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Development of techniques improving functional and programming abilities of intelligent CNC machine tools

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This paper covers the areas of importance in the development of intelligent machine tools (IMTs), including information/knowledge-based computing, advanced virtual modelling of machining systems, real-time process simulations with the use of digital twins (DTs) and intelligent control strategies based on the STEP-NC standards. Select examples of current industrial implementations are discussed, along with prognosing of future development trends. Moreover, the importance of human-machine interaction (HMI) and considering operator behavior and skill levels in the development of HMI is signified.

KEYWORDS: intelligent machine tool, information exchange, virtual simulation, STEP-NC interface

Introduction

In the last decade, there has been a clear intensification of research and development (R&D) and implementation work on intelligent machine tools (IMT) related to the development of virtualization of modeling and programming, as well as processing and analysis of information used to make decisions in the field of optimization of the machining process and monitoring. In fig. 1 the future structure of an intelligent machine tool developed by Japanese researchers about 20 years ago is shown, which accurately reflects the progress made in the last two decades. The key tasks in this area are located at levels 3 and 4.

It should be noted that in a conventional CNC machine tool, two main levels of the control system can be distinguished, i.e. servo control (level 1) and interpolation (level 2) for controlling axis movements. In turn, the control system of an intelligent CNC machine tool has two additional levels necessary to achieve advanced control, i.e. adaptive control (AC) located at level 3 and supervision as the highest level 4 necessary for intelligent monitoring of the machining process, the task of which is to detect the current state of machining regardless of the cutting conditions and the type of machining operation performed. In this case, effective feedback in the flow of information regarding the obtained process results (also based on measurements of the machined part) and their evaluation is necessary. An additional condition of the IMT functionality is the implementation of the autonomous process planning strategy, as one of the functions, which guarantees the generation of a flexible and adaptive machining plan (technological route). This task can be accomplished by introducing several functions in the field of process planning and information processing, including: operational planning, selection of cutting tools, determination of cutting parameters and generation of tool path for each machining operation. In the context of information processing, the results of product data analysis and recognition of cutting features (as an element of the FBM concept – "feature-based machining") [2].

In order to generate the operation plan autonomously, several planning and information processing functions are needed. Operation planning, cutting tool selection, cutting parameters assignment, and tool path generation for each machining operation are required at the machine level. Product data analysis and machining feature recognition are important issues, as is information processing.

