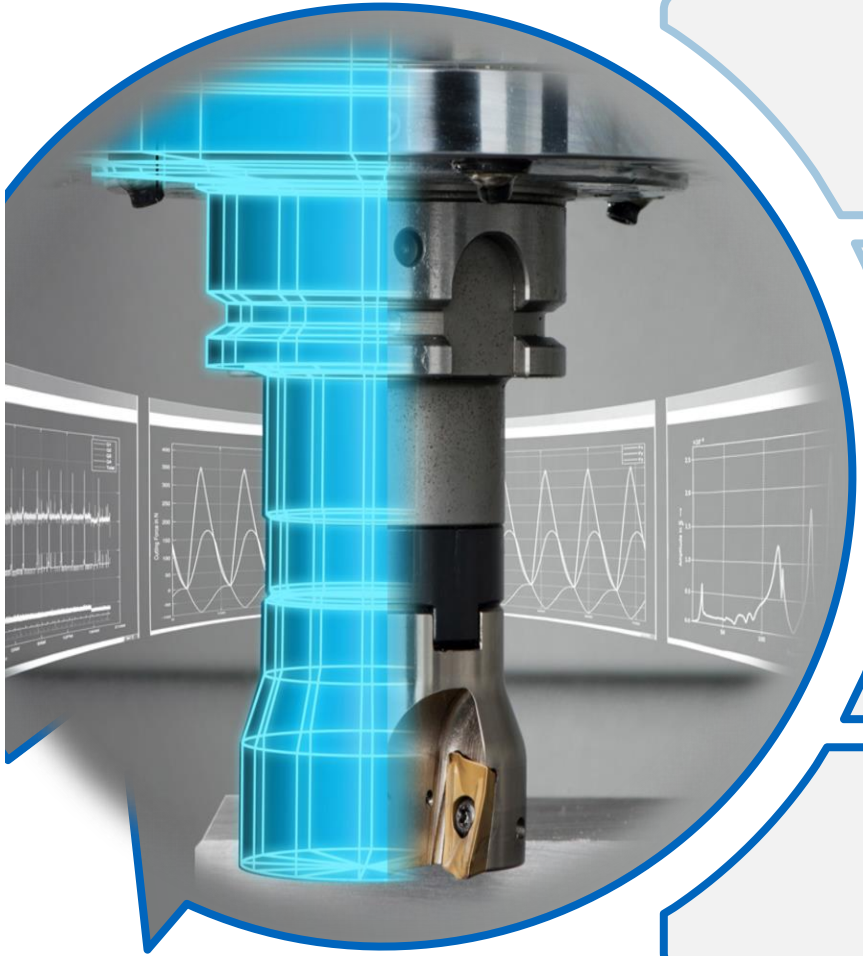
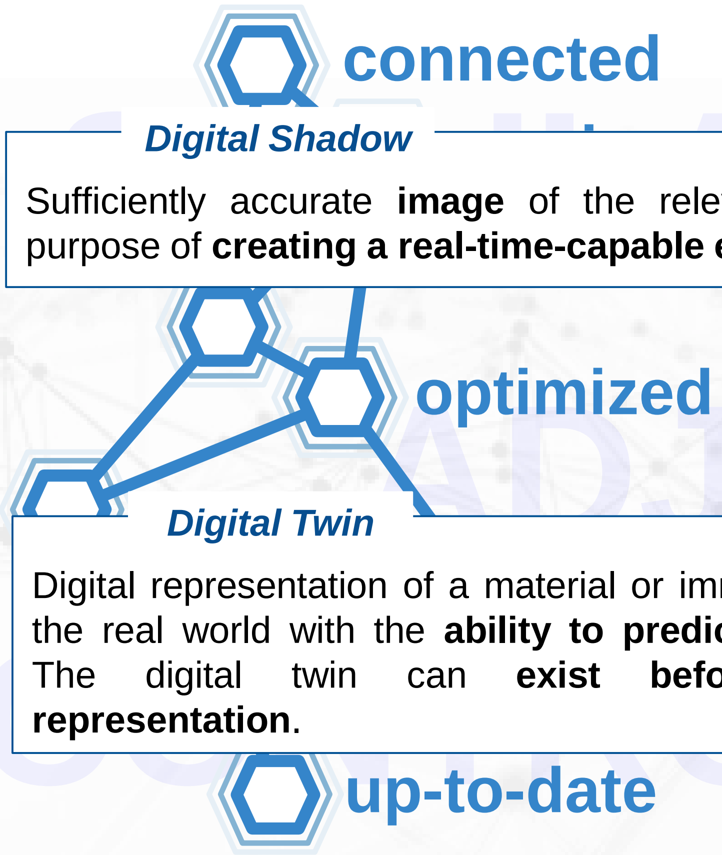


- Global Production Networks
- Local Production Shop Floors
- **Machine Tools**
- **Machining Processes**

The Machine Tool of the Future



Digital Shadow

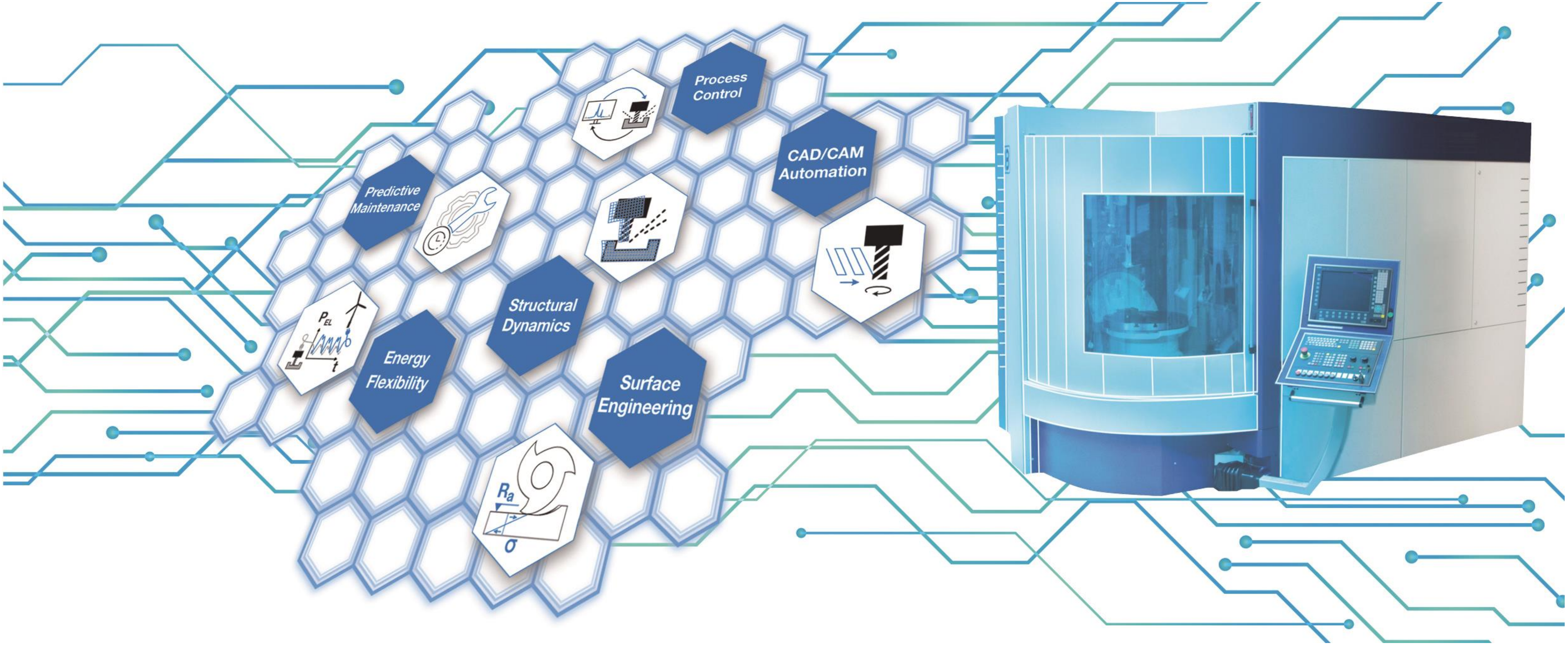
Sufficiently accurate **image** of the relevant data with the purpose of **creating a real-time-capable evaluation** basis.

Digital Twin

Digital representation of a material or immaterial object from the real world with the **ability to predict new conditions**. The digital twin can **exist before its physical representation**.

Digital Transformation of Machine Tools and the Application of Artificial Intelligence will unleash a New Level of Automation

Overview



Application of Digital Twins during the Life Cycle of Machine Tools and Workpieces

Overview

Phase	Development Phase, Production-Ready Design	Virtual Process Optimization and Quality Prediction	Realtime Process Parallel Simulations	Non-Realtime Process Parallel Simulations	Development Feedback for Design Changes
Machine Tool	Machine Design	Machine Simulation	Process Monitoring	Health Monitoring	Machine Optimization
Digital Twin	Model Generation	Preceding Model Usage	Online Model Usage	Posterior Model Usage & Update	Data-driven Model Update
Workpiece	Workpiece Design	Process Simulation	Process Monitoring	Quality Control	Process Optimization
Valorization	Simulation-driven Design of Machine Tools and Workpieces	Simulation-driven Planning of Machining Operations	Virtual Sensors and Process Monitoring	Predictive Maintenance and Audit-Proof Quality Inspection	Data-driven Machine and Production Process Optimization

Model Generation

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Structural Dynamics Simulation as the Backbone of the Digital Twin

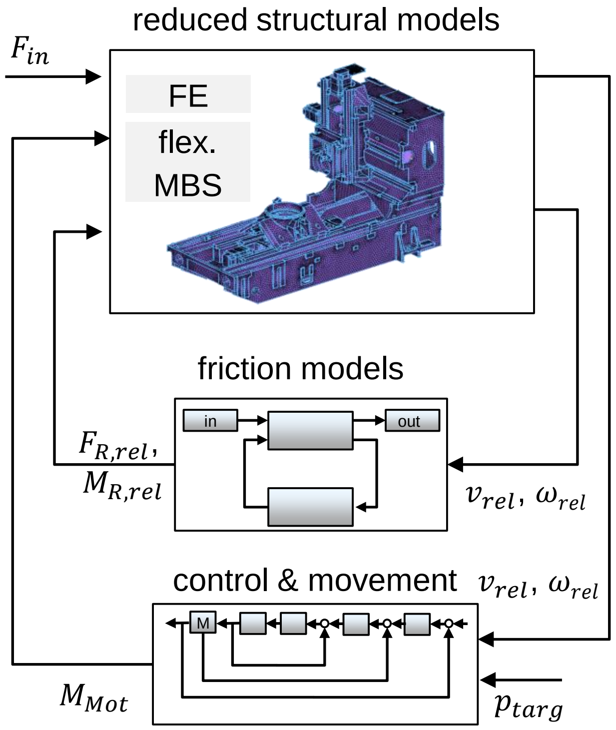
Virtual Machine Tool Structure

Model Generation | Preceding Model Usage | Online Model Usage | Posterior Model Usage | Model Update

Possibilities

- virtual prototypes for early testing
- targeted optimization of new machine generations
- visualization of machine behavior

…



Digital Twin architecture of machine tool

Benefits

- **reduce time to market**
- **reduce costs for prototypes**
- **increase machine performance**

…

Flexible Multibody Models allow fast and precise simulation of Structural Dynamics in arbitrary Axis Positions

