

# STRATEGY FOR IMPLEMENTATING PREDICTIVE PROCESS-ORIENTED MACHINE TOOL DIGITAL TWINS

MATEJ SULITKA<sup>1</sup>, PETR KOLAR<sup>1,2</sup>, JIRI SVEDA<sup>1,2</sup>, JAN SMOLIK<sup>1</sup>

<sup>1</sup>Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Production Machines and Equipment, Research Centre of Manufacturing Technology, Prague, Czech Republic

<sup>2</sup>Czech Technical University in Prague, Czech Institute of Informatics, Robotics and Cybernetics, Department of Industrial Production and Automation, Prague, Czech Republic

DOI: 10.17973/MMSJ.2022\_10\_2022121

e-mail to corresponding author: m.sulitka@rcmt.cvut.cz

Process planning for the productive machining of complex shaped parts is a comprehensive activity where the dynamic behaviour of a machine tool, workpiece and the process setting has to be taken into account. The predictive process-oriented machine tool digital twin is a digital simulation tool enabling full control of the process results with respect to the adjustment of the whole machining system and the machining process. The paper defines and describes four different levels of such a digital twin according to its complexity. An overview of key elements and modelling techniques employed for creating the process digital twins is provided. The strategy for implementing the process digital twin as an enhancement of the NC machining process planning chain is presented. Selected use cases in the field of mould machining or thin walled blade machining are used for the method demonstrated.

## KEYWORDS

machine tools, digital twin, process-oriented machine tool digital twin, machining chatter, cutting force simulation, process-machine interaction, workpiece surface quality

## 1 INTRODUCTION

The path from a CAD model of a part to its physical production is a long process with a series of steps, each of which affects the resulting productivity, geometric accuracy and quality of the machined part. Prediction of the machine tool behaviour during interaction with the process is one of the main motivations for the development of machine tool virtual models. In this field, intensive developments have occurred in the last two decades following the development of appropriate mathematical and modelling techniques and computer performance.

The diagram of the path to the physical workpiece is shown in Fig. 1. Preparation of a part production begins in a CAD/CAM SW environment, in which a complete machining strategy is designed, including the choice of part clamping, choice of cutting tools, tool paths and cutting conditions. The toolpaths are generated in a defined tolerance band around the initial geometry of the part model as a sequence of points (CL data) connected by linear sections, possibly using circular

interpolation. However, areas with a non-optimum distribution of CL points can occur, especially on parts with shaped surfaces, and the uneven distribution of points or their clusters can be one of the sources of later machining errors.

The conversion of the toolpath, which is defined by CL points, resp. by the NC code, from the geometrical domain into the time domain is realised in the CNC control system interpolator. The main and challenging task of the CNC interpolator is to ensure continuous tool movement through the linear segments, the sequence of which features just zero-order geometrical continuity. The position setpoints are designed by the interpolator within a user defined tolerance band around the NC points together with the setpoint velocity profiles. However, the quality of the position setpoints distribution and velocity profiles is strongly affected by a number of CNC interpolator functionalities, such as look ahead, filtering or CNC controller specific advanced features.

The task of the feed drive control is in realising the tool path movement according to the CNC interpolator output. The accuracy and quality of the tool path control is determined by the controller dynamics, the setting of which, however, is significantly limited by the dynamic properties of the feed drive and machine tool mechanics. From the feed drive theory, it can be shown that there is a direct link between the achievable gain of the position controller and the amplitude-frequency characteristic of the feed drive mechanics, especially the motor locked frequency.

The resulting accuracy and quality of the machined surfaces is finally affected by the cutting process, during which cutting forces and heat is generated as a side product of the material removal. Cutting forces represent process feedback as an external force excitation both into the feed drive controller and on the workpiece as well. The static component of cutting forces causes the static deflection of the tool and workpiece and leads to the deteriorated geometric accuracy of the machined surfaces. The dynamic component of the cutting forces is a source of periodic excitation, which may result in forced or self-excited oscillations.

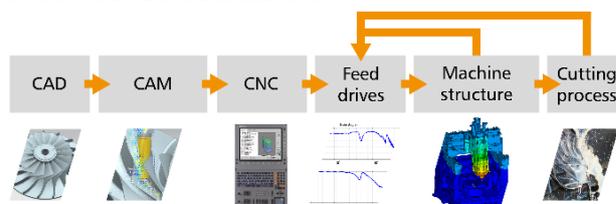


Figure 1: Chain of steps from the CAD model to a physical part machined on the machine tool.

The origins of the machine tool virtual model development focused mainly on simulations of machine tool dynamic properties as a coupled system of feed drive and machine tool structure in order to provide support for accelerated machine tool development and the verification of their properties prior to the physical prototype realisation [Berkemer 1997], [Zatarain 1998], [Maj 2005].