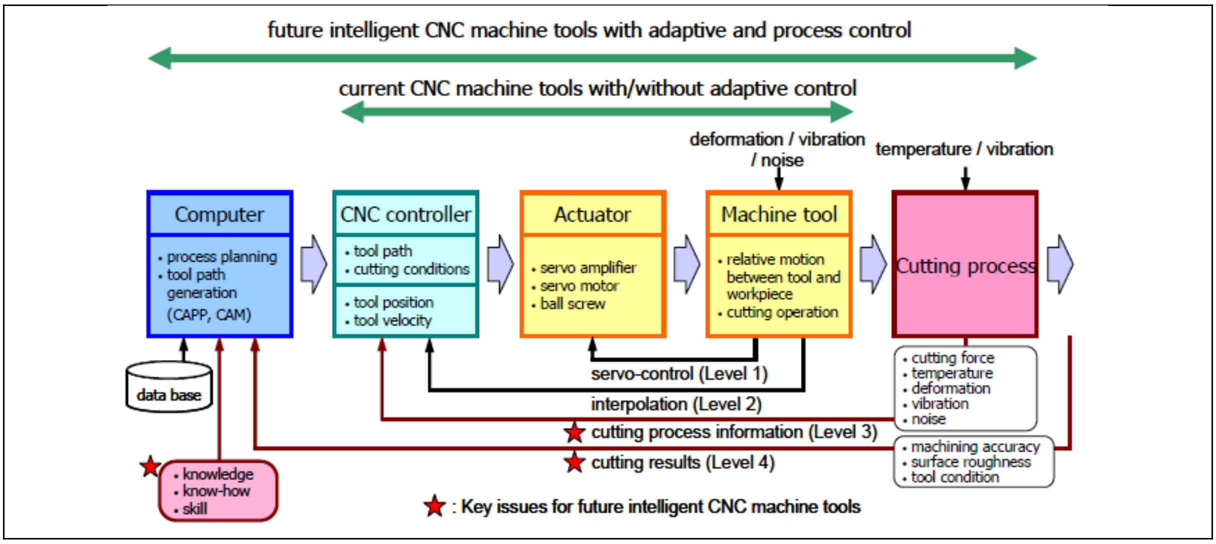

Fig. 1. Functional framework of an intelligent machine tool [1]

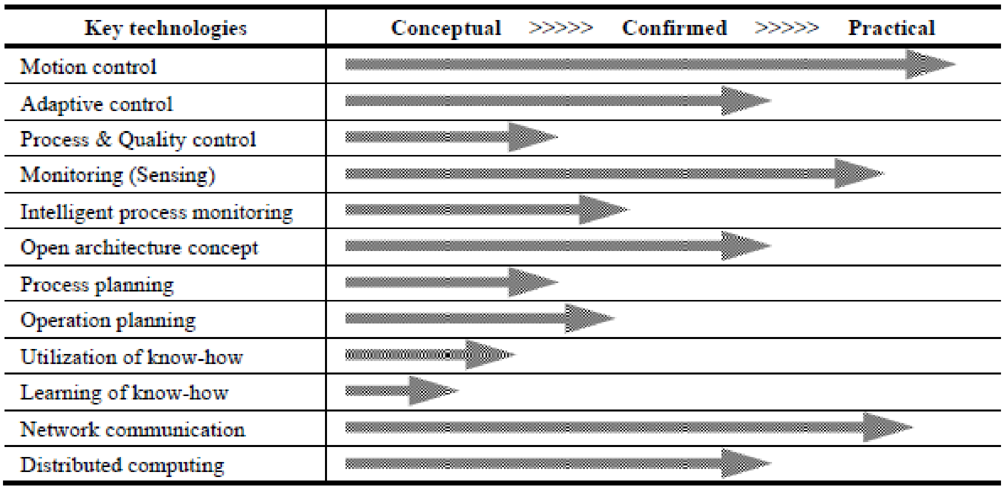

Fig. 2. Key techniques influencing the development of IMTs [1, 2]

In fig. 2 is shown the impact of key techniques used in process control, monitoring and planning, know-how application, data processing and information transfer on the development of intelligent CNC machine tools [1].

The main directions of development include [1, 2]:

- the growing importance of process and quality control compared to adaptive control –to achieve this goal, it is necessary to dynamically generate the tool path, modify the cutting parameters during the process (in-process) and intelligently monitor the process,
- achieving a sensible process control strategy and reliable indicators for evaluating machining quality,
- the need to use knowledge and learn on the basis of accumulated knowledge, know-how and skills in relation to machining operations,
- development of a planning strategy that will enable the creation of flexible and adaptive machining plans and the selection of tools and cutting parameters,
- autonomous creation of operation plans based on product data analysis and feature recognition.

Principles of information exchange in intelligent machine tools

In the development of intelligent machine tools (IMT – "intelligent machine tool") and entire manufacturing systems, the information sphere plays an important role, which was already pointed out in the initial phase of their industrial implementation [1, 3]. This was related to the ability of IMT to collect information and use it in new process conditions and machining operations. In advanced intelligent machine tools, two-stage information processing is used, including close cooperation of edge computations (edge computing) and virtual cloud computing (cloud computing) – also used as synonyms for edge computing and cloud computing [4]. This creates a new IMT architecture, designated with the acronym IMT-ECC ("edge-cloud collaboration"), as shown schematically in fig. 3. The entire information system in the IMT-ECC machine consists of three layers – data acquisition, network communication and the ECC module.