Virtual Machine Tool Structure

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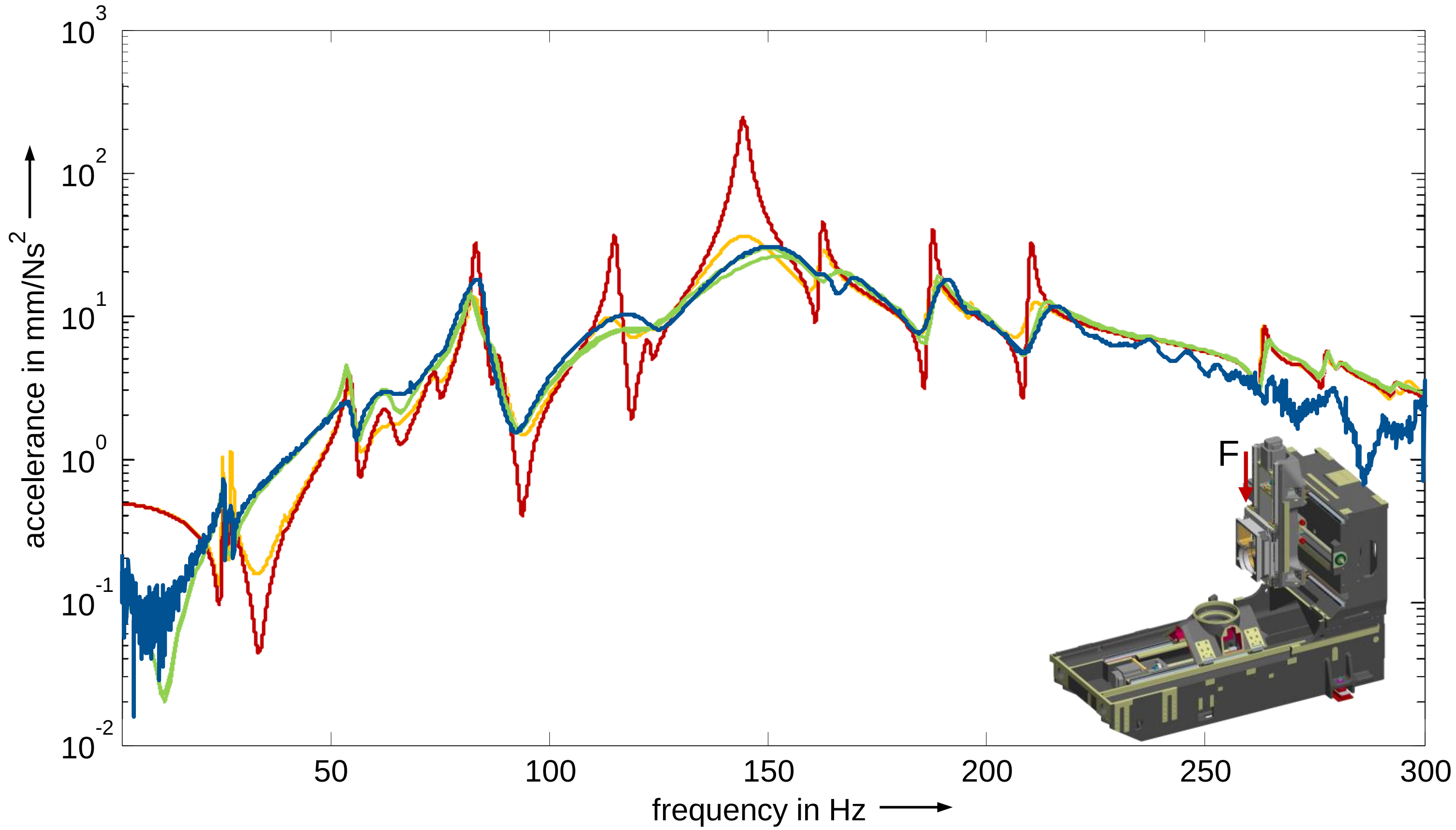


measured

simulated with linear damping models

simulated with local damping models

simulated with measured damping parameters

high accuracy by using local linear and nonlinear damping and stiffness models

reduced calculation times by using model order reduced flexible multibody models

FRF calculation time for a single axis position:

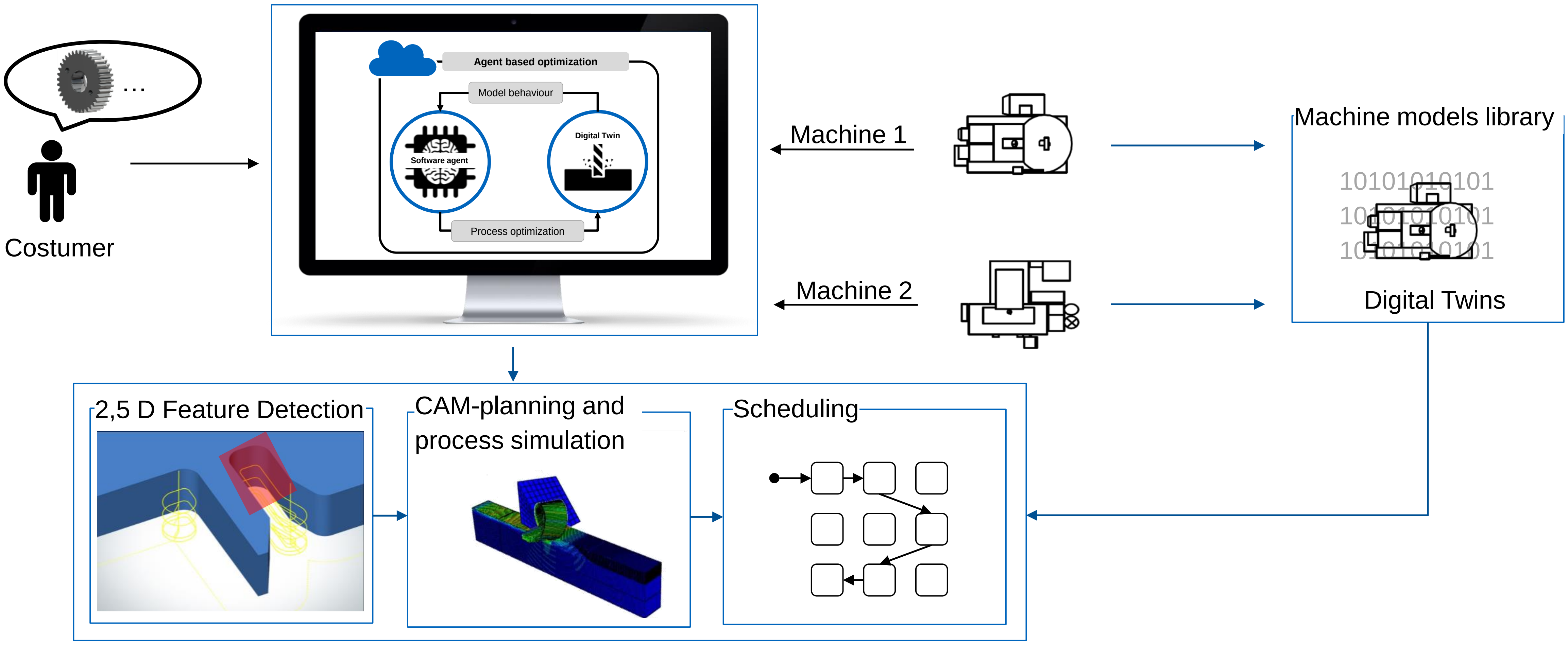
~ 1-10 h traditional FE-models

< 1 min model order reduced flexible multibody models

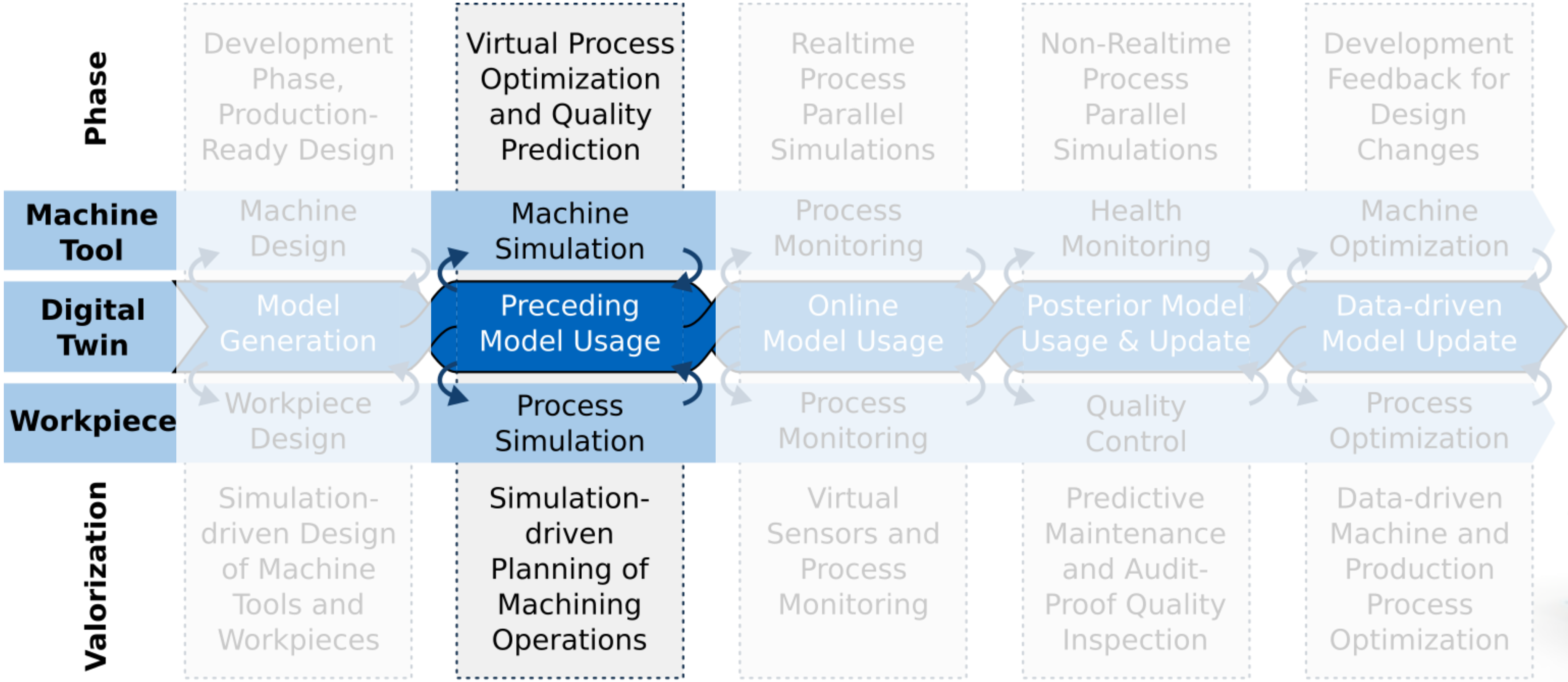
Process Automation to achieve Machining as a Service

Workpiece Design and CAD/CAM Automation

Model Generation | Preceding Model Usage | Online Model Usage | Posterior Model Usage | Model Update



Preceding Model Usage



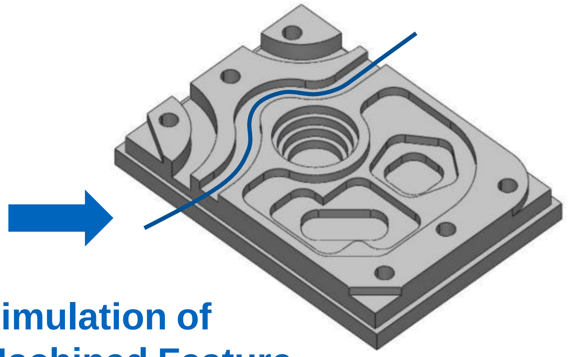
The Digital Twin can be used to Improve the Accuracy and Stability of Machine Tools

Process Simulation with Quality Prediction

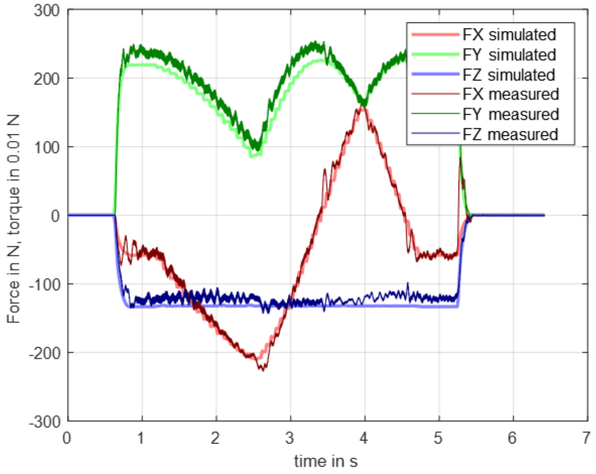
Model Generation | **Preceding Model Usage** | Online Model Usage | Posterior Model Usage | Model Update

