Supporting Direct and Indirect Manufacturing Control Tasks by Extended NC Simulator System

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Abstract
Modern manufacturing systems require the integration of Computer Aided Process Planning (CAPP), Production Planning and Scheduling (PPS) and Manufacturing Execution System (MES). The actual production progress and the management indices may deviate from the production plan. These deviations are measured by MES and modifications have to be made. This paper overviews some typical direct and indirect production control tasks in a jobshop environment focusing on metal cutting processes. An extended simulator of CNC machining operations using Artificial Neural Networks (ANN) models supporting control decisions will be also presented.

Keywords:
Computer Numerical Control (CNC), Simulation, Neural network, Production control tasks, Manufacturing Execution Systems (MES)

1 INTRODUCTION

Modern manufacturing systems are characterized by high level of automation and extensive use of computer applications. There are various aspects of enhancing the integration within a Computer Integrated Manufacturing (CIM) environment. This paper focuses on discrete part manufacturing of metal parts with special regards to cutting processes. A Computer Aided Process Planning (CAPP) application is responsible for generating the process plans including CNC part programs. Production Planning and Scheduling (PPS) applications perform the complex task of material requirements planning (MRP), scheduling of production activities, resources management including machine and labour assignments and costing production operations. A Manufacturing Execution System (MES) is a collection of hardware/software components that enables the management to control production activities from order launch to finished goods. While maintaining current and accurate data an MES guides, initiates responds to and reports on plant activities as they occur. MES provides mission-critical information about production activities to decision support processes across the shop floor level of manufacturing management. [1].

2 PRODUCTION CONTROL TASKS IN JOBSHOPS

In a jobshop environment factory and manufacturing system or cell leaders have the responsibility for the progress of production. If the actual production progress and the management indices deviate from the production plan, deviations are measured by MES and modifications have to be made. There are only four typical possibilities for interventions. These are as follows:

- (re)allocation operations to machines and workplaces;
- (re)scheduling of jobs, changing orders and earliest starting and latest finishing time;
- joining or splitting batches;
- modifying the processes by means of alternative process plans, alternative operations or by overriding cutting intensity of NC machines.

The latter one is very important because the intensity of cutting operation exerts influence on operation time, tool cost and faulty product rate.

There are two distinct types of production control activities which refer to the intensity of machining process by cutting conditions that we call *direct* and *indirect task* [2].

2.1 Direct task

Direct tasks refer to the pre-manufacturing planning activity where the optimum of cutting conditions and other tool path parameters to be searched. The cost or time optimal solutions should obviously satisfy the technological constraints such as machine, cutting process and tool limitations.

The optimal control theory suggests the use of robust control that assures less sensitivity for the changing of process parameters or constraints, and for the change of the goal function, in more general sense.

In analogy to robust control we can define the robust technology process plan. It represents that kind of planned cutting process, containing tool path, feed rate and cutting speed data which is less sensitive to technology parameters or constraints, and forms a group of alternatives (population) from which the production management can easily select the appropriate one in accordance with the actual demands [3, 4].

Tóth and Erdélyi [2] introduced an optimization technique for turning operations based on the Material Removal

Rate (MRR), which is also known as cutting intensity (*Q,* [cm^3/min]). This method has the advantage that the optimal solution can be decomposed to various machining parameters. For turning it is the product of three cutting parameter as indicated in the Equation 1.

$$Q=d \cdot f \cdot v \text{ [cm}^3\text{/min], where} \quad (1)$$

d – depth of cut [mm],

f – federate [mm/rev] and,

v – cutting speed [m/min].

2.2 Indirect task

An indirect task refers to the on line control of manufacturing activities where the optimum of actual management goals to be searched. On shop floor level where indirect production control tasks emerge new solutions have to be found due to the uncertainty or the changed properties of the environment, therefore new optimal parameters are required. A typical case is for example to resolve a bottleneck issue or a response to a change in business goals.

Good decision making on MES authority require reliable models and tools to support this activity. The most important factors to consider at this point are the operation times, operation and tool costs and the quality of the workpieces as well as the maximum cutting force, torque, energy consumption, etc. These factors are referred to as natural shop floor *management information.* The modelling difficulty lies in the complexity and nonlinearity, which are between the operation parameters and management indices.