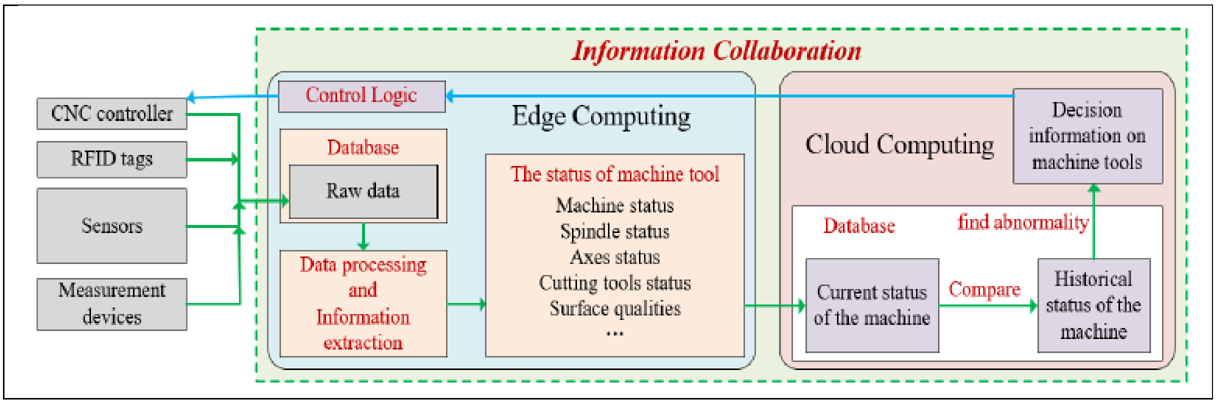

Fig. 3. Schematic representation of collaboration between edge and cloud computing in IMT [2, 4]

In the IMT-ECC intelligent machine tool architecture, the cloud data collection and processing are responsible for optimizing the virtual model algorithms [3], while the edge computing performs the function of fusion, preprocessing of the source data and analysis of the transmitted machine state data as a response in the loop real-time feedback. In this way, the intelligence of the machine tool, and therefore the efficiency of programming, increases as a result of the cooperation of ECC systems at the level of data, information and knowledge.

Development of real-time virtual modeling

In [2], basics and possibilities of practical application of various virtual reality techniques for modeling and simulating machining processes and systems, and consequently for supporting the programming of CNC machine tools, are discussed. It should be noted, however, that the authors do not take into account the dynamic properties of the machine tool and changes in the process over time (TDP – "time-dependent processes") in tool path planning, which may adversely affect the properties of the machined surface [3, 5]. For these reasons, it becomes necessary to locally correct the tool path and plan the change of the feed rate. In particular, this problem concerns the generation of tool motion paths for surfaces composed of irregular feed marks. The issue of classification of tool motion paths and their matching to scanned surfaces is described in [5].