Possibilities

- simulation of the coupled machining process
- prediction of the static deflection and dynamic stability
- optimization of the accuracy and process stability
- …



Simulation of Machined Feature



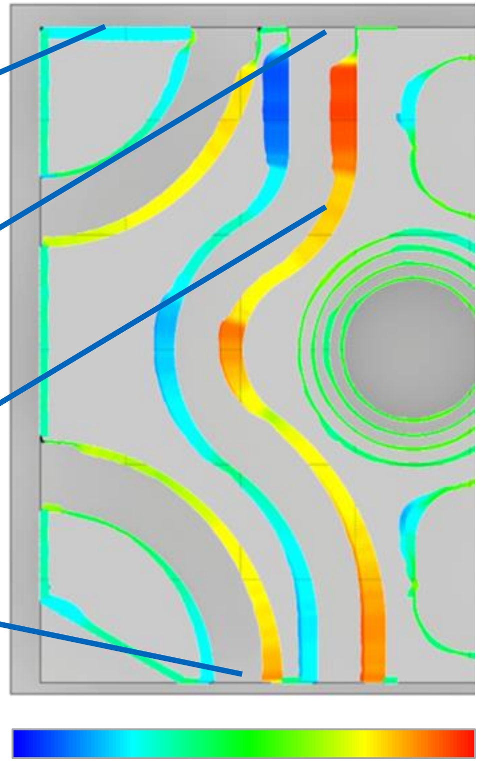
Without Deflection Compensation

dimesion of the outline is too small

large deviation at the workpiece exit

large deflection during changing feed directions

large deviation at the workpiece entrance



Deflection in mm: -1 0 1

Sources: Schnoes, F., and M. F. Zaeh. "Model-based Planning of Machining Operations for Industrial Robots." *Procedia CIRP*82 (2019): 497-502.

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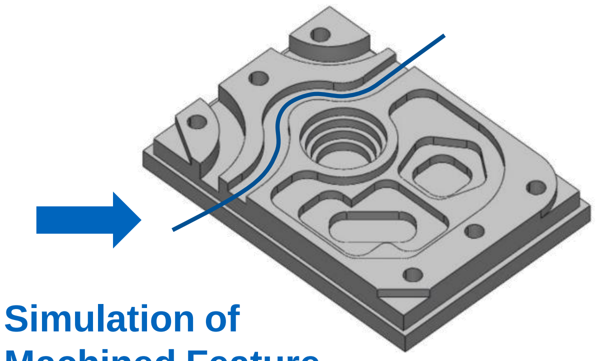
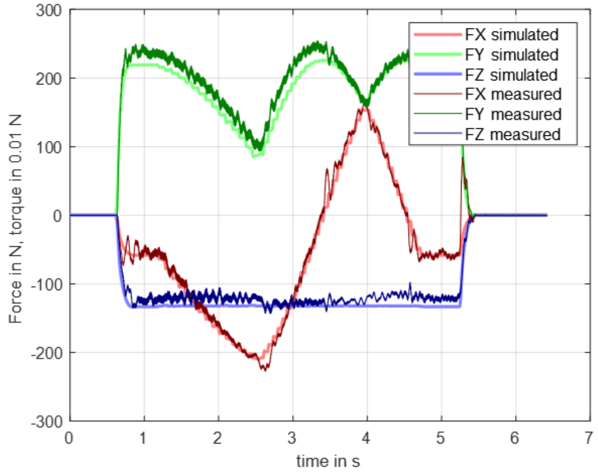
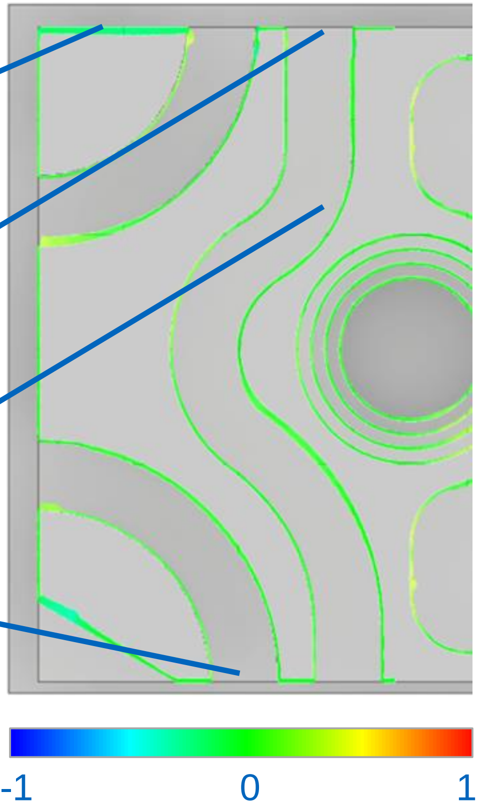


Simulation of Machined Feature



With Deflection Compensation

- accurate outline
- reduction of the error at the workpiece exit
- high accuracy while changing feed directions
- reduction of the error at the work-piece entrance



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Online Model Usage

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Closed-loop Manufacturing using Edge and Cloud Infrastructure

Process Monitoring and Control

Model Generation → Preceding Model Usage → **Online Model Usage** → Posterior Model Usage → Model Update

Machine Data Interface

Process Control

Process Data Acquisition and Process Control

- Spindle speed
- Motor current
- Accelerometers (spindle, machine table, ...)
- Tool position
- …

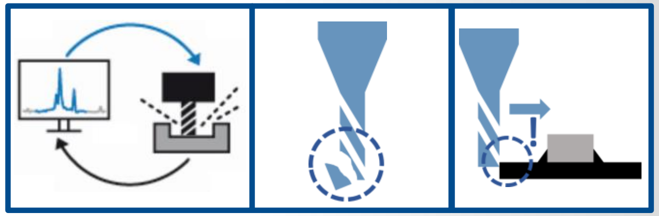
Real manufacturing process

Smart Box

Sensor and CNC data

Inner Control Loop:

- Chatter detection and avoidance
- Tool monitoring
- Collision avoidance

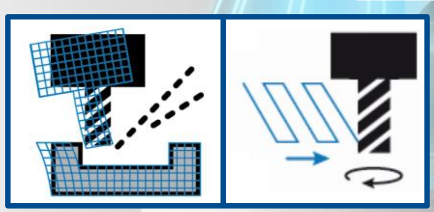


Cloud/Server

Outer Control Loop:

Machine learning approaches in the field of…:

- Output-Only-Modal-Analysis for modeling the position- and tool-dependent frequency response (Receptance Coupling)
- NC path planning and optimization



Inner Control Loop stabilizes the Process

Process Monitoring and Control

Model Generation | Preceding Model Usage | **Online Model Usage** | Posterior Model Usage | Model Update

Chatter Detection

Efficient and intelligent algorithms for **chatter detection** monitor the stability of the process.

Chatter Avoidance

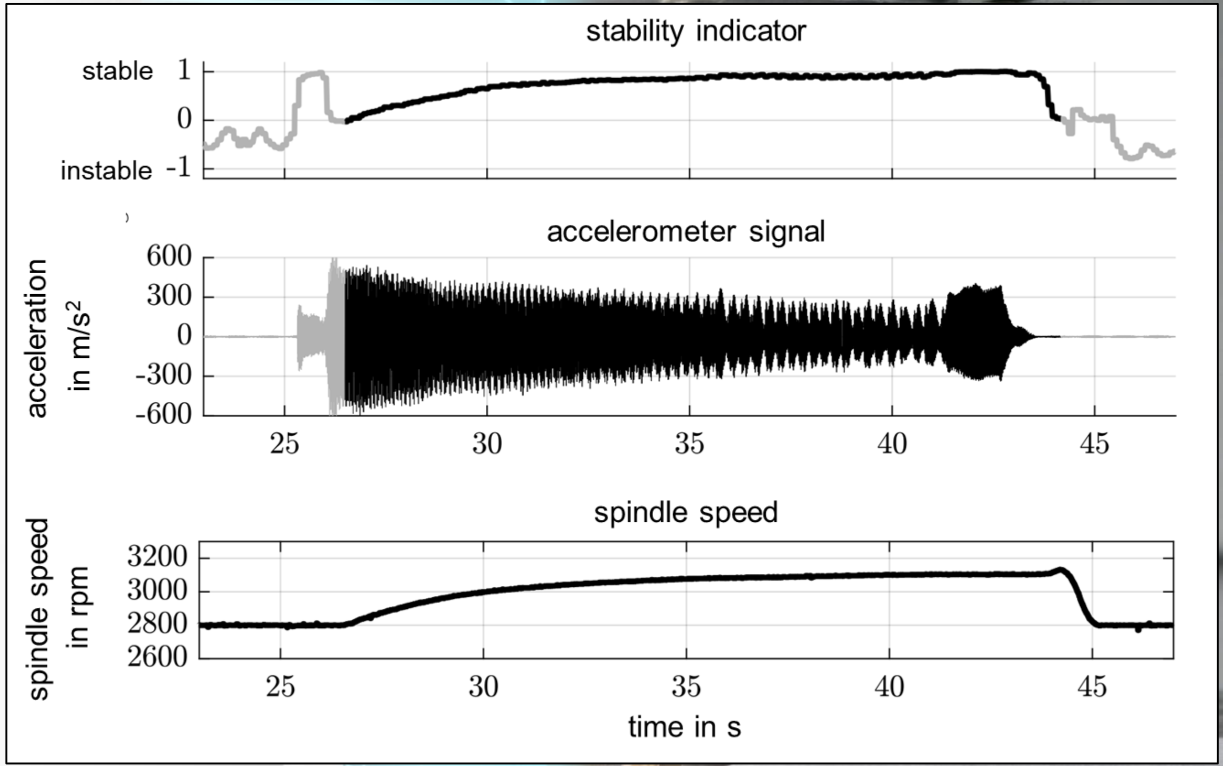
Chatter avoidance strategies within the **edge-based control loop** change process parameters to stabilize the process.

Knowledge Generation

Learn from instable machining conditions **for future machining processes**.

Machine Load, Tool Wear and Suface Quality

The occurrence of chatter results in a **reduction** of the machine components and tool **lifetime**. **Chatter marks** lead to poor **surface quality**.