The first state-of-the-art overview within this field was published by Altintas and Brecher [Altintas 2005]. With respect to the above-mentioned data chain, the following key parts have to be included in the machine tool virtual model: machine tool structural parts, feed drive mechanical structure, feed drive controllers and the tool path interpolator. The importance of the interpolator functionality and its setting to the tool path control has been presented by [Lin 1996]. Following the need of advanced virtual testing of new machine tool structures, multiple research teams developed various solutions for

simulating the interaction of the machine tool structure and the feed drive control [Weck 2003], [Zaeh 2004], [Brecher 2009], [Vesely 2009]. The concept of a comprehensive virtual machine tool model including structural properties, control and thermal deformation was published by [Yun 2003]. Erkorkmaz and Altintas proposed a method for feed drive control parameter tuning using a virtual machine tool [Erkorkmaz 2001a,b,c].

It was recognised quite soon that such complex models of virtual machine tools (later called machine tool digital twins with respect to the Industry 4.0 terminology) are very useful for process virtual planning, testing and optimisation. A process-oriented machine tool digital twin includes a machining process simulation, simulation of the process-machine interaction (prediction of chatter occurrence), machined surface prediction and, in the case of thin-walled workpiece machining, also the workpiece dynamics. At this point, we can speak about a predictive process-oriented machine tool digital twin because the primary focus of such a model is on predicting the machining process behaviour and machining results [Kersting 2014], [Wiederkehr 2016]. A postprocessing process-oriented machine tool digital twin has a very similar structure but different purpose. The postprocessing digital twins feature the same structure and are used for production quality control based on the analysis of the machine tool data acquired from the machine control system during machining with the sampling frequency higher than 500 Hz [Hänel 2019], [Hänel 2019], [Ganser 2021].

As presented above, the virtual machine tool (or, machine tool digital twin) with various structures is used for specific process analyses. Thus, a systematic taxonomy of existing process-oriented machine tool digital twin levels is presented in this paper. A formalised methodology for the implementation of these digital twins follows, including selected use cases based on published examples. The paper is organised as follows: The four possible levels of the process-oriented machine tool digital twin are presented in Section 2, including an overview of modelling techniques used for the creation of the digital twin. The generalised method for implementation of the digital twin is introduced in Section 3. The strategy is demonstrated on a few existing use cases described in Section 4. The paper concludes in Section 5.

## 2 PROCESS-ORIENTED MACHINE TOOL DIGITAL TWIN

We can distinguish four different levels of process-oriented machine tool digital twin according to their complexity, see Fig. 2. The basic level is represented by a *CAM level*, which consists of the machine tool kinematic model created within CAD/CAM software. Using the CAM generated CL data, tool centre point movement as well as the movement of the machine tool rigid bodies can be simulated. Typical applications cover the workpiece macroscopic shape visualisation and a preliminary collision avoidance analysis.

A more advanced level, which we call the *CNC level*, includes a CNC machine tool interpolator. This can typically be represented by CNC interpolator kernels, such as Siemens VNCK, or Heidenhain iTNC, or by training stations (e.g., Sinutrain). Using the CNC interpolated NC code provides typically two kinds of results: a) reliable machining time prediction thanks to integrating a real CNC interpolator functionality; b) tool centre point (TCP) motion including the CNC interpolator dynamics and possible errors resulting from non-optimum CNC parameter settings.

The representation of machine tool dynamic properties is a key extension of the digital twin at the *Machine tool level*. The

Machine tool structural bodies and feed drive mechanical structure is represented by finite element (FE) models, considering suitable model order reduction for reducing the model size. Together with the feed drive control, we get a “feed drive coupled model”. The machine tool level digital twin, or virtual machine tool in other words, can advantageously be used for e.g., analysing the impact of machine tool and feed drive structural properties or feed drive control settings on the tool path control [Zaeh 2004], [Brecher 2009], [Vesely 2009].

The model can read NC code and process the code by the CNC interpolator. Tool centre point (TCP) positions are generated as an output of the virtual machining simulation, including the machine tool structural vibration. The virtually-machined workpiece surface is visualised by a convenient workpiece discretisation technique, see the next section. Since the cutting process is not considered at this simulation level, such a type of machine tool digital twin is useful for planning the operations where cutting forces and their impact on the machine and workpiece is not important. Finishing the machining of rigid bulky workpieces may represent a typical case [Kolar 2019]. Optimisation tasks, including the feed drive control parameters, CNC interpolator parameters or optimisation of NC code, can be addressed by the virtual machine tool.

The fourth level of the digital twin, which we call the *Process level*, includes a cutting process simulation. We simulate the material removal process and related process quantities, such as tool engagement, material removal rate and cutting forces. If a workpiece with high compliancy is machined, its dynamics can be represented during the material removal simulation by an independent model based on FE. Cutting forces and the machine-process interaction allow for a detailed analysis of the cutting tool load, cutting tool and workpiece deflection, and chatter and vibration avoidance.

A brief overview of the key modelling techniques used for creating the machine tool digital twin at different levels is provided in the following sections.