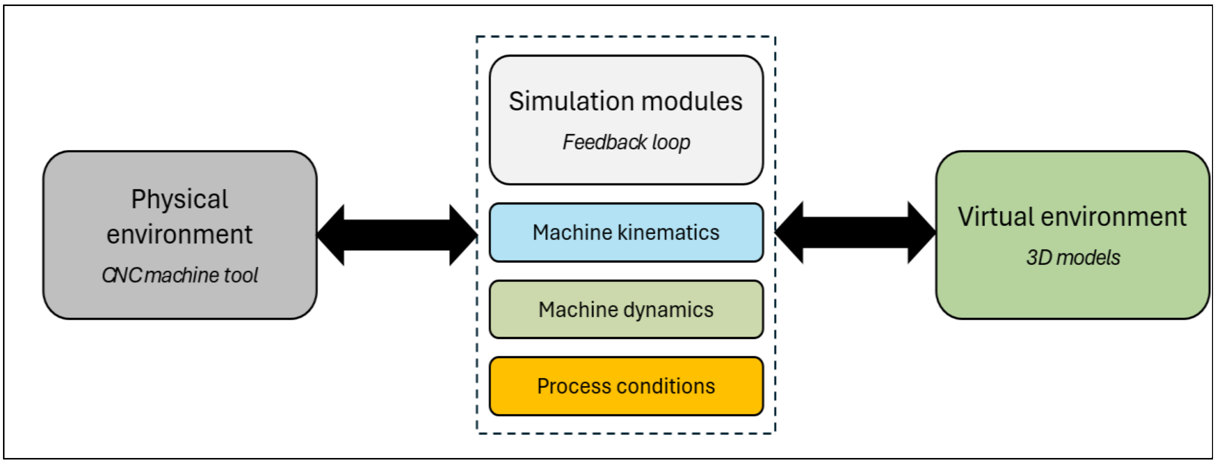

Fig. 4. Concept of a modified real-time simulation of CNC machine tools [2, 6]

In order to achieve a largely realistic simulation of the machine tool kinematics, the simulation module can take into account the dynamic behavior of the machine tool and an additional feedback loop between the workpiece and the NC control system to take into account the influence of the shape change of the workpiece (fig. 4). The DIN VDI 3441 standard distinguishes three machine tool characteristics – static, dynamic and thermal. The workpiece is composed of large network elements, the so-called voxels, and the simulation of the machining is carried out by their successive removal. During the simulation, changes in the position of the controlled axes resulting from the removal of voxels are recorded, which are transferred to the simulation model of the machine tool kinematics, and on this basis a new tool center point is determined ("tool center point" – TCP). The TCP is then used in the simulation of material removal from the workpiece to determine new cutting parameters. The final results of the controlled axes positions are sent back to the physical NC system. Thus, there is a reverse exchange of information between the digital twin and the physical twin [7,8]. An example of a commercial application of the digital twin (DT) concept in CNC machine tool programming is the Create software package MyVirtual Machine and Run My Virtual Machine for the virtual Sinumerik One digital control offered by Siemens [9]. In 2023, the "native" SINUMERIK ONE control system was tested in the context of creating and using a digital twin on a 5-axis training machine SLV EDU from SolidVision [9] As a result, the machine operator has its full virtual representation on a PC in the form of a digital twin, as shown in fig. 5.

Software integrity is ensured at the stage of prototyping, commissioning, programming and servicing of the machine tool and in cooperation with CAD-CAM-CNC support systems. In such cases, the digital twin is created in the Create environment MyVirtual Machine. It is also possible to configure the virtual part of the CNC system, PLC controllers and HMI interface, as well as the mechanical part of the machine. The level of virtual representation of the machine reaches 99%. As a result of using DT, the time of implementing a new machine in production is shortened by 30% and the time of its launch by 50%. These activities fully correspond to the implementation of the INDUSTRY 4.0 strategy in the Polish industry.

In the case of performing operator tasks, the ability to simulate collision risk assessment and object measurements taking into account the zero point shift is important. In turn, using the Run MyVirtual Machine software means that programming, production preparation and operator training can significantly replace tasks performed on a real 5-axis machine.