Cutting Force Identification using internal Signals

Process Monitoring and Control

Model Generation | Preceding Model Usage | **Online Model Usage** | Posterior Model Usage | Model Update

Sensorless Process Monitoring

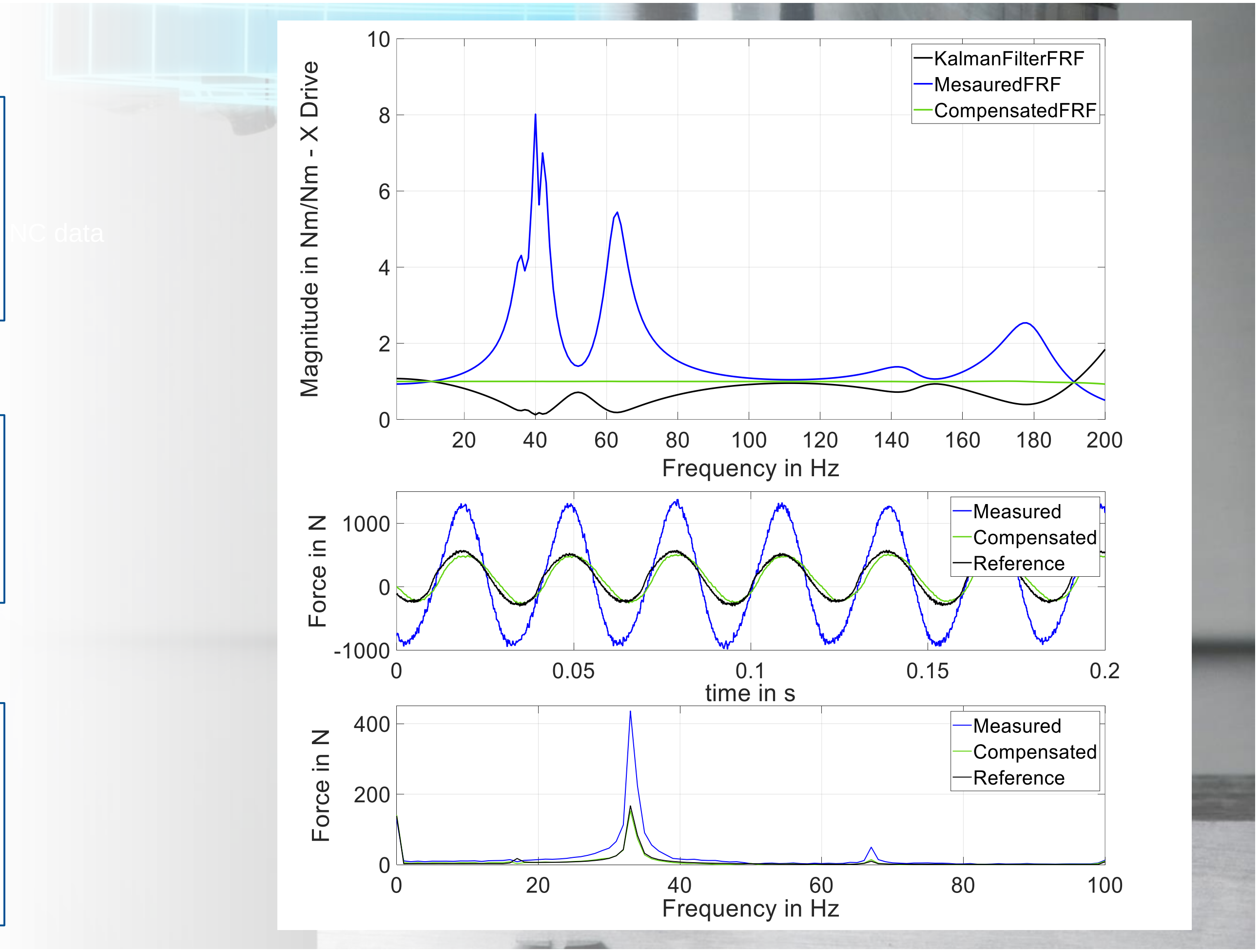
Modern control and machine tool generations have a large number of **internal sensors** that can be accessed via **various IoT interfaces**. This enables detailed process monitoring without additional external sensors.

Machining Forces

By previously determining the **transfer characteristics** between motor and TCP, it is possible to **determine the process forces with motor current measurements** during machining.

Data resolution

The selected process parameters such as the feed rate and the spindle speed influence the **variation of the process forces**. Therefore, **high frequency data acquisition** and **resolution** is essential.



Comparing Simulation Results with CNC signals on an Edge-Device unleashes a new Level of Process Monitoring

Process Monitoring and Control

Model Generation | Preceding Model Usage | **Online Model Usage** | Posterior Model Usage | Model Update

Tool wear monitoring

The tool wear monitoring technique will be used for **high-strength metal alloys** and **carbon fiber reinforced polymers**.

Machine Learning

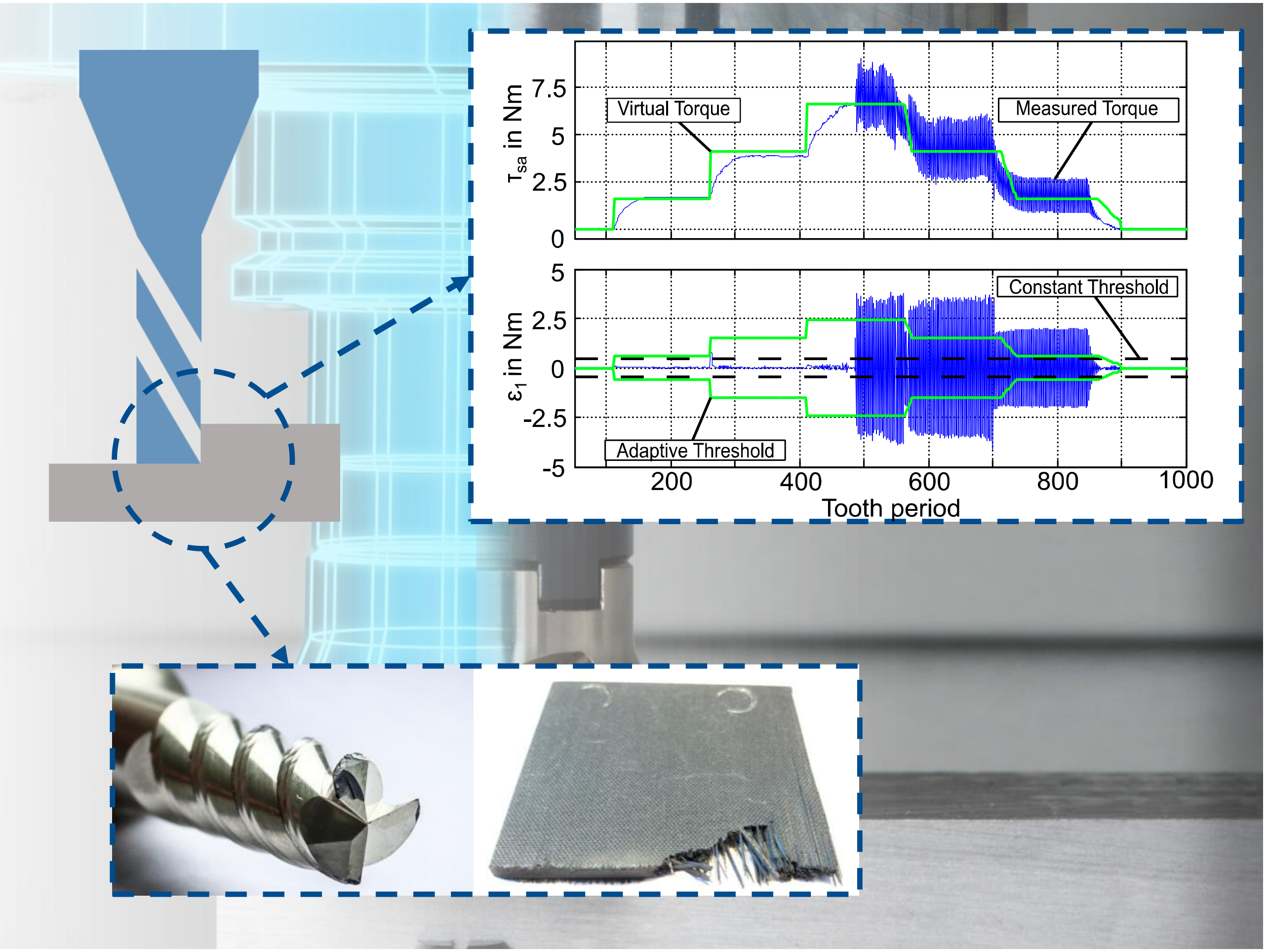
Application of **machine learning algorithm (random forest)** for **tool wear monitoring** using cutting force and vibration data.

Surface Quality

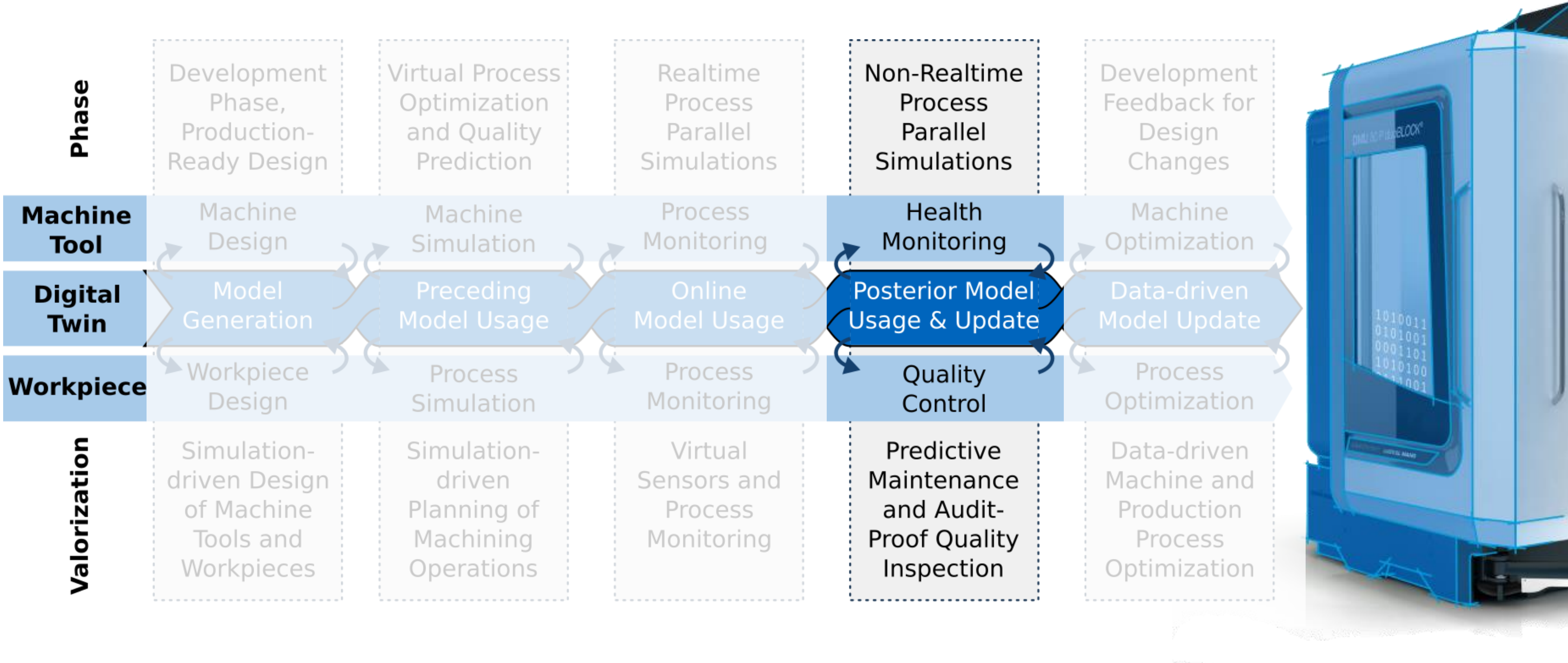
Quantitative relationship between **tool wear progression** and **machined surface integrity** will be developed.

Tool breakage detection

In addition to monitoring tool wear, sudden **tool breakage** during machining should also be **detected immediately to prevent damage** to machine and tool.