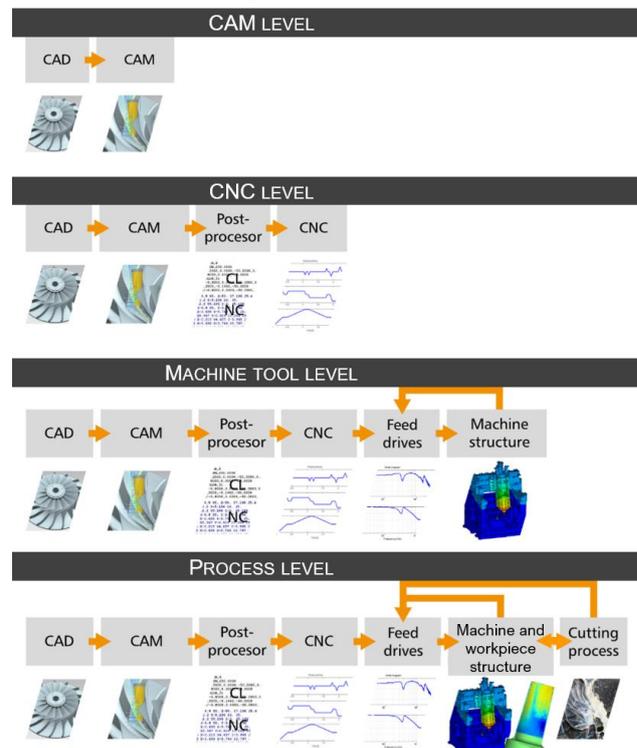


Figure 2: Four levels of the process-oriented machine tool digital twin.

## 2.1 Interpolator integration

The CNC interpolator is responsible for the transformation of the geometry-based information in the NC code into the time-based input data for the feed drives. This transformation is done with respect to the kinematic structure of a specific machine tool. The interpolator algorithm is controlled by a set of parameters with a specific impact on the tool path accuracy, quality and machining time.

There are two possible ways to integrate an interpolator into the simulation. The first option is to use the CNC interpolator of a real machine tool [Altintas 2005], [Vesely 2009]. Since the real machine tool interpolator is used in this case, the output tool path data is identical to real machining. An alternative option is using the CNC virtual station for NC code simulation. These stations are available from various control system producers. Verification of the machine tool kinematic transformation setting and interpolation functions is necessary in this case [Kolar 2019].

## 2.2 Coupled model of feed drive and machine tool mechanical structure

The coupled model of ball screw drive mechanics and the machine tool structure represents a core part of the machine tool full digital twin.

### Model of machine tool structure

FEM is commonly used for modelling the machine tool structural behaviour, including the flexible multi-body models as well. However, the main limitation is the big size of such models (number of degrees of freedom, DOF), typically in the order of  $10^6 - 10^7$  DOFs, which is not acceptable for running time domain transient machining simulations.

Model order reduction techniques (MOR) provide a solution for speeding up the calculation of a FE model response. The idea of MOR is to reduce the number of unknowns while producing a good enough approximation of the system behaviour considering the required inputs and outputs. Krylov subspace-based reduction ranks among the most effective techniques in terms of the order of reduction and accuracy of preserving the properties of the original model. Krylov reduction is about 1000 times more computationally efficient than the full FE solution and the approximation error is almost negligible [Sulitka 2014].

Another widely used MOR technique is the modal decomposition and modal truncation method, which features easy implementation within a standard FE modal analysis and provides acceptable reliability in the dynamic tasks of typical machine tool structures even for a high degree of order reduction up to  $10^1$  DOFs.

### Model of feed drive mechanics

The most effective approach to modelling the ball screw drive mechanics consists in creating a simplified FE model composed of 1D continuum elements and discrete elements (lumped mass and spring elements), described by Newton Euler's equations of motion outside of FE software environment. This allows obtaining a feed drive parametric model, which can effectively be used especially for design and optimisation tasks with many design variants [Maj 2005], [Altintas 2005], [Vesely 2009].

### Model coupling and feed drive control

The coupling of the machine tool reduced FE model and ball screw drive model is often done in state space by using force interaction between both models. Force interaction typically represents ball screw ball bearings, or a ball nut, to which the machine tool structure is connected.

Feed drive cascade control is modelled as a block scheme usually in Matlab/Simulink. The current control loop is replaced by a combination of low-pass filter and time delay, which provides sufficient reliability and significantly simplifies work with the model at the same time. All other control loops and elements (e.g., desired current filters, etc.) are included in the model, although some more advanced control functions are difficult to model since their description is protected as know-how of the control system manufacturers. Inputs and outputs of the velocity and position controller are modelled in the same way as on the real machine, i.e., by virtual measuring the required rotary and translational coordinates [Vesely 2009].

A two-way connection of the control model with the coupled model of the mechanical structure is done in the following way:

- Actual position and speed signals obtained from the model of mechanical structure are used as internal inputs of the feed drive control;
- Motor torque signals resulting from control algorithm are used as force inputs to the feed drive mechanical structure.