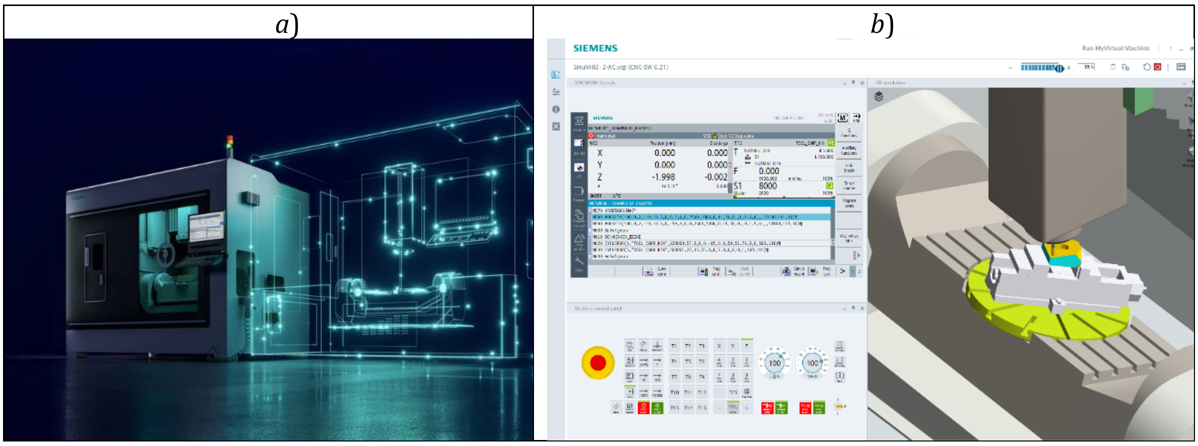

Fig. 5. Virtual representation of a CNC machine tool in the form of a digital twin in the SINUMERIK ONE control system (*a*) and an example of an integrated virtual model of a titling rotary including machining simulations (*b*) [9]

STEP-NC Interface Development

The development of the STEP-NC interface is mainly focused on the implementation of intelligent control, which makes the machine tool/CNC controllers subject to intelligent actions, such as machining optimization. An example is the autonomous STEP-compliant CNC (ASNC), which was developed at the National Research Laboratory for STEP-NC Technology in South Korea. Data stored in ISO 14649 format is converted to ASNC format and then converted into a process sequence graph (PSG) [10]. PSG is created from nonlinear sequences of work steps using AND-OR relations. This provides additional flexibility in gaining robustness to unpredictable events and optimizing the process sequence. Another advancement concerns the replacement of the EXPRESS language (ISO 10303 AP21) with the universal markup language XML (ISO 10303 AP28), which makes the data transfer suitable for e-manufacturing. The data model enables the location, extraction/selection and archiving of tool paths in XML format (extensive markup language). A set of instructions is created to format texts in a machine-readable way. STEP-NC programs are created by the data input module (XML DATA INPUT) and the data interpreter (INTERPRETER) based on the supplied CAD files.

In fig. 6 the concept of a closed-loop self-learning STEP-NC machining system that uses high-level information, including data on the processing conditions and the results of control carried out online and real-time, is shown. STEP-NC interpreter adjusts the technological parameters of the machining on the 5-axis CNC machine tool according to the knowledge about the process, the condition of the machine tool and the tool. Sensors operating in the feedback mode provide the necessary knowledge about the course of the process and on this basis, the optimal technological parameters are determined using an adaptive control algorithm. After completing the working step of the machining, they are verified based on online control of the required dimensional tolerances [11].