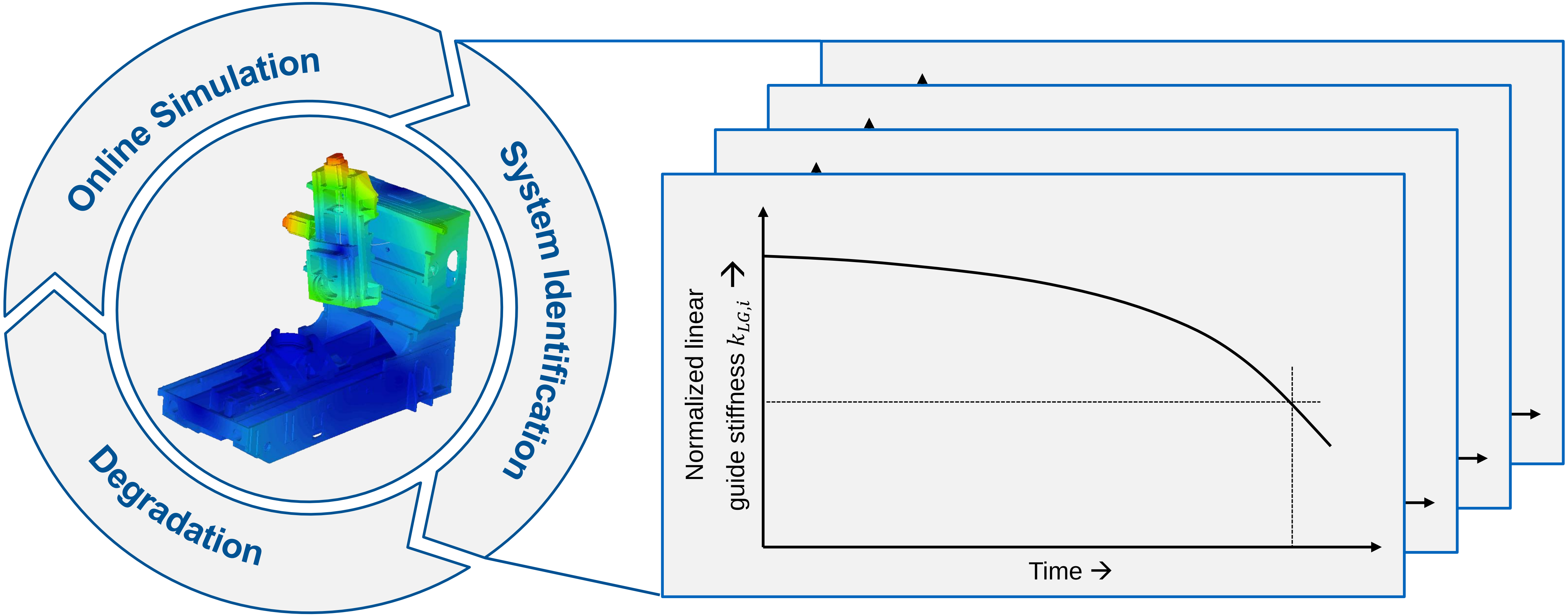
Posterior Model Usage & Update



Self-Monitored Fault Identification using Digital Twins

Model Generation | Preceding Model Usage | Online Model Usage | **Posterior Model Usage** | Model Update

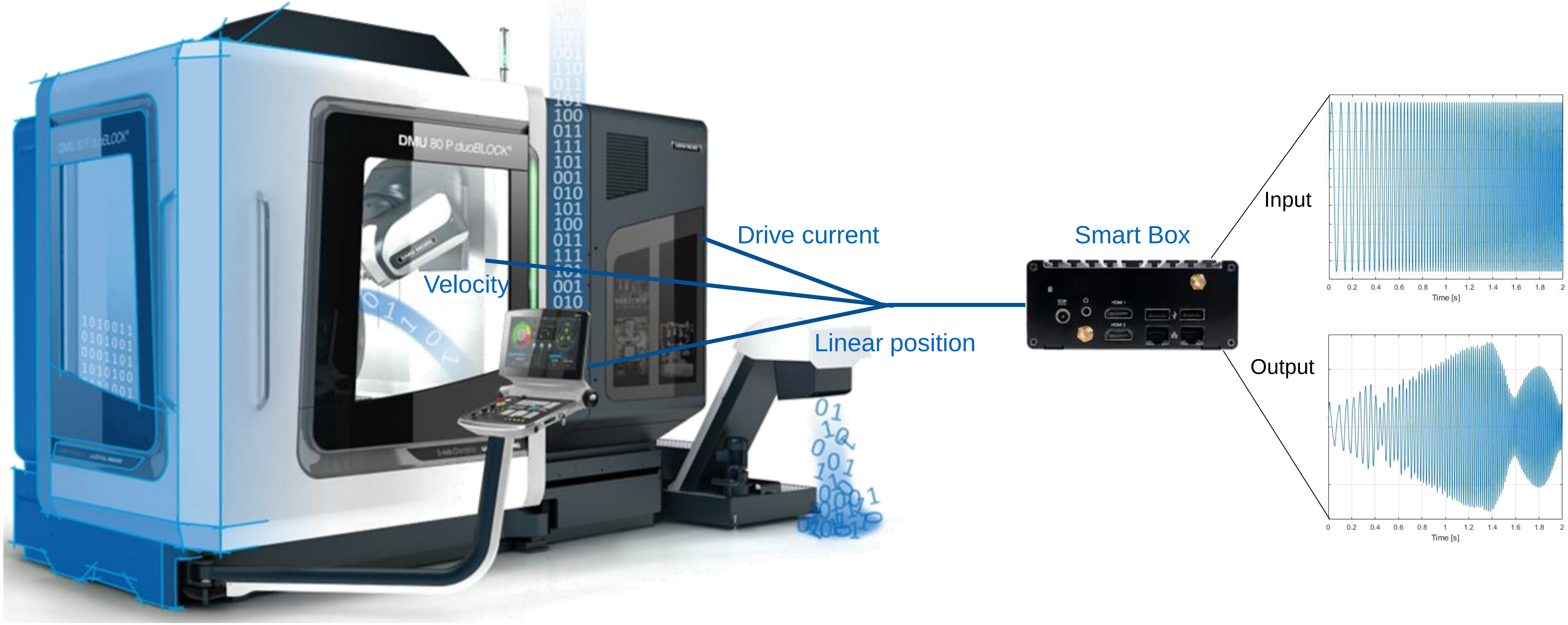
Machine Health Monitoring



Updating the Digital Twin via IoT gateway

Machine Health Monitoring

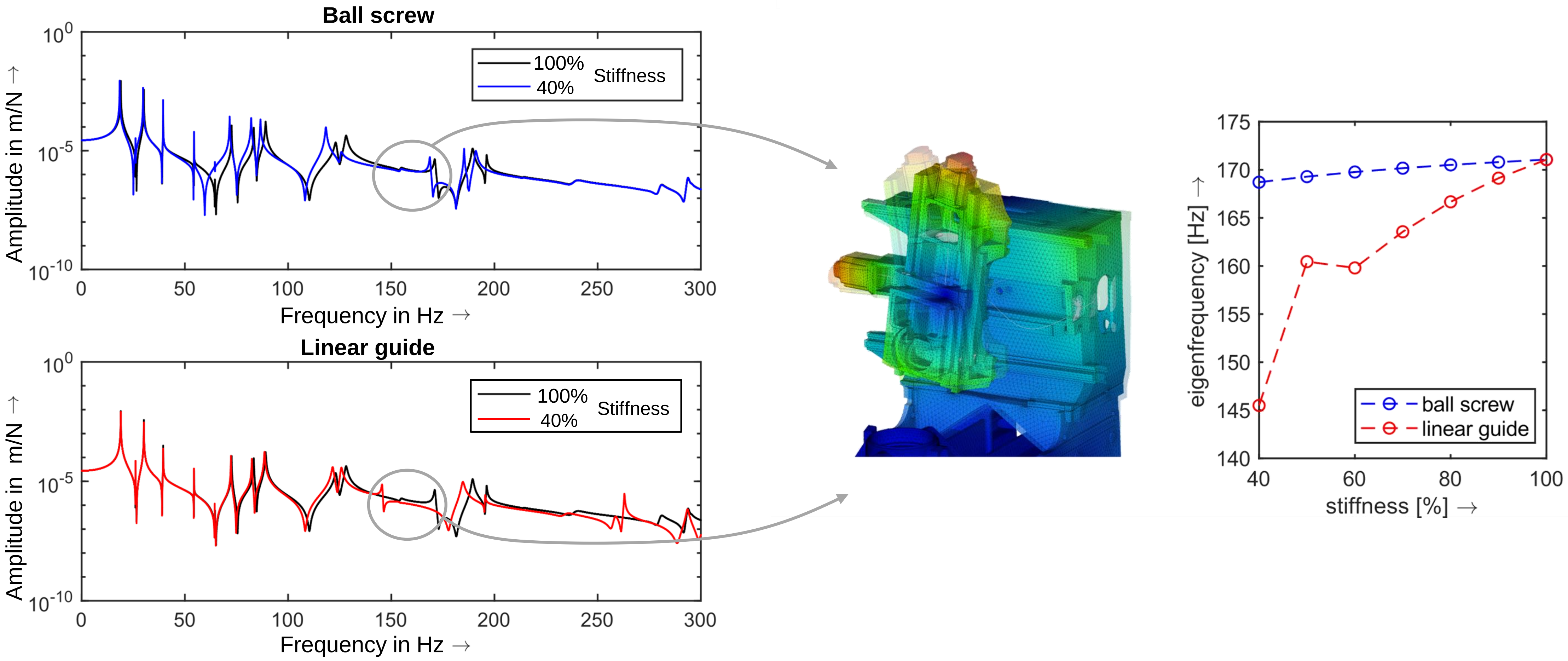
Model Generation → Preceding Model Usage → Online Model Usage → **Posterior Model Usage** → Model Update



The Digital Twin can be used to detect and even locate Wear

Model Generation | Preceding Model Usage | Online Model Usage | **Posterior Model Usage** | Model Update

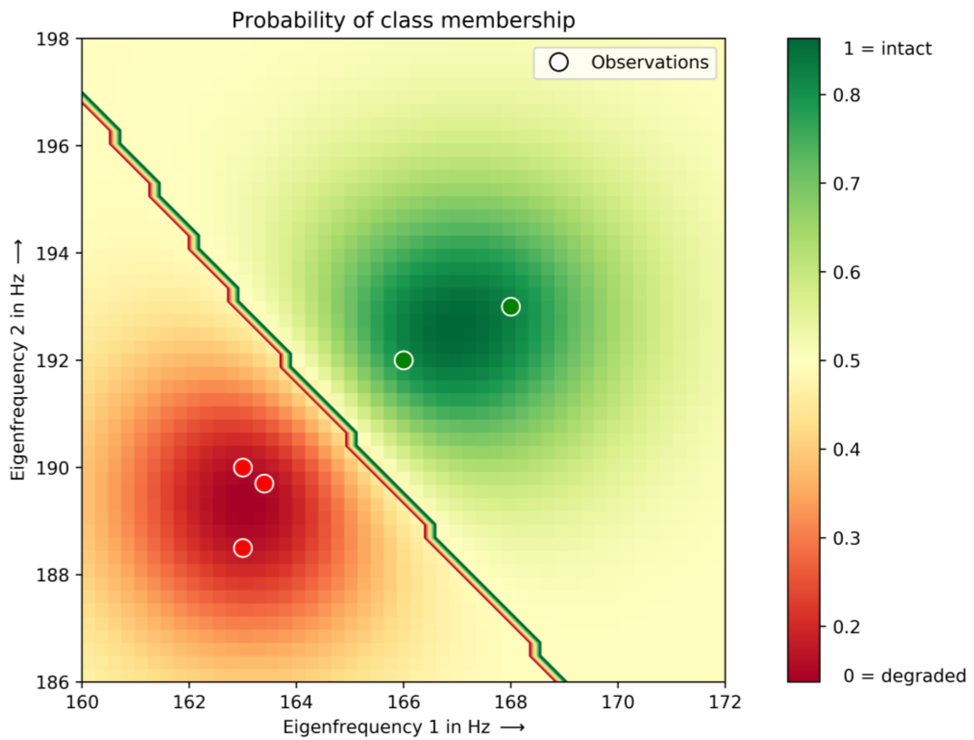
Machine Health Monitoring

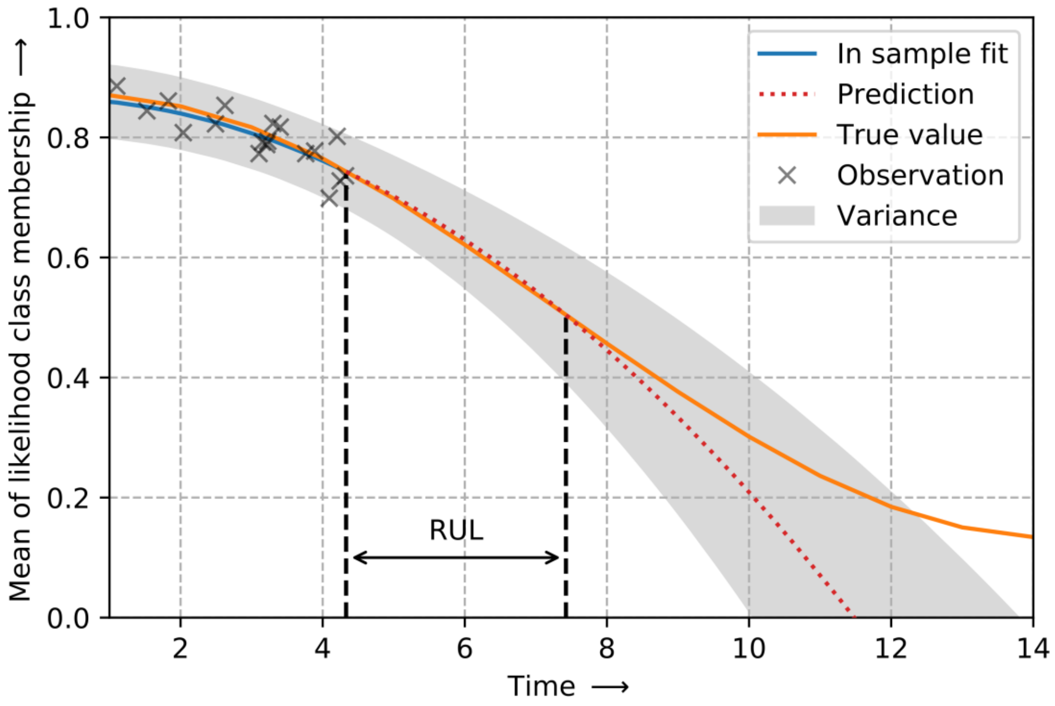


Bayesian Machine Learning enables the Estimation of Remaining Useful Life

Model Generation | Preceding Model Usage | Online Model Usage | **Posterior Model Usage** | Model Update

