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ADVANCED SIMULATION OF NC TURNING OPERATIONS

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Abstract. Modern Manufacturing Execution Systems (MESs) provide new possibilities for employing robust process plans including technological alternatives. Decision making activities on MES level can be based on alternatives which had been created at the process planning stage. This requires the improvement of computer aided NC Programming (NCP) and simulation capabilities. This paper deals with the complex simulation and modelling problem of cutting processes and summarises the technical-economic model of turning operations. The operation level model of turning is discussed. The simulation software layout is also presented.

Keywords: MES, NC Simulation, Turning, Artificial Neural Networks

1. Introduction

In modern manufacturing the 80 % of metal parts are machined by means of cutting. The reason of this fact is that in most cases the geometry of cutting tools are relatively simple; and the shaping process on the machine tools is based on NC path generation with the part geometric model. In general, other types of manufacturing cannot compete with cutting on required geometric accuracy and smoothness. In the last years, cutting operations have improved their efficiency. The main directions of improvement are as follows:

- improvement of the real time functions provided by the CNC controllers,
- high concentration of machining operations on machining centres,
- improvement of machine tool materials and tool life,
- widespread use of Flexible Manufacturing Systems and Cells,
- more applications of Computer Aided NC Programming and MES systems.

The manufacturers using CNC technology require more efficient tools for planning and controlling cutting operations. Their needs can be summarized as follows:

- ability to machine sophisticated sculptured surfaces,
- high utilization rate of automated CNC machines,
- reduction of operation times and increasing productivity,
- increased quality requirements,
- new computer tools to support process planning (CAPP, NCP, CAD/CAM),
- more reliable process modelling for optimisation of operation elements,
- more precision prediction of operation times, costs and resources consumption ,
- more accurate forecasting of quality, dimensional accuracy and risk of waste production, and
- creation of alternative process plans.

Computer aided NC programming tools play significant role to meet these demands. The NCP and CAD/CAM systems are the most frequently used tools of Computer Aided Process Planning (CAPP) applications. Conventionally, NCP systems are used to design the cutter location path and then to transform it into NC program. The execution of this program on NC machine tool by means of controlled positioning results the required work piece shapes.

Majority of the modern NC programming systems have their own built-in simulator. The main services of these simulators include the syntactical checking of the part program and the generation of the geometrical model of cutting. By means of the geometrical model, collisions, undercuts and interferences can be detected; estimation of operation times, etc. can be performed. In most cases, however, the physical aspect of cutting process is not modelled at all, thus technical-economic parameters that describe the effectiveness of the cutting process cannot be predicted.

The problem stems from the extreme complexity of cutting processes [3]. Significant research work has been carried out in the field of cutting theory since the 1930's and accumulated in the form of engineering handbooks and electronic databases. However, it is remarkable that even the most widely used NCP applications have no underlying physical models. The research results have not turned into industrial practice. The heuristics of mature technicians and operators are still playing their important role in decision-making.

2. Integration of planning and execution

The improvements in the field of computer networks (LAN) provide opportunity to integrate Process Planning (CAPP), Production Planning and Scheduling (PPS) and Manufacturing Execution Systems. Nevertheless, the existing computer applications which fall into the three major areas of applications mentioned before, do not provide the appropriate services to meet the demands discussed in the introduction.

At MES level numerous criterions are used to assess the goodness of process control. These are as follows:

1. Manufacturing costs;
2. Makespan and lead times;
3. Readiness for delivery (or: delivery capability);
4. Level of work in progress;
5. Utilization rate of resources;

6. Rate of waste products;
7. Flexibility and stability of operations.

Any re-scheduling at the MES level is a dynamic problem which requires the decision making to be supported.