This coupled model can be used for simulating the machine tool behaviour, especially the relative motion of the cutting tool and workpiece, based on the set point position signals resulting from the CNC interpolator. The model covers all of the dynamic effects resulting from the machine tool mechanical structure and feed drive control.

## 2.3 Material removal simulation and workpiece visualisation

The material removal simulation is essential for both the process parameters analysis and a detailed evaluation and visualisation of machined surface geometrical deviations and surface quality. Tool-workpiece engagement is a key characteristic needed for calculating cutting forces and machining stability limits.

Several strategies for workpiece geometry virtual representation are known, as summarised in e.g. [Altintas2014]. Constructive Solid Geometry (CSG) models, described by e.g., [Surmann2008], such as boundary representation or constructive solid geometry, lead to a very precise workpiece geometry representation, but are rather too complex to be widely used. Predicting the surface quality affected by machining vibration including the impact of the thin walled workpiece dynamic properties is presented by [Kersting2014], [Wiederkehr2016].

Discrete models are generally easier to implement and enable fast updating of the workpiece geometry during the simulation. The most commonly used are dixel- and voxel-based models. Their accuracy depends on the resolution of the spatial discretisation which on the other hand influences the memory requirements, which are rather high.

Another means for improving the voxel model accuracy and resolution is the distance field. Instead of spatial grid of voxels with assigned binary value indicating whether a voxel is inside or outside, the vertices of voxels contain the signed distance to the closest point on the workpiece boundary [Tunc2015]. This distance function has a positive sign if the vertex is outside, and a negative sign for the vertices inside the workpiece.

In the implementation, the workpiece is represented by cubic blocks that are further divided into cells. Each block is marked either as outside, surface, or inside, while the workpiece surface intersects only the surface blocks and only the vertices belonging to at least one intersected cell contain the distance function values (Fig. 3). For all points of such a cell, the distance to the workpiece surface can be easily reconstructed by

trilinear interpolation. For the vertices far from the workpiece surface, the distance value function is for simplicity set to plus or minus infinity, as the actual value is not needed.

The workpiece represented by a distance field can be effectively visualised using the ray-tracing method, which provides high fidelity of the machined surface details. To visualise the deviations from the ideal shape, both models are represented by a distance field. Again, using the ray-tracing method, for each visible point on the workpiece surface, its distance from the desired shape is computed using the block's characteristics and the distance function values.

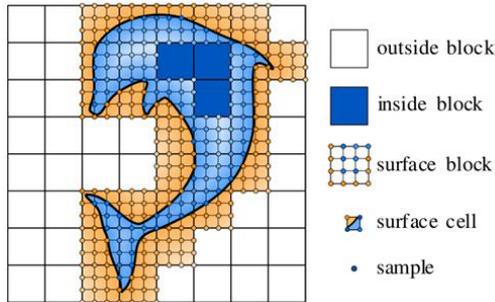


Figure 3: Distance field scheme

In the material removal simulation, the surface and inside blocks that are close to the tool are identified. Then for each cell it is checked whether it is intersected by the tool and, if so, the distance function values in the corresponding vertices are updated. In practice, the distance field representation of the workpiece geometry has proved to be precise enough while still keeping the memory requirements reasonable, as usually lower precision is needed for larger workpieces, and vice versa.

#### 2.4 Cutting force modelling

Various papers focusing on predictions of the cutting force size and the cutting stability along the tool path have been presented. Methods for simulation of the machining process interaction with the machine tool structure and tool path control were presented by [Brecher 2005]. The state-of-the art in virtual machining is presented in [Altintas 2014].

The accuracy and reliability requirements of the cutting force model depend on its purpose. Simple catalogue models of the cutting coefficient of the tangential component in the Kienzle power function model [Kienzle 1957] are sufficient to estimate the required maximum power transferable to the cut. Conversely, to simulate the dynamic behaviour of the tool-workpiece structure, it is often necessary to know the change in force with respect to the cutting speed or the geometry of the tool in contact with the workpiece, described for example by the angles of the face and the inclination of the blade.

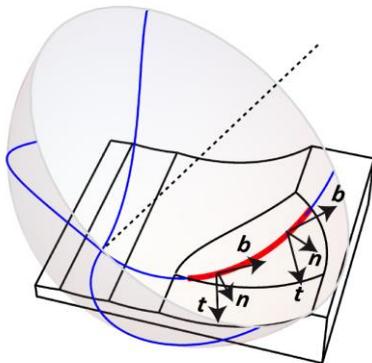


Figure 4: Example of local coordinate systems on the engaged cutting edge (red) at two points during milling with the ball-end tool.

Currently, the most widely used approach for this more accurate modelling is the Montgomery and Altintas model [Montgomery 1991], which is based on the integration of a specific force acting on the blade element, where the model force components are related to the basis of a local coordinate system on the blade consisting of tangential direction  $t$ , normal (radial) direction  $n$  and bi-normal (axial) direction  $b$ , see Fig. 4. The advantage of this approach is that it allows the total cutting force on the tool to be calculated quite reliably by considering the local geometric parameters of the cutting process at the cutting edge based on empirical models of the specific cutting force per unit chip width. These models can be identified from a series of experiments performed on simpler cutting edge geometries.