3 EXTENDED SIMULATION OF CUTTING OPERATIONS

There are numerous computer tools on the market that support the verification of a CNC program. The major categories of these are the standalone simulators, the simulators built in to a CNC programming system, and simulators supplied with the controller by the numerical control system manufacturer. A comprehensive overview is given in [5] about the available services of the standalone CNC simulators. They provide various facilities but besides the operation time they do not fulfil management indices for supporting decision making activities. The target of conventional simulation includes:

- program verification;
- graphical animation;
- definition of work-piece and tool geometry;
- post-processing;
- tool path optimization;
- machining simulation;
- multi-axis geometrical simulation,
- integration with CAD/CAM and CNC programming systems;
- simulation of operator panel;
- calculation of cross sections;
- comparison of the virtually manufactured workpiece with CAD model;
- calculation of operation times;
- calculation of volume of material removed.

In order to support decision making on MES level some extended functionalities are required. They include the estimation of

- operation cost;
- list, quantity and cost of tools used;
- type and postprocessor of the selected controller;
- cutting forces, torque, power;
- surface roughness, dimensional accuracy, rate of refuse rejects.

To cope with the complex nonlinear relationship between the process parameters and the manager indices it is expedient to use a hybrid model which combines explicit equations with Neural Network models.

3.1 Neural Network modelling for extended simulation

During the research work of the late years carried-out at the University of Miskolc, Department of Information Engineering a hierarchical Neural Network model has been developed for extended simulation.

This model requires the full description of the tool and workpiece geometry as well as the tool path. The CNC part program contains all required information to perform the verification, besides it can provide data for a Neural Network to estimate the cutting force. The Neural Network model has need of experimental data from the machines to learn and expects the invariance of the cutting environment (machine tool, tool material and geometry, work-piece material, etc.).

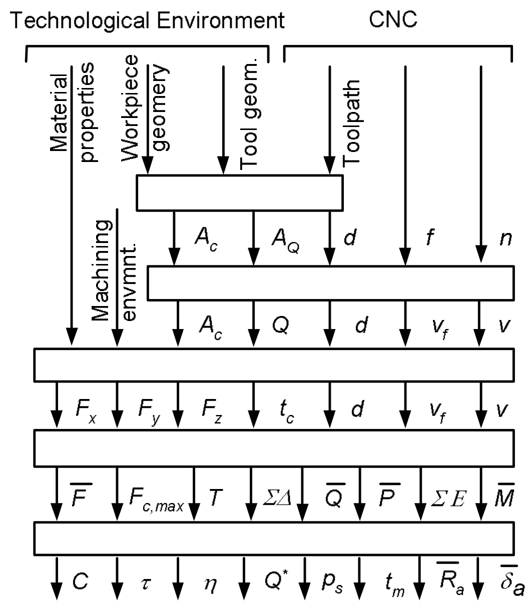

Figure 1: Multi level hierarchical Neural Network model

Figure 1 shows the multi level hybrid hierarchical model for CNC turning operations. A set of process management indices like torque, power or quality parameters is the function of the cutting force. The former two can be expressed explicitly by a simple equation. However, defining the relationship between the machining parameters, tool wear, cutting force and the Material Removal Rate as input and the achievable quality descriptors as output, is almost impossible. If experimental data is available a second Neural Network can provide estimation on the expected average surface roughness and toleration. At present there are excellent and flexibly applicable force measuring sensors in the market. They are suitable to collect the teaching data set for the ANN.

There are two distinct types of input of the model. One of them is the CNC program which contains the geometrical description of the toolpath as well as other technological parameters like spindle speed and federate. The depth of cut can be also calculated by means of maintaining the actual geometry of the workpiece during the simulation. The model requires the initial workpiece geometry and the tool geometry to be defined. At the first hierarchical level an interpreter extracts these data from the CNC program and calculates the current cross section (A_c) of the chip and the active cross section (A_Q) which can be considered as the projection of the surface contacting the tool and the parts per one rotation of the main spindle. The active cross section is travelling at feed speed (v_f) thus sweeping the volume to be removed. The second layer calculates the feed speed and the MRR. At the third level a Neural Network is used to estimate the cutting force and its components (F_C). Figure 2 (a) depicts the layout of the NN model for estimation of cutting force. Besides the cutting parameters the NN uses the cutting angle (κ) as input. The cutting time is also calculated at this level. The fourth level of the model calculates some aggregated indices such as average and maximum cutting force ($\overline{F}$, $F_{c,\max}$), tool life consumption, accumulated tool wear (T, $\Sigma\Delta$), average MRR ($\overline{Q}$), average power and torque ($\overline{P}$, $\overline{M}$) and energy consumption (ΣE). In order to model non-stationary tool wear a linearization technique was used which based on the Taylor's tool life equation [5].