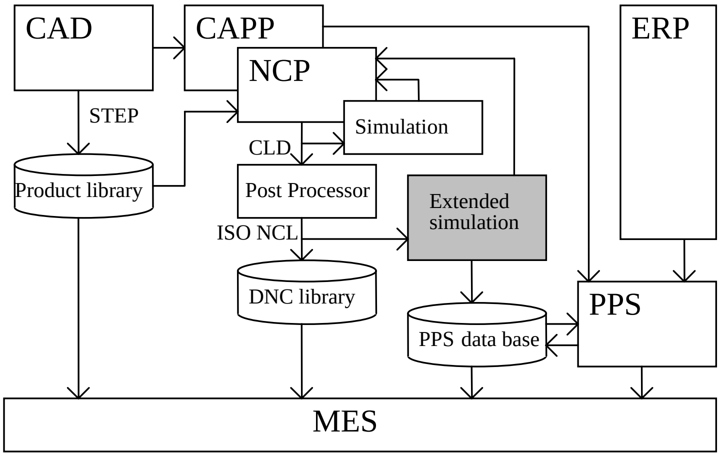


Fig. 1 The role of extended simulation in CIM

Consider the following MES task. Suppose a product assembly where priorities of some orders have been changed due to business reasons. New deadlines have been set which require certain parts to be produced or purchased faster than it does usual or planned originally. At MES level this could be achieved by "make or buy" decisions, rescheduling of jobs, releasing assigned resources or disrupting batch sizes. This would require the knowledge about the range of parameters in which the makespan time of cutting processes can be reduced guaranteeing the same quality, using the cutting tools more intensively which is often coupled with higher probability of waste production. It can be accomplished by having alternative CNC programs archived on the DNC server which had been tested with simulators and ready to download and use. Nevertheless, such alternatives can only be computed on the base of reliable technical- economic models.

The goal of using robust and alternative process plans is to increase the flexibility of MES systems. The supervised amendment of operation times can be successful if the alternatives of the operations are created at design (pre-manufacturing) stage. The synthesis of alternative solutions requires computer aided modelling and simulation techniques. The simulation should include the technical and geometrical aspects of machining as well as the aspect of utilization of resources and the production quality.

3. Technical-economic modelling of turning

The importance of technical-economic modelling of cutting processes is reflected in the fact that CIRP established the "Modelling of Machining Operations" working group in 1997 which presented its comprehensive keynote paper in 1998. [4]. Research work has been carried out in the University of Miskolc, Department of Information Engineering related to the general and specific modelling of cutting includes as follows:

- Solving process-monitoring issues by means of Artificial Intelligence (AI) techniques.
- Optimisation of cutting parameters using the Material Removal Rate (Q, [cm^3/min]) as state variable.
- CAPP-PPS-MES integration using Group Technology (GT).
- Extending the real time MES functions applying robust and alternative process plans.

The simulation of cutting operation can be carried out at six abstract levels. They are as follows:

- physical level,
- operation element level,
- feature level,
- operation level,
- job level,
- production order level.

At the first three levels the physical processes of the technology and the continuous state variables are of great importance. Therefore such models are required, which represent the geometrical, kinematical, dynamical and physical characteristics of cutting. The latter three levels belong to the scope of Event Driven Discrete Modelling (EDDM), which does not correspond to the objective of this paper.

The conventional methods of cutting, process planning and CNC programming are able to solve certain modelling tasks. These are the geometrical and physical models. However, they cannot support the technical-economic modelling and simulation of cutting operations. The reason of this phenomenon can be found in the difficulties of modelling of machining operations. They are as follows:

- The models should handle great number of inputs and outputs.
- The relationship between the parameters is extremely complex.
- Consideration of material properties cannot be done without empirical knowledge.
- Some of the sub-processes can only be described with stochastic variables.

Some computerized methods, which are promising to solve the difficulties listed above, are as follows:

- using database of cutting parameters,
- AI methods to handle non-linearities,
- state equations to describe the dynamic behaviour of processes,
- object oriented programming methods,
- component based software engineering, as well as
- graphical representation and interactive human-machine interface.

The feature level has a significant role among the other levels. It is possible to create a model at this level which can utilize the advances of computer technology listed above and, on the other hand, can facilitate the construction of appropriate models at lower and higher levels.