Machine Health Monitoring





- Regular condition monitoring test cycles between manufacturing periods
- Probability of class membership from Gauss Process Classification model can be tracked over time and extrapolated in order to predict the remaining useful life (RUL)

Determination of Current Machining Accuracy by continuously Updating Machine Models

Health Monitoring with Quality Prediction

Model Generation | Preceding Model Usage | Online Model Usage | **Posterior Model Usage** | Model Update

Possibilities

condition monitoring by observing manufacturing accuracies

prediction of component quality depending on machine tool wear

detect when maintenance is necessary to ensure quality standards can be met

Benefits

prediction of contouring errors through updated structural dynamics models

no failure data necessary for predictive maintenance

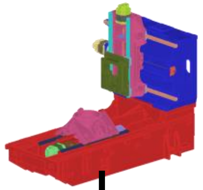
schedule maintenance tasks depending on decreasing production quality

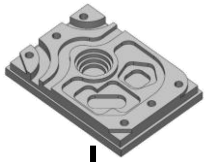
Real manufacturing process

- Data acquisition via IoT interfaces (OPC UA, MQTT,…)
- Receptance measurement using internal and virtual sensors

Virtual Representation

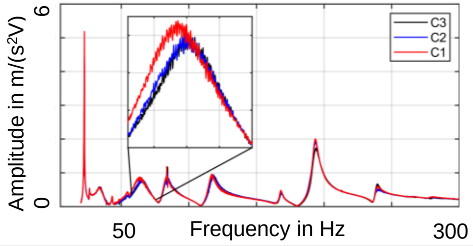
- Update machine tool simulation model with acquired machine data
- Simulation machining process and determine resulting workpiece quality

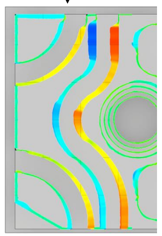




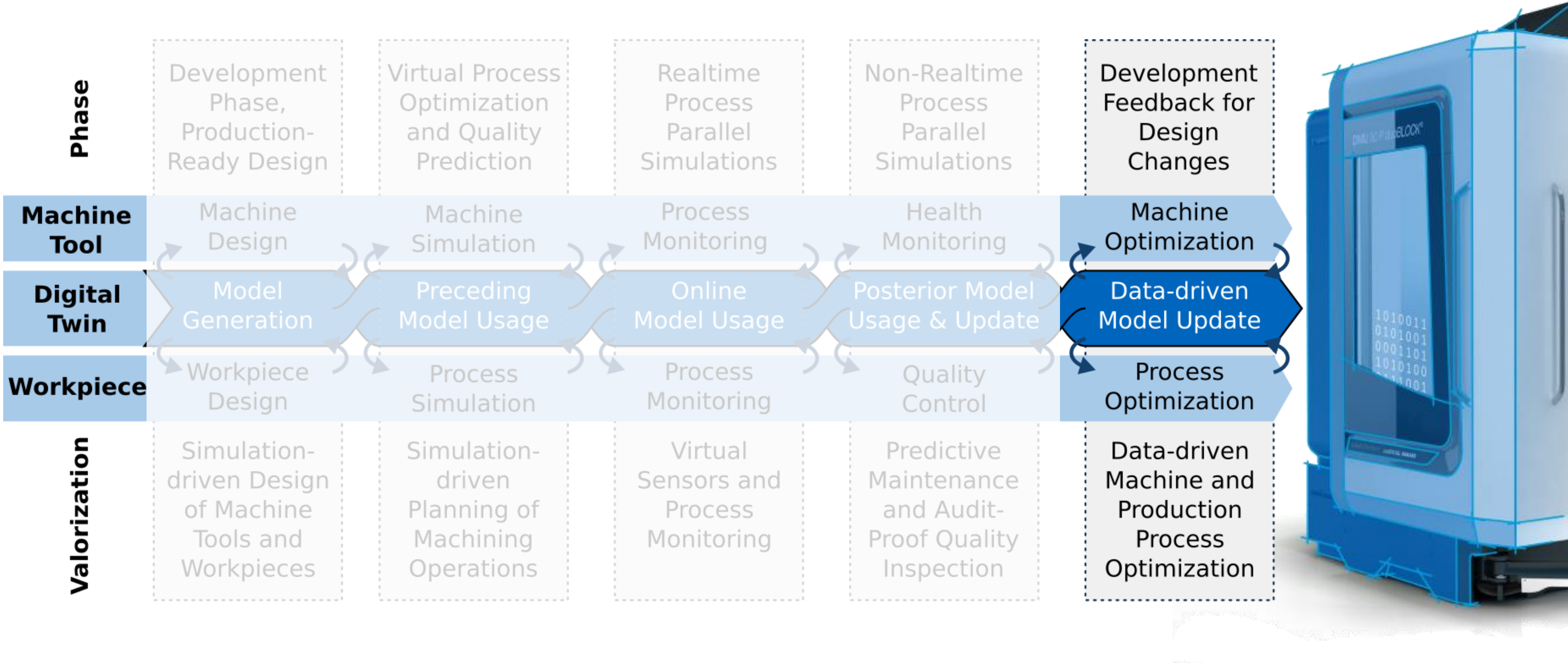
Data analysis

- Determination of machining accuracy with updated machine model
- Predicted component quality enables health monitoring of machine tools





Posterior Model Usage & Update

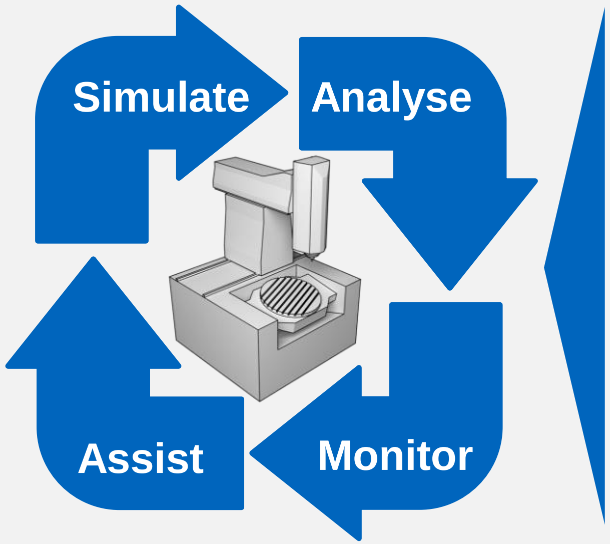


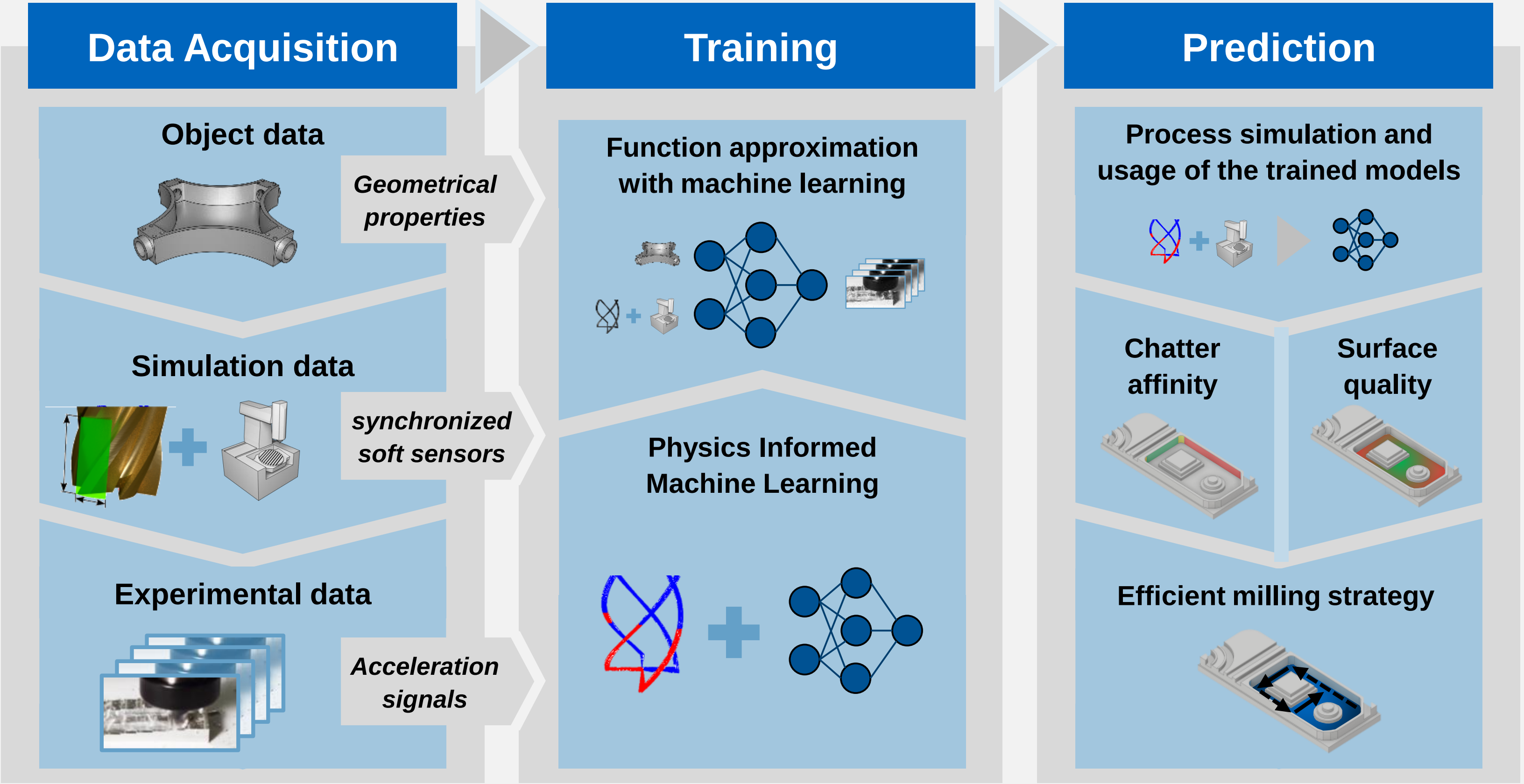
Data-driven Model Updates can Improve the Prediction Accuracy of Digital Twins

Self-adaptive Digital Twin of a Milling Machines

Model Generation → Preceding Model Usage → Online Model Usage → Posterior Model Usage → **Model Update**

Data-driven approaches of artificial intelligence can **identify and compensate** hidden, unknown or unmodeled **physical effects** of the machining process.