The nature of the cutting force is more or less periodic on time scales relevant to dynamics, and it is often sufficient to know only the first few terms of the Fourier series of the cutting force. An example of use is the mean value of the total cutting force Jacobian with respect to regenerative displacement for the formulation of machining stability (the zero-order approximation method - ZOA [Budak 1998]).

#### 2.5 Stability modelling in thin walled workpiece machining

The analysis of the machining stability results from the connection of the dynamics of the structural elements (machine tool, workpiece) with the force action in the machining process, including the consideration of the feedback between the structural vibrations and cutting process forces. Similar to structural stiffness or damping, it is necessary to determine in the cutting process how the cutting forces respond to small changes in the actual position of the structure at the cut point, the position in time of previous cuts (process stiffness), or how the force application changes with respect to the vibration rate (process damping). The cutting process stiffness is based on the well-known principle of regeneration of the undeformed chip thickness [Tlustý 1954], [Tlustý 1957].

In the case of process damping, two approaches are usually distinguished in the literature. The first models process damping separately as the effect of the contact between the tool back and the waves generated by the vibration on the workpiece [Stone 2005]. The other considers process damping as an effect mainly associated with the projection of cutting forces in a direction considering the velocity of the self-excited vibrations in addition to the nominal velocity in the cutting process [Molnar 2018]. Apart from the projection of the cutting force itself, the effect of the velocity direction on the actual geometry (rake angle and inclination angle) is considered. Physically, this can be interpreted through the effect of the vibration velocity on the chip flow across the face and the associated projection of the frictional force on the rake face into the vibration direction.

#### 2.6 Implementation of a flexible workpiece and cutting tool

A challenge that is closely related to the previously-discussed stability calculation is the implementation of the dynamic properties of the machine and workpiece in a real-life application. This requires the determination of the dynamics on the tool and workpiece in a wide range of states. In the case of the tool, it is mainly a question of the change of dynamic properties depending on its kinematic positions. In the case of the workpiece, the most challenging task is the machining of thin-walled workpieces, which have different dynamic properties depending on the position of contact with the tool and with respect to the amount of material removed. Most of the authors dealing with this problem have chosen simpler workpiece geometries, where it is feasible to prescribe the tool position and the amount of material specifically for a given case

[Bravo 2005, Budak 2012, Li 2020]. Digital twin processes that consider both the structural dynamics and the general material removal process are rather rare, since the calculation of changing dynamics requires fast adjustments of the mass and stiffness matrices based on the finite element method [Wiederkehr 2016].

In the MillVis software solution [Sulitka 2021], developed at the Czech Technical University in Prague, RCMT, an effort is made to link the voxel-based and the distance field-based material removal system with the calculation of the process forces and the tool and workpiece dynamics. The calculation of the cutting force is based on the model described in [Budak 1998], with the tool engagement area determined by the SW part responsible for the material removal calculation. At the internal points of this region, the elementary cutting forces in axial, radial and tangential directions are calculated [Tunc 2015]. The total forces are then obtained by numerically integrating the specific forces along the cutting edge given by the empirical models. So far, the dynamic behaviour of the structure has only been implemented for specific cases using modal analysis developed in third-party software. The dynamic properties of the workpiece are stored in a mesh of points on the workpiece and transformed into a distance field during cutting to use the closest dynamic data to calculate the stiffness matrix and static deflection or to predict stability.

### 3 STRATEGY FOR IMPLEMENTING THE PROCESS-ORIENTED MACHINE TOOL DIGITAL TWIN

The strategy for implementing the process-oriented digital twins follows the process planning steps and extends them by additional control steps with the help of various simulation models. Virtual machining simulation delivers course of process variables, which allow deeper understanding of the process status, and provide the detailed analysis and visualisation of the machined surface quality, dimensional accuracy and process productivity. A check of the process parameters results in possible optimisation measures for the process setting (Fig. 5).

Successful machining starts with a CAD data quality check. All of the surfaces have to be completely connected to define the closed workpiece volume. Especially in the case of complex-shaped parts like blades or moulds, the tangential connection of key surfaces has to be checked. This evaluation is done within the CAD SW using available tools.

The machining process is planned within the CAM SW. The main tasks here are: choice of clamping, fixturing, tool path generation using an appropriate strategy, cutting tool selection and setting of cutting conditions. As soon as the tool path is generated, the quality of CL data needs to be checked. One of the key issues is the uniformity of CL points distribution. Sudden changes in the CL points distribution density may cause problems during CNC interpolator processing.

An NC code is generated by a machine tool postprocessor based on CL data. The additional modification of the cutting conditions or tool path might be done during CL data postprocessing [Vavruska 2018]. The final NC code should be checked against a collision risk. For this purpose, commercial SW tools, like CAD/CAM packages (e.g., NX) or dedicated software (e.g., Vericut) are available.