4. Operation level model of turning

The operation level model of turning, which has the capability to support management decisions, can be summarized as follows:

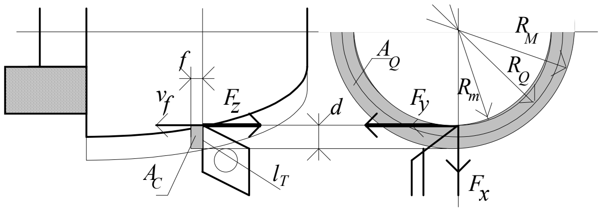


Fig. 2 Geometrical model of turning

4.1. Geometrical relations. The mean diameter of turning is:

$$D_Q(t) = \frac{1}{2}.(D_M + D_m)\text{, where} \quad (1)$$

$D_m(t)$ is the smallest diameter swept by the generating surface of the tool at a given time;

$D_M(t)$ is the largest diameter of the actual pass. It depends on the workpiece geometry and is calculated by the simulator.

The current depth of cut calculated by the simulator as:

$$d(t) = \frac{1}{2}(D_M - D_m)\,. \quad (2)$$

The active cross-section is:

$$A_Q(t) = D_Q \pi .d = \frac{\pi}{4}.(D_M^2 - D_m^2)\,. \quad (3)$$

The feedrate:

$$f(t) = \frac{v_f}{n}\ \text{[mm/rev].} \quad (4)$$

The current (active) cross section of the chip:

$$A_c(t) = d(t).f(t)\ [\text{mm}^2]. \quad (5)$$

The current average thickness of chip is:

$$h_c(t) = \frac{A_c}{l_T}\text{, where} \quad (6)$$

$l_T(t)$ is the length of tool edge being in cut (dependent to the geometry).

4.2. Kinematical relations. The mean cutting speed can be evaluated as:

$$v(t) = D_Q(t).\pi.n\text{, where} \quad (7)$$

n [rev/min] is the spindle (rotation) speed.

The feed speed is:

$$v_f = n.f \ \text{[mm/min]} \text{, where} \quad (8)$$

f [mm/rev] is the feedrate.

Here we introduce the most important technical-economic variable, Q the Material Removal Rate in general form.

Definition: In rough cutting operation the technological can be characterised by the material removal rate, which is the product of the active cross section of the cutting process and the feed speed.

The active cross section can be considered as the projection of the surface contacting the tool and the parts per one rotation of the main spindle.

$$Q = A_Q.v_f \ \text{[cm}^3\text{/min]} . \quad (9)$$

In case of turning:

$$Q = D_Q.\pi.d.v_f = D_Q.\pi.d.n.f = v.f.d. \quad (10)$$

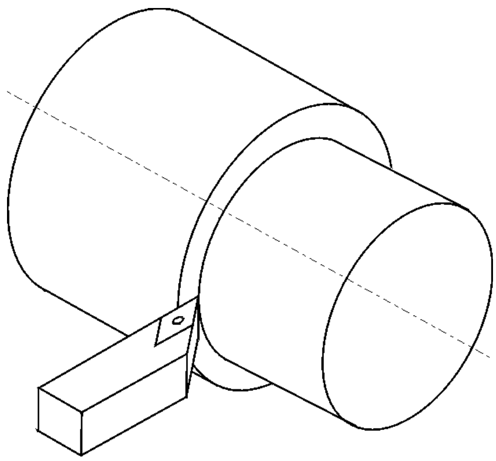


Fig. 3 Active cross section o outer turning operation

4.3. Dynamic relations The mean cutting force can be calculated as:

$$F_y(t) = k_q(h_c, \text{workpiece material}).A_c(t) \ \text{[N], where} \quad (11)$$

k_q is the unit force. In industrial practice empirical relations are very popular:

$$F_y(t) = C_F(\text{workpiece material}).v^{y_F}.f^{x_F}.d.\prod_i K_i \text{, where} \quad (12)$$

K_i is the cutting coefficients describing the lubrication, rough material, clamping, etc.