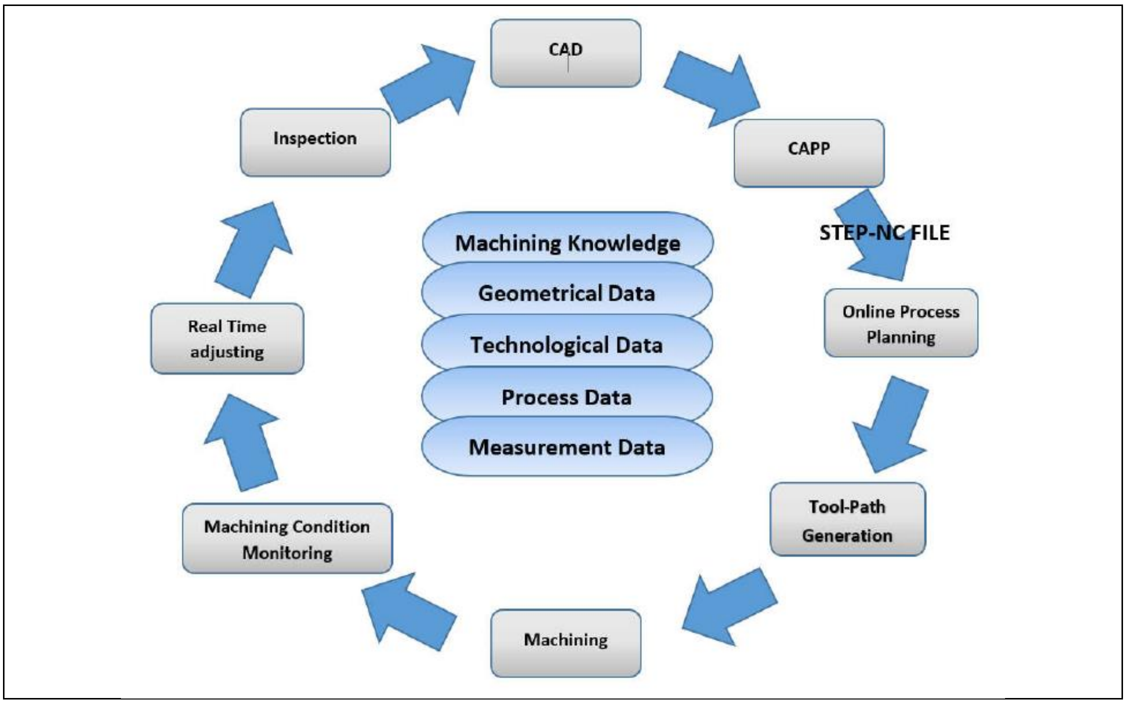

Fig. 6. An example of a closed-loop self-learning STEP-NC machining system [2, 10]

Based on the STEP-NC platform, the concept of sustainable manufacturing can be developed, which involves creating an energy-efficient manufacturing environment and intelligent manufacturing, which requires the introduction of intelligent controllers at the industrial level [11, 12].

Exchange of information between CAD and CAM systems

The initial concept of information exchange in the CAD-CAM system in the form of feedback is shown in fig. 7. It fulfils, as mentioned earlier, three basic functions, i.e. monitoring, adaptive control and learning. It consists of a CAD system, a database and a controller in real time.