Input for the *CNC level* digital twin simulation is the NC code. Position set point values and velocity profiles should be analysed against discontinuities in acceleration and jerk profiles. Moreover, a check of tool path errors caused by the interpolator setting is very important. Optimisation of the CNC

interpolator setting may typically shorten the production time, or improve the surface quality.

Feed drive control parameters should be set on a real machine tool. A *Machine tool level* digital twin can help in testing the impact of multiple options and in finding an optimum setting in a short time with respect to the machine tool dynamic properties [Zaeh 2004], [Brecher 2009], [Vesely 2009].

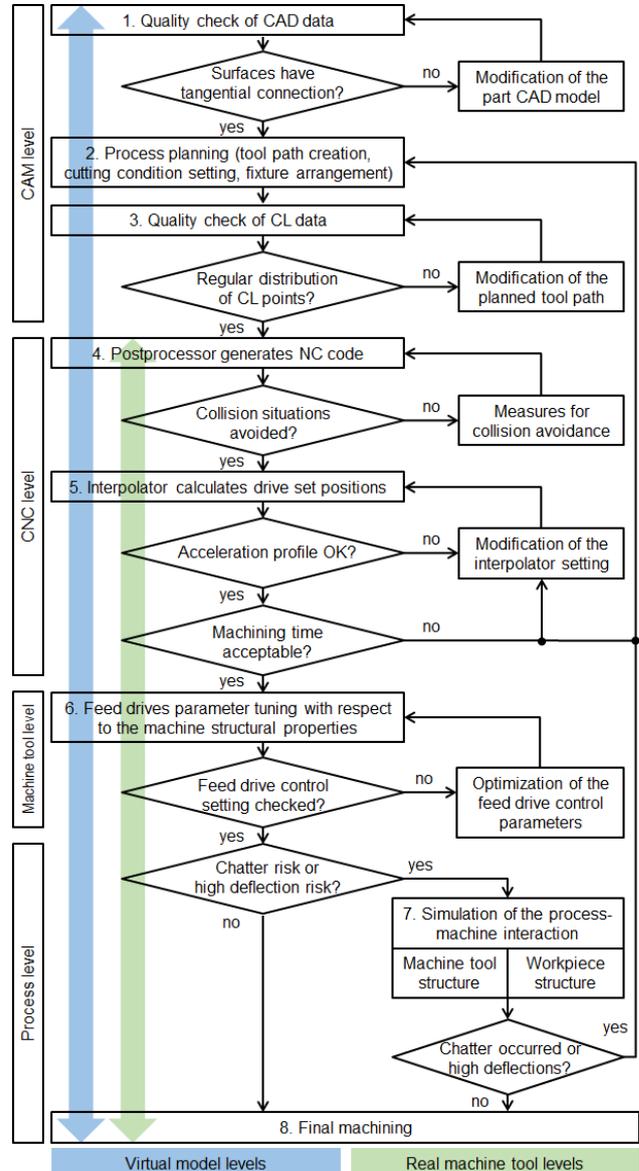


Figure 5: The process planning chain. Implementation of various process levels and their digital twin model or real process parts is marked on the left margin.

The process-machine interaction analysis plays an important role if the structural compliance of the machine tool or of the workpiece becomes a critical factor. This is typically the case in thin walled workpiece machining or in the case of the machine tool configuration with low stiffness, e.g., for large machine tools with extendable slender rams. Slender cutting tools used in finishing machining represent another case with a high risk of elevated vibration. In such cases, the simulation of cutting forces and machining stability limits can identify regions where cutting conditions need to be modified in order to avoid chatter. Several actions can be performed – from different workpiece clamping, through different tool path strategies, tool postures up to machining parameters.

The process digital twin provides a detailed virtual analysis of the machining process and prediction of machining results,

which significantly increases the machining reliability without the need of performing time- and cost-demanding machining testing.

Please note that the CAM level digital twin is a virtual simulation only. The other three levels involve both real and virtual machine tool twins in the practical implementation, see the region marked with the green arrow in Fig. 5.

#### 4 APPLICATION EXAMPLES

Selected use cases are presented in this section for demonstrating the potentials and benefits of industrial applications of process-oriented machine tool digital twins. Three published use cases are referred here as a demonstration of the taxonomical view following Fig. 2 and Fig. 5.

##### 4.1 CNC interpolator setting for mould machining

In this case, an aluminium alloy mould has been machined (Fig. 6) on a five-axis portal milling machine with the rotary-tilting spindle head. The part itself was rigid as well as the machine tool. The first machined part revealed a deteriorated surface quality in many places. At the same time, machining productivity has not been satisfactory. Therefore, the challenge was to improve the machined surface and to shorten the machining time [Kolar 2019].