The force component at the feed direction is:

$$F_x = \lambda_x(\text{cutter angles}).F_y \ \text{[N]} \quad (13)$$

The orthogonal force is:

$$F_z = \lambda_z(\text{cutter angles}).F_y \text{ [N], where} \tag{14}$$

λ_x and λ_z are experimented parameters and dependent on tool geometry. The spindle torque is:

$$M(t) = \frac{1}{2} D_Q.F_y.10^{-3} \text{ [Nm],} \tag{15}$$

and the cutting power is:

$$P(t) = M.\frac{2\pi}{60} n \text{ [Nm/s].} \tag{16}$$

4.4. Technological relations. The technological relations can be modelled using empirics. The most important state variable is the tool life. In stationary cutting the Taylor equation is the most applicable if the cutting parameters fall into certain range. In non-stationary cutting a load-dependent linear model based on experiments can be used. This model uses the tool wear speed as state variable (v_Δ) which dependent on the tool material and load. To describe the load of coated inserts the following state variable can be used:

$$T^m = \frac{C_v}{d^{x_v} f^{y_v} v}. \tag{17}$$

$$L_T = (d^{x_v} \cdot f^{y_v} \cdot v)^q . \tag{18}$$

$$q = 1/m \approx 4 . \tag{19}$$

According to the model:

$$v_\Delta = k_\Delta(\text{tool material}).L_T \text{ [mm/min], where} \tag{20}$$

$$k_\Delta = \frac{1}{C_v^q} \tag{21}$$

$$\delta(t) = \frac{\Delta(t)}{\Delta_{ref}}, \quad 0 \le \delta \le 1, \quad \Delta(t) = \Delta_0 + \int_0^t v_\Delta(t)\ dt , \tag{22}$$

This model uses the cumulative wear theory, which gives the Taylor equation in a stationary case. The statistical modelling is also feasible when the k_Δ variable has an exponential (or other) distribution. The tendency to self-induced oscillation is also belongs to the technological modelling. It is dependent on the workpiece and tool geometry and the characteristics of the machine-clamping-workpiece-tool system, which is regarded as a flexible mechanical system. The possible methods for modelling this can be as follows:

- Setting up a dynamic model at simulation time based on measurements.
- Transferring the stability factor into the model.
- Using Neural Networks estimation.

The cutting energy consumption is

$$E_c(t_c) = \int_0^{t_c} P(t)\ dt . \tag{23}$$

The cutting time is:

$$t_c = \int_0^s \frac{ds}{v_f(ds)} \text{ where} \tag{24}$$

d_s: cutter path incremental length.

The modelling of the average surface roughness ($\overline{R}_a$), the dimensional accuracy ($\overline{\delta}_m$), the geometrical trueness ($\overline{\delta}_a$) and the rate of waste products (p_W) is extremely difficult. Using AI methods based on the measured data on existing machines could provide usefull models.

4.5. Technical-economic relations. Some technical-economic state variables, and their integrated or average values are required to assess turning processes. The operation time can be evaluated for each operation element as:

$$t_m = t_c + t_r + t_i \text{ , where} \tag{25}$$

t_r is the time spent with rapid feeding , t_c : is the cutting (feed) time and t_i is the time consumed without movements (e.g. insert replacement or tool change time). The operation times are easy to calculate using the NC program as input. The expected cost of an operation element can be calculated with special regard to the circumstances, i.e. based on the operational data and conventions of the given firm. The cost can be evaluated as:

$$C_\Sigma = C_m + C_t = c_w.t_m + \frac{t_m}{T}(c_w.t_{ch} + C_T) \text{ , where} \tag{26}$$

c_w is the cost of one work minute, C_T is cost of tool insert replacement, t_{ch} is the tool change time, C_t is the portion of tool insert replacement cost per operation element.

The average Material Removal Rate (often regarded as technological intensity):

$$\overline{Q} = \frac{V}{t_c} \text{ , where} \tag{27}$$

V is the material volume to be removed [cm^3].