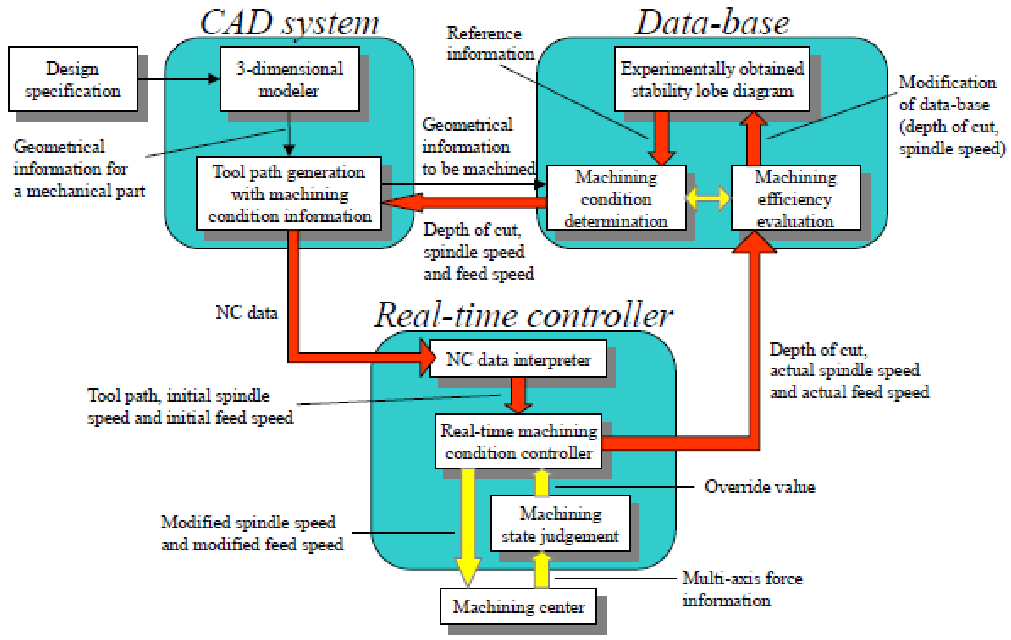

Fig. 7. Configuration of a CAD-CAM system with mutual information feedback [1]

The machine is equipped with a 6-axis force sensor, which is intended to enable the determination of a stability lobe diagram [4]. Cutting parameters such as: depth of cut, cutting speed (equivalent to the machine spindle speed), feed are modified dynamically as a result of the determined sequences of stable cutting states (which is also the basis for determining the process stability diagram). It is crucial to avoid cutting in the areas of self-excited vibrations (chatter) [2, 4].

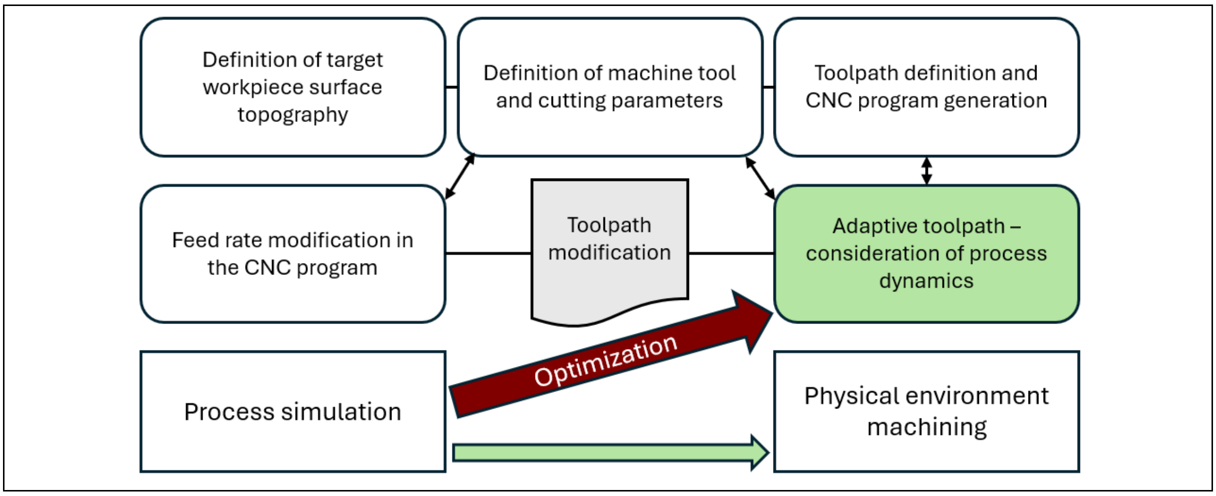

Fig. 8. Overview of the process planning flow in TDP [5]

In quality control, taking into account the dynamic properties of the machine tool and process changes over time ("time-dependent processes" – TDP) in tool path planning, which can affect the properties of the machined surface, the inverse and concurrent (literally "forward") problem is analyzed as in fig. 8. [3, 5]. In the latter case, programming is supported by real-time surface creation simulation [14]. Similar to traditional process planning, first (1) the required surface topography is defined and constraints are imposed on the scope of quantitative process characteristics, i.e. volumetric rate of return (MRR), layer deposition or geometric structure changes based on consideration of deviations from the initial topography. These possibilities are in principle achievable in a CAD system based on part data before or after machining or contour correction, usually based on 3D measurements on a coordinate measuring machine. In the next step (2), a decision is made on the process conditions and the so-called process influence function (PIF) is identified/predicted. The next step (3) concerns determining the CL data of the tool path based on the predefined total tool path. In this case, the information is available in the used CAM program. The generated information is used to optimize the feed based on measurements of cutting force components, i.e. indirectly similar in principle to the post-process mode. This is done because the source data for determining the key performance indicator (KPI), which is the basis for feed optimization, are recorded, depending on the process kinematics, in the recorded curves of the cutting force and/or cutting torque components [4].