Learn from the Machines in the Field to Optimize Future Machine Designs

Machine Tool Optimization

Model Generation → Preceding Model Usage → Online Model Usage → Posterior Model Usage → **Model Update**

Machine Data Interface

Process Control

Smart box

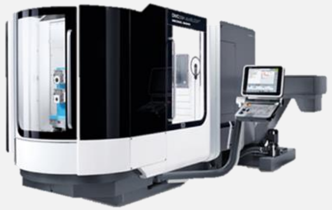
OPC UA umati

Process data, e.g. TCP acceleration or process forces

Cloud/Server

Process Data Acquisition and Process Control

- Spindle speed
- Motor current
- Accelerometers (spindle, machine table, ...)
- Tool position
- …



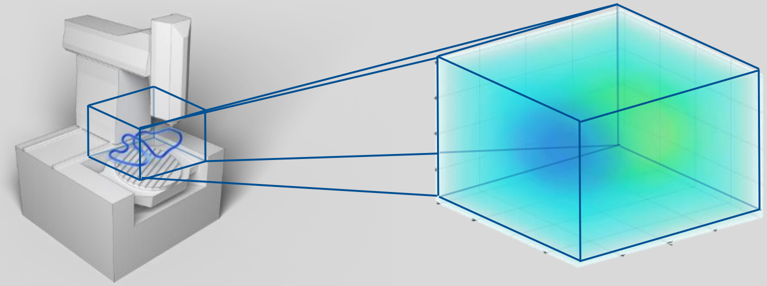
Manufacturer

User

In-Process data agglomeration

Detailed stability analysis based on internal and external sensor data

Universal assessment of machine stability in the workspace



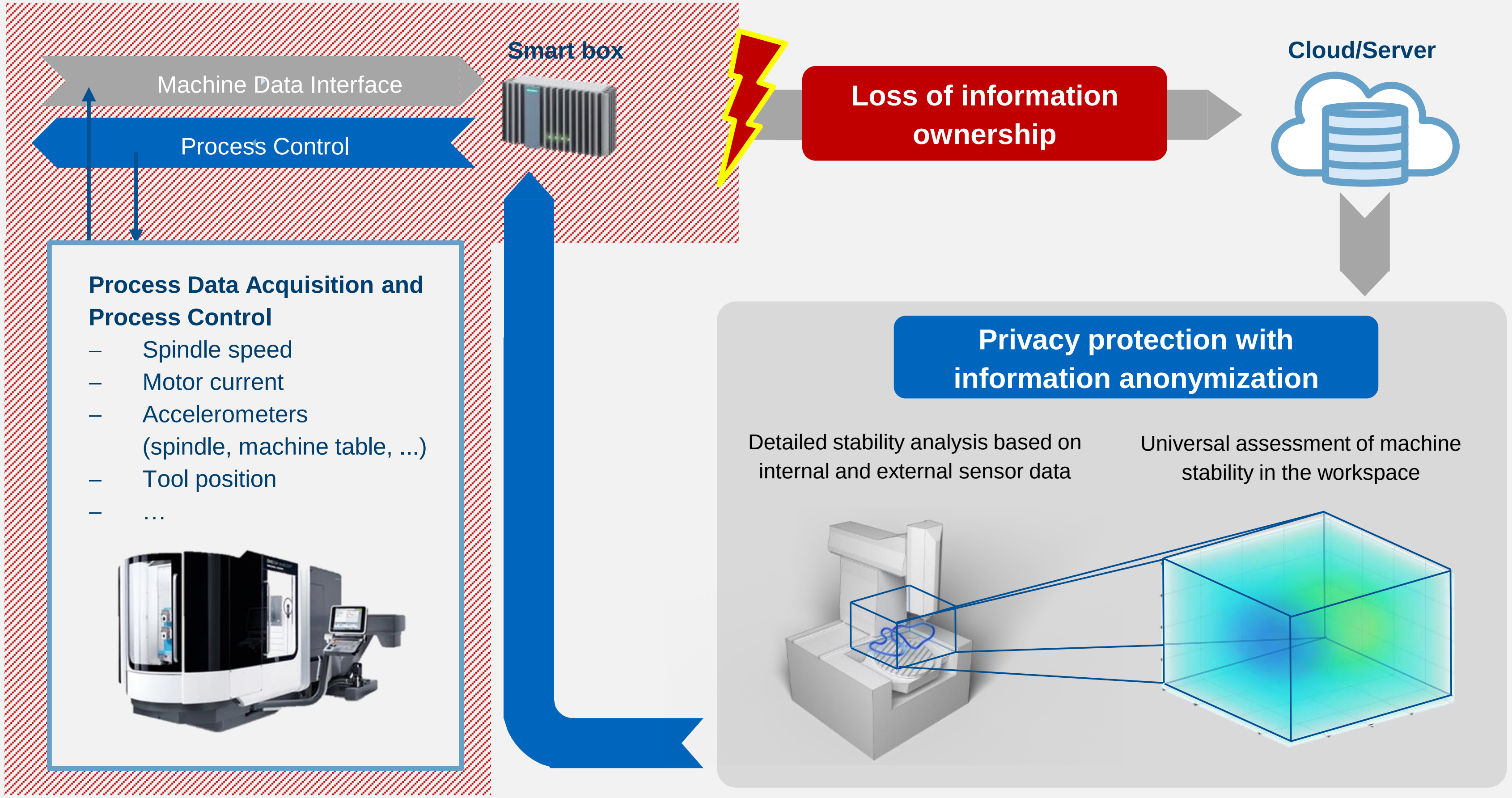
Process data analysis provides valuable information for machine tool manufacturers and users

- Detailed shop floor usage data
- Agglomeration of multiple machines in the field enable in-depth comparative analyses
- Modern big data algorithms support manufacturers in finding actions for improvements

Data Privacy must be Guaranteed during the Usage of the Connected Digital Twin

Digitization, Edge and Cloud Computing and Data Security

Model Generation | Preceding Model Usage | Online Model Usage | Posterior Model Usage | **Model Update**



Open challenges are

- When and where should we encrypt the data?
- What kind of encryption is suitable?
- How can we anonymize industrial data?
- How can we quantify the accompanying loss of information?
- What are the requirements for the cloud-service provider?

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iwb expert seminar „Digital Twin for Machine Tools”

Key topics:

- What are the benefits of the Digital Twin for users, machine tool and control manufacturers?
- What are the advantages of the Digital Twin in the various phases of a product or production?
- Which challenges and questions arise during the digitization of the machine tool and the machining process?
- How much effort will my company face during the introduction and use of digital twins?

Speakers and guests:

- Keynote: „Digital twin for machining“ - Prof. Dr. Y. Altintas (*UBC*, *MAL Inc.*)
- Presentations from industry and research :

BMW GROUP · c-Com · EMAG · Fraunhofer AISEC · GROB · HAWE HYDRAULIK · HEIDENHAIN · UBC · MAL manufacturing automation laboratories · ModuleWorks Get There Faster. · rexroth A Bosch Company · SCHAEFFLER · TUM · SIEMENS · UNIVERSITY OF WATERLOO

Holistic Approach to Digital Twins for Machine Tools

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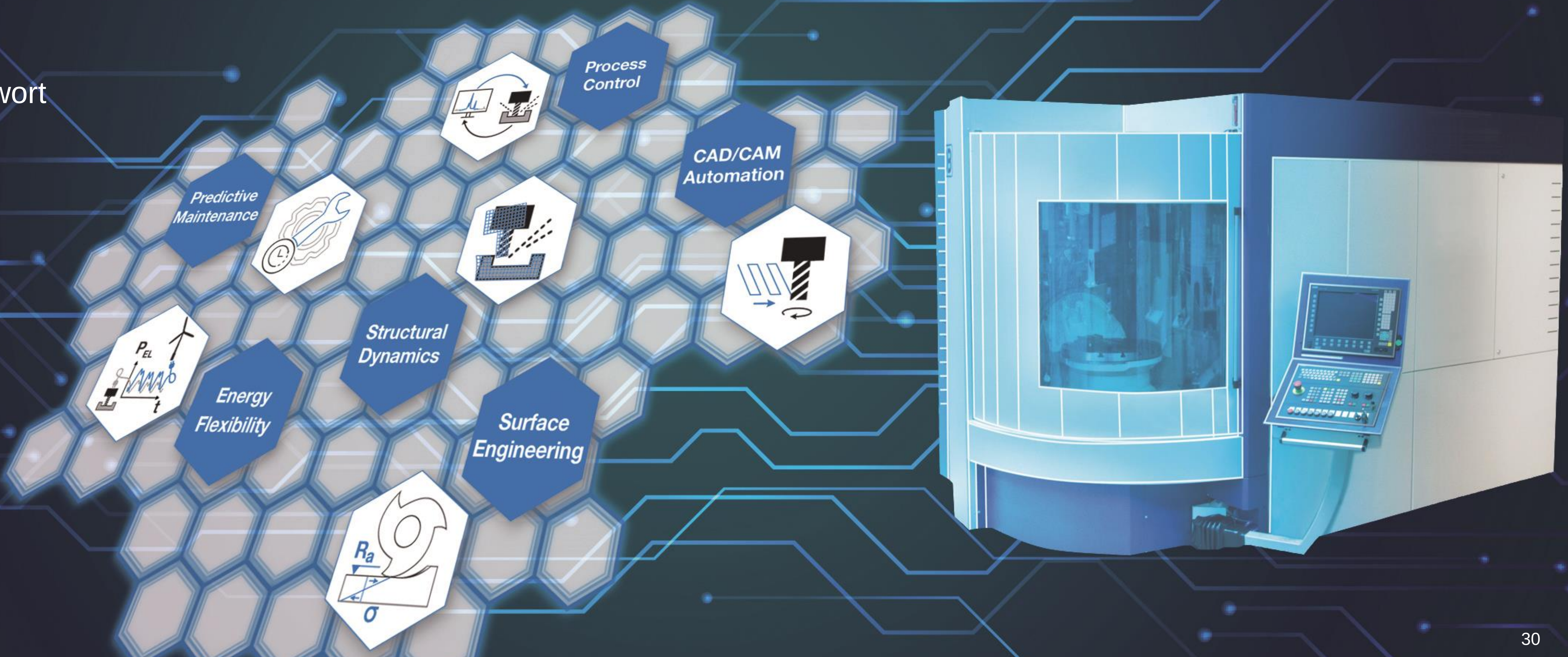

Outer Control Loop learns from Machines in the field

Process Monitoring and Control

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Monitoring of Machine Load Limits

The operating range of a machine tool is **limited by dynamic stability, feed drive, and spindle torque limits.** These limits must be maintained to ensure a **long service life of the drive components and the tool.**