A first check of the NC code quality revealed no issues in the quality of CL points distribution. Following this, the attention has been focused on the CNC interpolation quality and machine tool dynamic behaviour. The subject of the process improvement was the finishing machining with low cutting forces by a ball end mill, therefore the impact of the cutting tool – workpiece force interaction could have been neglected.

A machine tool level process digital twin was used to address this task. The goal of the study was to find the optimum setting of CNC controller parameters with respect to machine tool dynamic properties (Fig. 7).



Figure 6: View of the tested workpiece (a mould) [Kolar 2019].

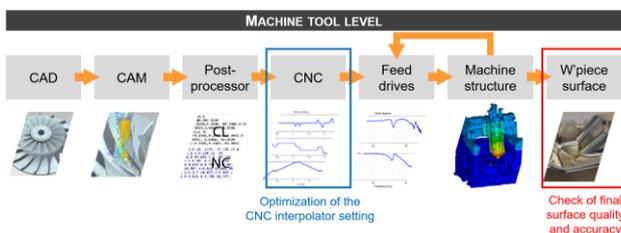


Figure 7: Schematic presentation of the implemented machine tool level digital twin. Optimisation of the interpolator setting was used for improving the surface quality.

Experimental validation of the digital twin model confirmed a very good match of the process time and surface structure prediction. Consequently, a simulation model has been used for a study on the CNC parameters setting. The approach consisted in testing parameter sets for roughing, semifinishing and finishing for balancing machining speed and accuracy between all operations. It has been shown that within the prescribed geometrical surface accuracy we can speed up the machining time by about 18.4% and at the same time we can significantly

suppress the surface quality errors. This use case clearly demonstrated the importance of the CNC interpolator setting on the machining time and surface quality in multiaxis milling operations.

##### 4.2 Blisk thin-walled blade machining tuning

This study was focused on the multi-axis machining of thin-walled and complex-shaped blisk blades made of aluminium alloy. The key issue was the structural compliance of the workpiece that caused workpiece dimensional errors due to static deflection, chatter limiting the machining productivity and the workpiece deteriorated surface quality [Sulitka 2021].

Due to dominant workpiece compliancy, a solution consisting in integrating a thin-walled workpiece dynamic model directly into the Process level digital twin for a virtual machining simulation has been developed (Fig. 8). A workpiece FE model was transformed using modal reduction into eigenvectors and eigenfrequencies and those are used for calculating both the static and dynamic response of the workpieces during the machining simulation. The process stability problem was resolved by a generalised eigenvalue problem, in which the maximum real part of the system eigenvalues is an indicator of stability. If the parameter is negative, the process is stable and the chatter does not occur.

The initial machining strategy used fixed cutting conditions and recommendations of cutting tool producers. An integrated virtual machining simulation, including the blade dynamics implemented into a material removal simulation, allowed the efficient optimisation of both the cutting tool lead and tilt angles with respect to blade dynamics and the tool – workpiece process interaction. The optimised strategy showed a significant reduction of the blade critical static deflection and chatter avoidance (Fig. 9).

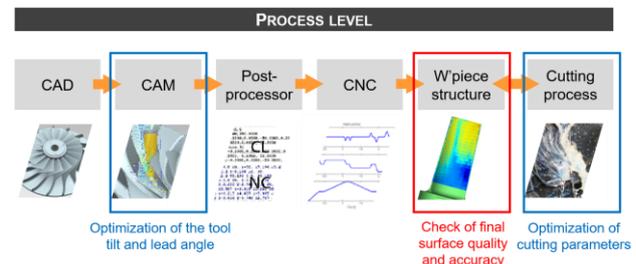


Figure 8: Schematic presentation of the used process level digital twin to resolve issues related to the compliant workpiece. The optimisation of the cutting process parameters and tool tilt and lead angle were done to ensure the requested quality and dimensional accuracy.

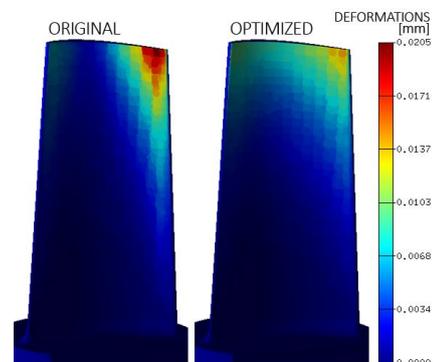


Figure 9: Static deformation at the blade tip is significantly reduced in the optimised strategy on the right.

Two parts were machined and measured. The first one with the initial machining strategy and the other one with the optimised one. The experimental results confirmed the predictions achieved by the virtual simulations and showed a surface without vibration marks and with better geometrical accuracy.

### 4.3 Steam turbine thin-blade machining

A large steam blade (Fig. 10) made of duplex stainless steel was the subject of a case study [Vavruska 2019], the aim of which was the elimination of a number of surface quality errors and vibration marks, which occurred in the machining of the first testing sample. The main issue in this case is the structural compliance of the workpiece and also the compliance of the machine tool structure.



Figure 10: The blade clamped in the multifunctional machine tool.