The optimal MRR can be calculated considering the technological constraints. According to the model described in [7]:

$$\tau = \frac{C_\Sigma}{V.c_w} = \frac{1}{\overline{Q}} + \frac{\overline{Q}^{\,q-1}}{R^q} \tag{28}$$

$$R = \frac{d^{1-x_v}.f^{1-y_v}C_v}{t_H^m} = \frac{Q.T^m}{t_H^m} \tag{29}$$

$$t_H = \frac{C_t}{c_w} + t_{ch}\,. \tag{30}$$

The technological intensity optimised for cost when the depth of cut is constant and a force (feedrate) limit R_M is given can be calculated as

$$Q^* = \frac{R_M}{(q-1)^m} \tag{31}$$

$$R_M = \frac{d^{1-x_v} \cdot f_{\max}^{1-y_v} \cdot C_v}{t_H} \tag{32}$$

(Here we assumed that the active constraint is the feed limit). We can define the efficiency of technological intensity:

$$\eta = \frac{\overline{Q}}{Q^*} \text{ ,where} \tag{33}$$

$$Q_m \le \overline{Q} \le Q_M \ . \tag{34}$$

The result should be compared with the average technological intensity coded into the NC program. The maximum intensity (Q_M) which is still feasible can be derived from the fact that the tool life of the current tool cannot be smaller than the operation time of the operation elements. To save (tool) cost, the technological intensity can be reduced when the capacity of the machine tool allows it. The minimum intensity can be derived from the τ_{Max} value as:

$$Q_M = \frac{V}{T} = V^{\frac{m}{m-1}} \cdot \frac{1}{R_M^{\frac{1}{m-1}} \cdot t_H^{\frac{m}{1-m}}} \tag{35}$$

$$Q_m \cong \frac{1}{\tau_{Max}} \tag{36}$$

$$t_{c,\min} = \frac{V}{Q_M} \tag{37}$$

$$t_{c,Max} = V.\tau_{Max} \ . \tag{38}$$

Having knowledge about the boundaries of Q makes it possible to measure the current and maximum values of cost reserve, minimum operation element time, time reserve and the related MRR, efficiency of the synchronisation of tool life. If the minimum value of tool life is prescribed or the power of the machine is limited then the current $\overline{Q}$ value must be compared to the $Q_{T,Max}$ and $Q_{P,Max}$. This can be achieved using the model discussed above.

This model is easy to aggregate with the upper levels of modelling. Aggregation is referred as a complex modelling function which based on the data of lower levels creates the upper level model parameters. The aggregation of operation elements is an additive function in the aspect of time and cost.

In the direction of lower levels certain decomposition is required, which should be carefully considered due to the non-linear internal relationships of the model. It is difficult to predict the accuracy of the model as a whole. A significant factor is the measurability of the sub-models. The final validation must be accomplished by laboratory experiments.

5. Hierarchical layout for extended simulation software

The hierarchical system layout for extended simulation software is shown in Figure 4 This architecture allows mixed models to be used. At the first layer some basic system variables are evaluated. As the simulator software maintains the actual parameters the evaluation of these is based on the mathematical relations (1)-(5).