Also noteworthy is the concept of "machine tool 4.0" using supporting technologies such as: cyber-physical systems and the Internet of Things (IoT) [7, 13]. The basic task in this case is the integration of machine tools and devices on the production floor by connecting them with each other in order to facilitate monitoring, planning and intelligent control of manufacturing processes [2, 13].

Improving (responsiveness) of the interface between IMT and the operator

One of the key issues in the design of intelligent CNC machine tools is the design of interfaces taking into account the optimal interaction between the operator and the machine interface (human-machine interaction). Such an approach should account not only the design aimed at optimizing the user experience while working with the system ("user experience design" – UXD), but also eye-tracking data allowing to determine which elements of the interface are most often used by the operator. Additionally, behavioral studies can allow for the design of the interface and the entire machine tool in a way that takes into account the needs of the end user.

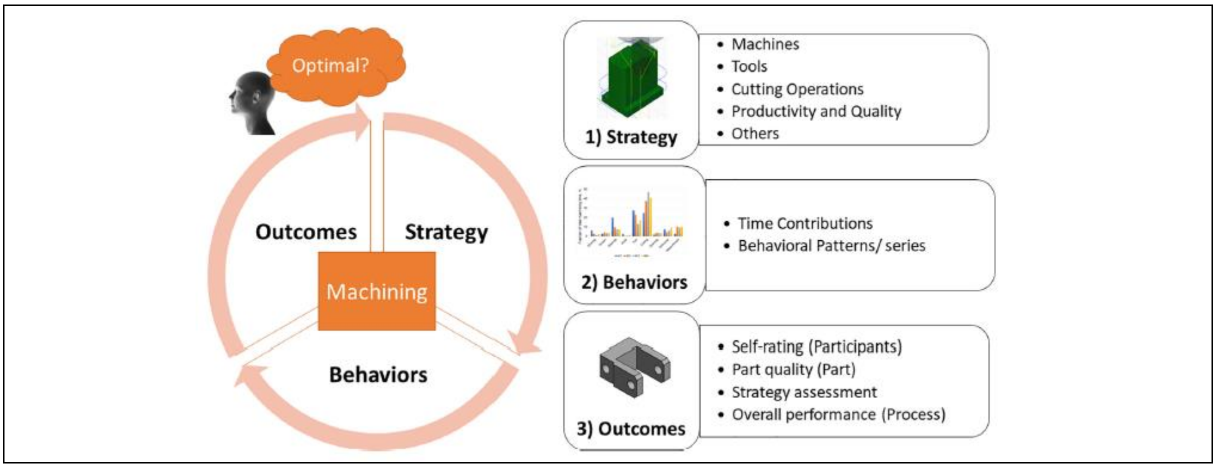

Fig. 9. A conceptual study on human behavior and the influence of MT operator experience on process outcomes and human-machine interaction [15]

A case study based on the concept presented in fig. 9, published in [15], showed that the operator spends a significant part of the total machining time on interacting with the machine interface. This share decreases with the increasing experience of the operator, but it still remains significant, which opens up further possibilities for improving the productivity of the machine. The basic direction of improving the interface of intelligent CNC machines comes down to their orientation towards more intuitive operation. Current research focuses on the analysis of eye-tracking data obtained from several operators with different amounts of professional experience in order to collect input data for the optimization of intelligent CNC machine interfaces.

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