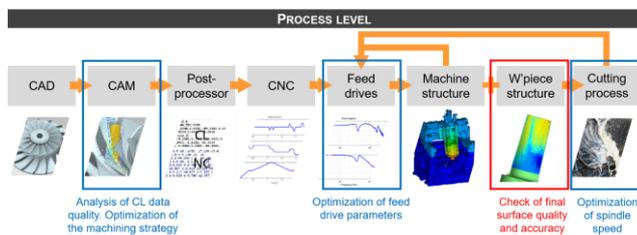


Figure 11: Schematic presentation of the used process level digital twin to resolve issues related to the compliant workpiece and machine tool dynamics. Optimisations on the level of the tool path planning, feed drive control setting and cutting conditions were done to ensure the requested quality and dimensional accuracy

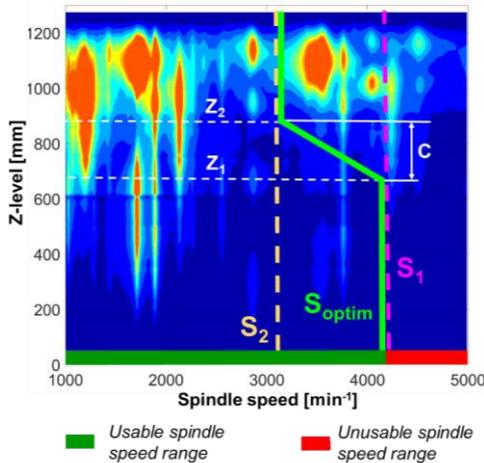


Figure 12: Optimised spindle speed control strategy along the blade Z-level.

To capture the wide extent of possible sources of machining errors, a *Process level* digital twin was created, including the blade FE model (Fig. 11). In the first step, the CAD data quality was analysed. Some minor surface correction was done to ensure a tangential connection of the blade key surfaces. The CL point distribution was analysed, especially at the blade's leading edge. Subsequently, the cutting tool tilting and leading angle was optimised to achieve a specific scallop height, to minimise the workpiece deflection and to reduce the machining time. The real raw geometry part was acquired using 3D scanning. A geometrical simulation considering the complete machining system was used for collision avoidance. The feed drive control setting was optimised before the real machining started.

The strategy for achieving vibration suppression of the blade consisted in applying a continuous change of spindle speed as a function of the blade Z-coordinate in the finishing operation where the surface quality requirement is critical. The energy norm of forced vibration as a function of spindle speed reveals regions with low vibration energy, suitable for selecting the optimised spindle speed, as can be seen in Fig. 12. The optimised strategy and process planning resulted in a successful part produced within defined quality requirements with reduced machining time.

## 5 CONCLUSIONS

The paper defines and describes four levels of a predictive process-oriented machine tool digital twin. This kind of digital twin is a complex simulation tool enabling full control of the process results with respect to the adjustment of the whole machining system and the machining process. A strategy for implementing the process digital twin as an enhancement of the process planning chain is presented. Three selected use cases of process digital twin applications are demonstrated on an example of 3-axis mould machining and 5-axis thin-walled blade machining.

## ACKNOWLEDGMENTS

The authors would like to thank their colleagues Barbora Hauptfleischova, Vojtech Matyska and Jiri Falta for their support completing the manuscript. The authors would like to acknowledge funding support from European Structural and Investment Funds and the Operational Programme Research, Development and Education via Ministry of Education, Youth and Sports of the Czech Republic, under the project CZ.02.1.01/0.0/0.0/16\_026/ 0008432 Cluster 4.0 - Methodology of System Integration. Support of the companies BRAY and KOVOSVIT MAS for the case study realisation is also gratefully acknowledged.

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## CONTACTS:

**Czech Technical University in Prague,  
Czech Institute of Informatics, Robotics and Cybernetics,**  
Department of Industrial Production and Automation,  
Jugoslavských partyzánů 1580/3, 160 00 Prague, Czech Republic  
Website: <https://www.ciirc.cvut.cz/teams-labs/ipa/>

**Doc. Ing. Petr Kolar, Ph.D.**  
E: [p.kolar@rcmt.cvut.cz](mailto:p.kolar@rcmt.cvut.cz)

**Ing. Jiri Sveda, Ph.D.**  
E: [j.sveda@rcmt.cvut.cz](mailto:j.sveda@rcmt.cvut.cz)

**Czech Technical University in Prague, Faculty of Mechanical  
Engineering,**  
Department of Production Machines and Equipment,  
Research Center of Manufacturing Technology (RCMT),  
Horska 3, 128 00 Prague, Czech Republic; <https://rcmt.cvut.cz/>

**Ing. Matej Sulitka, Ph.D.**  
E: [m.sulitka@rcmt.cvut.cz](mailto:m.sulitka@rcmt.cvut.cz)

**Ing. Jan Smolik, Ph.D.**  
E: [j.smolik@rcmt.cvut.cz](mailto:j.smolik@rcmt.cvut.cz)