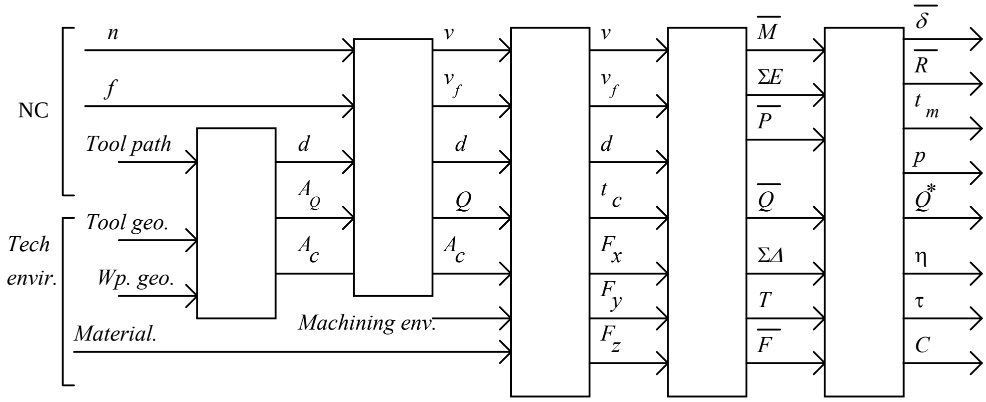


Fig. 4 Chain layout of sub-models

5.1. Cutting force modelling by means of ANN. At the second layer the MRR and the cutting and other additional times are calculated. At this level a backpropagation (BP) feed forward neural network is used to predict the cutting force.

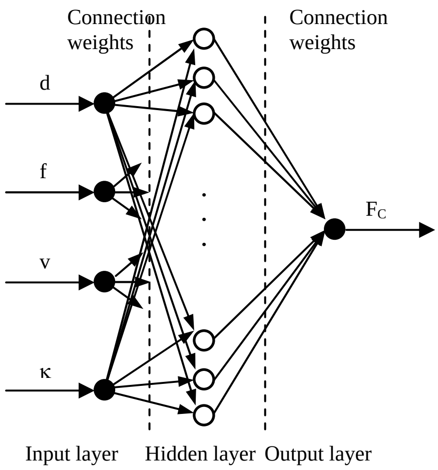
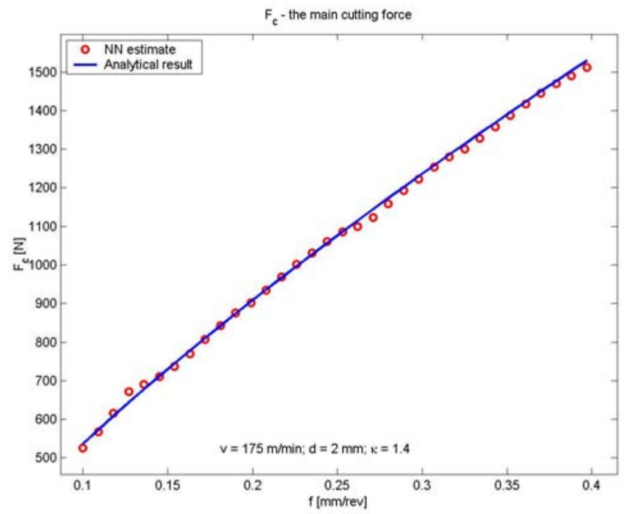


Fig. 5 Single hidden layer ANN for cutting force prediction

The BP network is a supervised continuous valued network. The scaled conjugate gradient (SCG) algorithm had been used to train the network. Compared with the basic BP algorithm, which alters the weights in the steepest descent direction (i.e. the direction in which the performance function is decreasing most rapidly) the SCG algorithm provides faster convergence. [8]. A single hidden layer ANN had been used having 30 neurons. At the input layer the hyperbolic sigmoid transfer function had been used while on the output layer a pure linear transfer function had been applied. The training set was a set of 75 input samples generated as it is described in [9]. Figures 6 (a) and (b) show the testing accuracy of the Neural Network model.