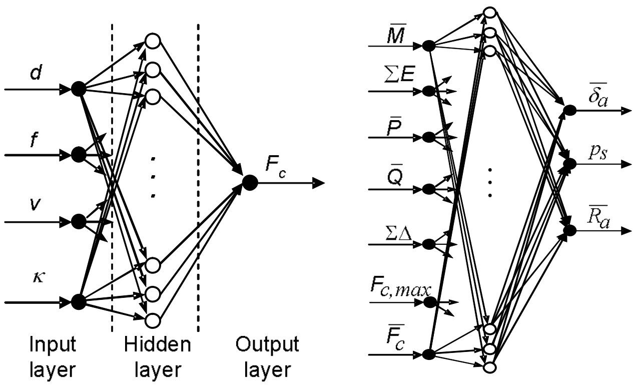

Figure 2: Neural Network for estimating

(a) cutting force (b) other technological outputs

The fifth level of the simulator uses a second Neural Network to estimate management indices which describe the quality of the product, see Figure 2 (b). The output of the extended simulator is as follows:

- average dimensional accuracy ($\overline{\sigma}_a$);
- average surface roughness ($\overline{R}_a$);
- machining time (t_m);
- rate of rejected products (p_s);
- the optimum of MRR (Q^*);
- the efficiency of stock removal, i.e. the current MRR relative to the optimum MRR (η);
- cost-equivalent time [2] (τ);
- machining cost, tool cost, total cost (C).

Based on the model an extended CNC simulator for turning operations has been implemented using object oriented software engineering [3, 5].

4 SUPPORTING DIRECT AND INDIRECT TASKS BY MEANS OF EXTENDED SIMULATOR

4.1 Supporting direct tasks

The extended simulator developed within the framework of this project is able to support direct jobshop tasks with its conventional facilities. In the frame of direct tasks the optimal MRR is calculated by constrained optimization algorithm. Robustness of the CNC part programs may be achieved by decomposing the MRR into different depth of cut, federate, and cutting speed parameters. Considering the physical constraints of the machining the decomposition may result a set of cutting parameters for certain machine tools thus forming a set of CNC programs. The CNC program variants have to be verified by the simulator, which provides the following functionalities:

- syntactical check;
- semantic analysis;
- locating collision and geometrical undercut events;
- verification of the management indices defined by planning activities.

The syntactical verification is based on the lexical description of the CNC program language used. During semantic analysis, certain tool path degeneration can also be detected. Recognition of undercut and collision events also requires investigation and evaluation of the geometrical model of the part and the actual tools.

For supporting these features the extended simulator provides a CNC program editor and graphical animation. Robust CNC programming requires the preparation of CNC program variants. Management indices can be assigned to each instance of the variants. Thus the correctness of the process planning can be verified.

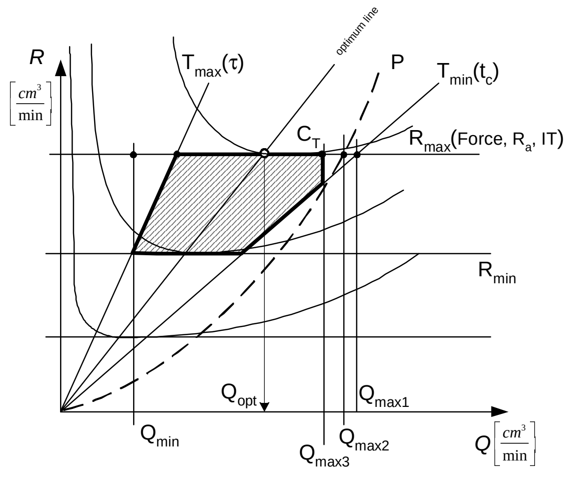

Figure 3: The search space for the optimal MRR

Figure 3 depicts the search space for the optimal MRR in case of turning operations. The tool life (*T*) limitation and the power constraints (P) are considered. The nomenclature used in Figure 3 is as follows: R refers to a new state variable introduced by Tóth and Erdélyi [2] which has the same unit as the Material Removal Rate (Q) and is a monotonic function of the depth of cut, federate and other parameters. The achievable $R_{\max}$ depends on the cutting force, and the prescribed surface roughness (R_a) and ISO tolerance (IT).