Contouring Accuracy

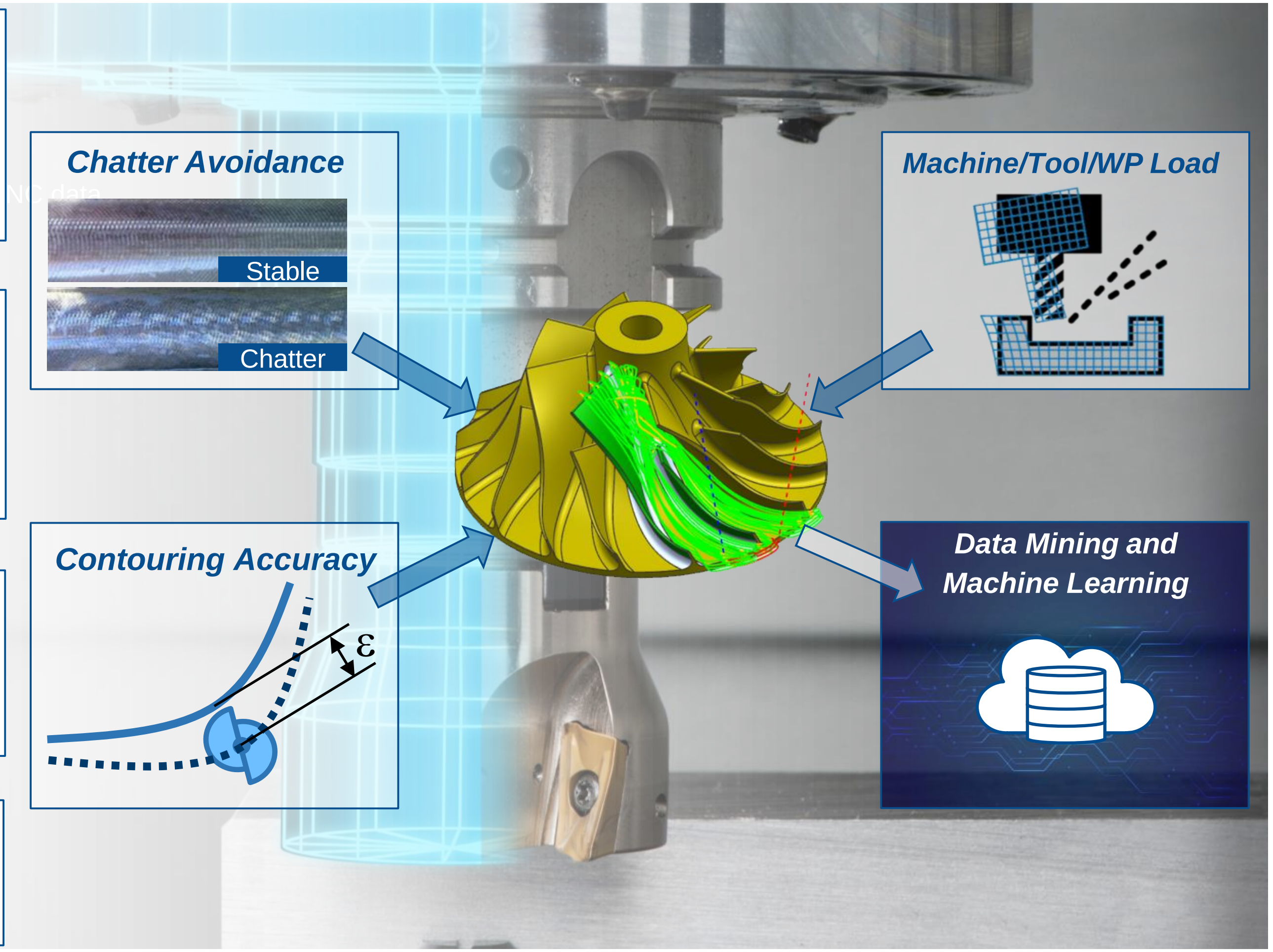
High process forces have also a **negative influence on the workpiece quality**. The **quasi-static stiffness** of the tool and the spindle components have a decisive influence on the form error that occurs during machining.

Feed Drive Optimization

Machine load limits, stability limits, and the contouring error needs to be **monitored and tracked** during machining. On the basis of these data **feed drive optimization** can be carried out.

Information Gathering and Preservation

The automated optimization process chain ensures that the results **flow back into the CAD/CAM chain.**



CLM 4.0 - Collision Avoidance System

Machine Kinematics

The tool path will be checked for collision in respect to the **actual machine kinematic** and **machine components**.

CNC Integration

The ModuleWorks real-time Collision Avoidance System (CAS) is **integrated directly onto the CNC controller** to avoid collisions in real-time during the machining process.

Support of different tools

All milling operations, drill blocks, cutting with saws, optimization for large panel parts, tools with concave shapes

CNC modes

Supports AUTO, MDI and JOG operation modes. **Collision avoidance based on interpolated axes positions** as calculated by CNC; no G-Code parsing required. Look-ahead, forecasted position data are used for collision avoidance.

CLM 4.0 - Operational Modal Analysis

Online Determination of Cutting Forces

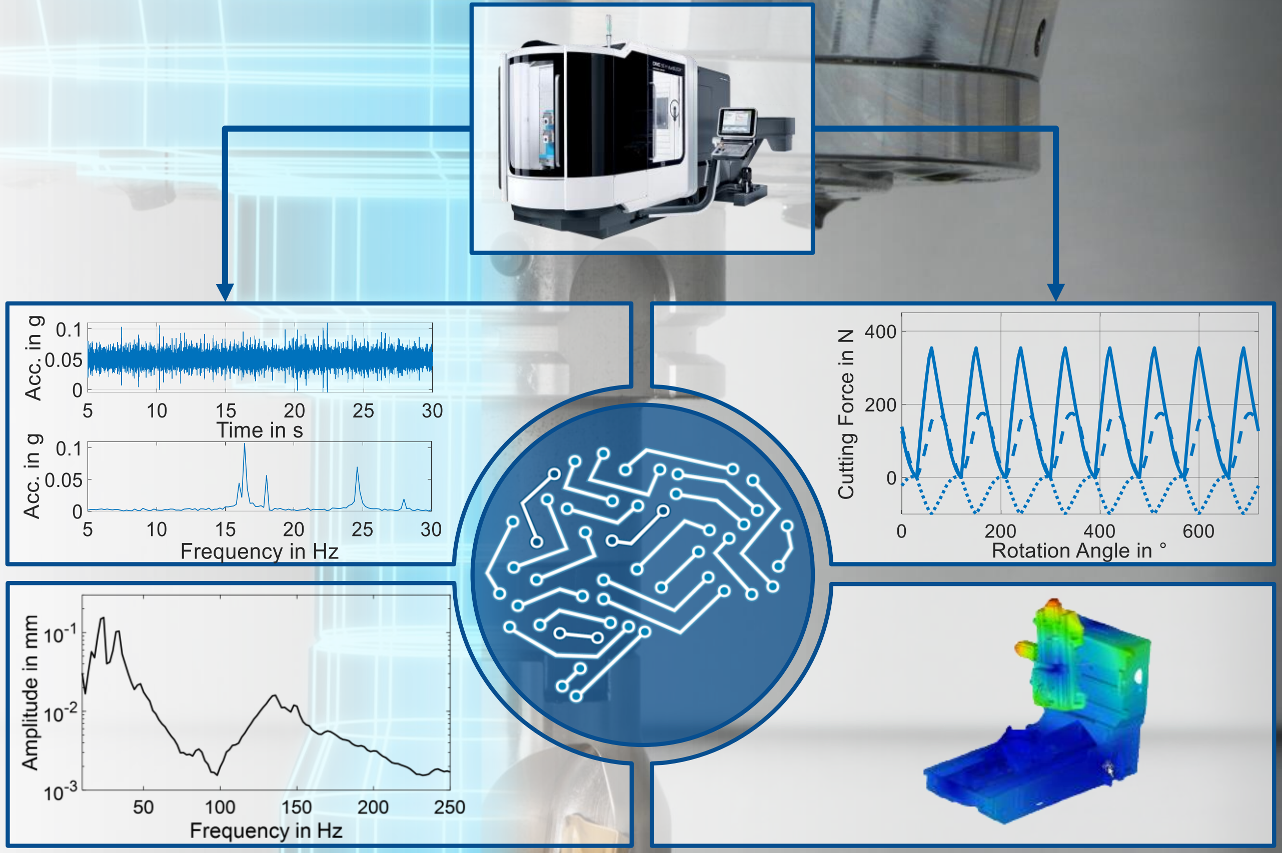
For the Operational Modal Analysis, the process forces occurring during machining have to be determined to identify the **excitation of the machine tool structure**.

Frequency Response Function

The general **receptance of the machine tool structure** can be determined **using FRF-estimators**. This requires both the **excitation and displacement** of the structure resulting from the machining process.

Position and tool dependent FRF

The receptance of the machine tool depends on the **current position in the working area** as well as on the **tool/tool holder combination** which is mounted to the spindle.



ModuleWorks Get There Faster. UNIVERSITY OF WATERLOO manufacturing automation laboratories UBC TUM

CLM 4.0 - Multi Input Multi Output (MIMO) Drive Model

Generalized MIMO drive model

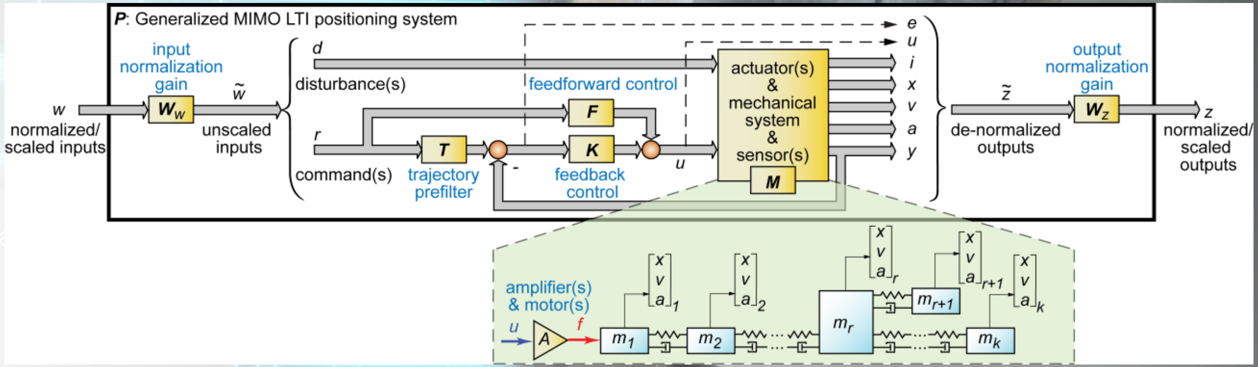
A requirement for Industry 4.0 manufacturing is the ability to **identify, update, and utilize mathematical models** of machine tools and processes, in a **non-intrusive and effective manner**.

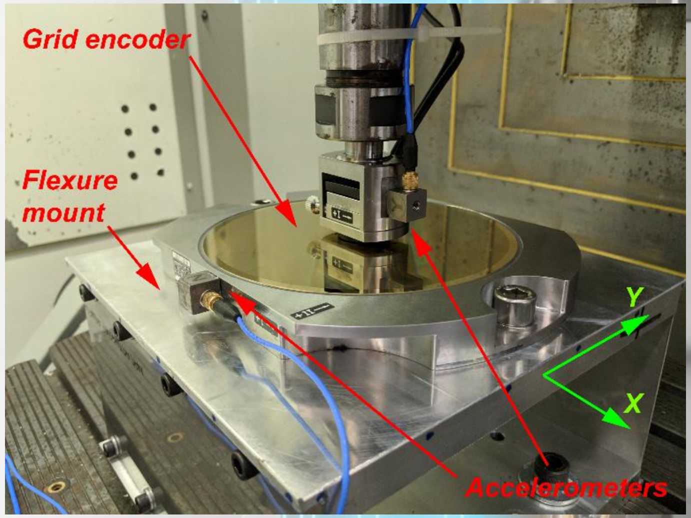
Key Parameters from In-process Data

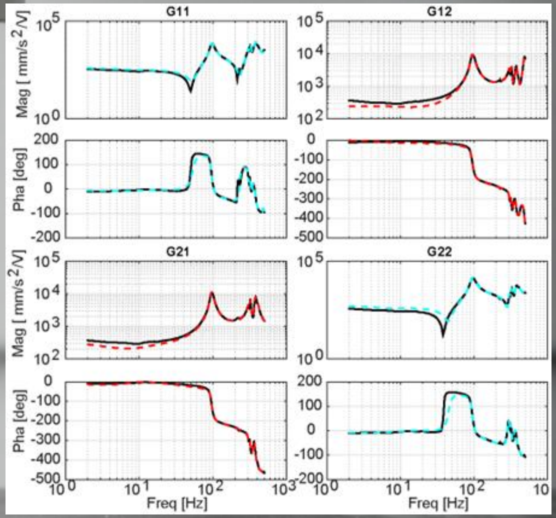
MIMO models can be used to **simulate and optimize multi-axis manufacturing trajectories**, so that quality and cycle time reduction **objectives can be met**.

True Response and Prediction

A good correlation between **experimentally measured** and **online calculated transfer functions** could be demonstrated at the University of Waterloo.







Energy Flexibility based on Digital Twins Enables Competitive and Independent Production Schedules

Energy Flexibility

Possibilities

- react to changing energy supply
- fill the company internal energy buffers, when energy is available and low-priced
- demand-driven energy consumption

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Benefits

➡ **optimize production to use the energy you produce**

➡ **save energy and money to become competitive**

➡ **production without dependence on volatile energy market**

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