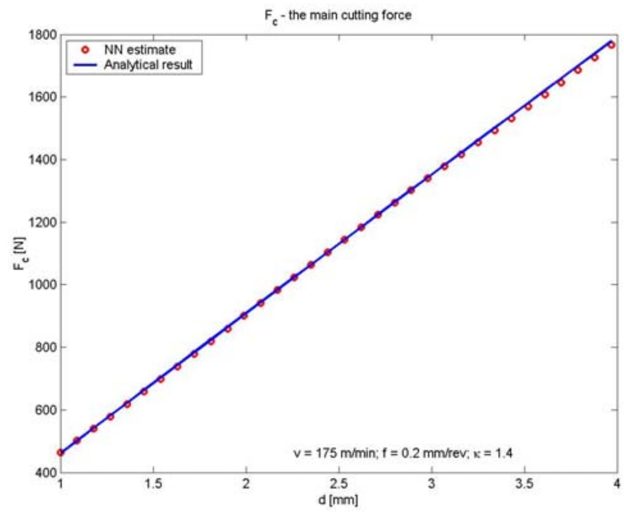


Fig. 6 (a) (b) Testing stage of ANN performance for cutting force

It is well known that the *training session* having multiple epochs of the ANN requires much more computing effort that that of single pass *simulating* the network. Thus it is expedient to separate the training from the simulation. This allows a client-server ANN approach where a server application performs the training sessions and stores the network layout (i.e. number of input, output neurons, number of hidden layers with the number of neurons it has, the calculated weights for each connections and biases of each neuron and the transfer function for each layer) and the client (i.e. the NC simulator) implements only the propagation passes. This requires an Application Program Interface (API) between the client and server application to be implemented as shown in Figure 7.

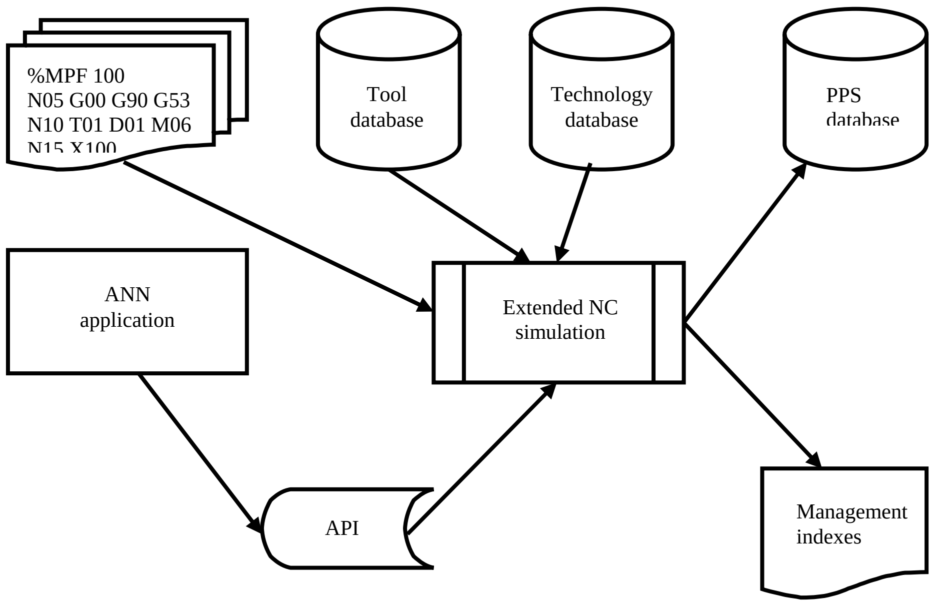


Fig. 7 Architecture of extended simulator software

5.2. Subsequent models. The subsequent models can go on the cutting force model. The required power, the total energy consumption an the torque can be evaluated according to the equation (15) and (16) respectively. The cutting time is evaluated as (24). According to the tool life constraint the time spent with cutting for certain tools must be les than the allowed time limit of the cutter.

The modelling of the workpiece quality can be again an AI model where the relevant input variables are:

- the cutting force,
- the torque,
- the time spent with cutting so far ,
- cutting speed,
- federate,
- cutting edge radius.

5.3. Software engineering approach. The advantage of this chain layout is that the sub models can be implemented in separated classes or components utilizing the advantages of Object Oriented Programming (OOP). This also allows a mixture of the sub models (analytical, numerical, AI-based) to be used. However the major disadvantage is that any error introduced at the beginning of the chain will be rolled over the whole system.

6. Conclusions

Creating alternative NC programs by varying the technological parameters can be an essential tool for modern production management. The extended NC simulators over geometric simulation could provide the required data for supporting production planning and MES systems. This could be a step for realising Virtual Manufacturing in the field of NC turning.

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