4.2 Supporting indirect tasks

For supporting indirect task, the simulator provides its extended functions. The goal is at this point to determine a *feasible context* of the optimal cutting parameters, which are physically and technologically achievable on the machine tool. One of the most important constraints is the tool life, which is a nonlinear function of the technological intensity. The tool change within an operation is discouraged. If the intensity should be increased in order to resolve a bottleneck problem the decrease of the tool life needs to be known. Similarly, the maximum of the allowed cutting force and torque may act as constraints.

From the management point of view, it is important to check the effects on cost and quality descriptors. The extended simulator is able to provide estimated data for the management.

If the cutting operation is not a bottleneck under the production process as a whole then the technological intensity can be reduced. This action results savings on tool life and tool cost and additionally it may reduce the amount of reject products. Obviously, there are also lower limits of the cutting parameters, which also have to be satisfied.

The change in technological intensity can be achieved by feed rate or cutting speed override or by regeneration of the CNC program in order to modify the depth of cut encoded into the program. The latter case requires the application of conventional simulator facilities as discussed above.

Figure 4 shows the feasible context of the MRR that was defined as optimum, during the process planning. The feasible context is bounded by a minimum and maximum cutting intensity. The cutting operation time (t_c), tool cost (C_T) and total cost (C_Σ) can be represented on the $Q-t_c$, $Q-C_T$ and $Q-C_\Sigma$ diagrams. The intensity based approach provides clear survey for all the possibilities of process management on MES level.

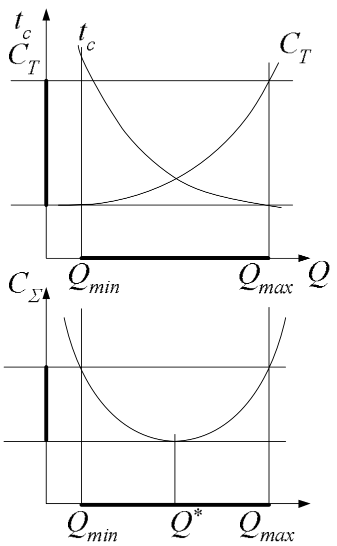

Figure 4: The feasible context of the optimal MRR

5 CONCLUSIONS

Extended CNC part program simulation promises a new effective tool for supporting the robust process planning in manufacturing industry. The intensity based management of cutting condition is a new method to find the optimum parameters when machining in variable or uncertain environments. The extended CNC simulator gives a good estimate of cutting force, which is the base of calculate manager indices on shop floor level. CNC part program variants may also be generated having different operation time, tool cost or tolerable rejects rate. Operation management at shop floor level may get enlarged decision space for supervising, control and schedule production processes.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] Barkmeyer, E., Denno, P., Feng, S., Jones, A., Wallace, E., 1999, NIST Response to MES Request for Information. NISTIR 6397, National Institute of Standards and Technology. p. 124.

[2] Tóth, T., Erdélyi, F., 1997, The Role of Optimisation and Robustness in Planning and Control of Discrete Manufacturing Processes. The 2nd CIRP World Congress on Intelligent Manufacturing, Budapest, Hungary, p. 205-210.

[3] Erdélyi, F., Hornyák, O., 2001, Simulation tools for supporting robust process planning in the field of NC turning. Proceedings of the 3rd Workshop on European Scientific and Industrial Collaboration, June: p. 27-29.

[4] Phadke, M.S., 1989, Quality Engineering Using Robust Design. Prentice Hall, Englewood Cliffs.

[5] Hornyák, O., 2002, Extended computer simulation of turning operations by means of intelligent methods, Ph.D. dissertation, (in Hungarian). p. 104.

[6] Dorf R.C., Kusiak A., 1994, Handbook of design, manufacturing and automation. John Wiley and Sons Inc, New York.

[7] Jawahir, I. S., Dillon, O. W. Jr., Balaji, A. K., Redetzky, M., Fang, N., 1998, Predictive modeling of machining performance in turning operations, Machining Science and Technology, Vol. 2(2), pp. 253-276.

[8] Van Luttervelt, C.A., Childs, T.H.C., Jawahir, I.S., Klocke, F., Venuvinod, P.K., 1998, Present situation and future trends in modeling of machining operations: progress report of the CIRP working group 'modeling of machining operations', Manufacturing Technology, Vol. 47, pp. 587-626.

[9] Tipnis, V.A., Ravignani, G.L., Mantel, S.M., 1981, Sensitivity analysis for macro-economic and micro-economic models of new manufacturing processes Annals of the CIRP, Vol. 30, p. 401.