Optimization of Cutting Conditions and Improvement of Production in Economic Terms

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***Abstract* –In order for companies to succeed in terms of a market economy, rapidly growing competition and changing customer preferences, managers have to aim their activities mainly on optimization, cost reduction, increasing production flexibility and product quality. This paper deals with problems of economic costs of individual manufacturing operations. Optimization criterion addresses the minimization of production costs. In many cases, this can be done also by a maximization of productivity**

***Keywords* – Optimization criterion, economic costs, production cost minimization, optimization potential**

1. Introduction

Production processes are considered to be the main global profit generator for enterprises. Therefore, the highest optimization potential exists in this area. Enterprises in a way provide these rationalization measures themselves, but after certain period of time they reach threshold beyond which they could jeopardize a continuity of the production and supply of finished products to own customers as they lack optimization know-how. This is also caused by insufficient data, so important for responsible and rational decision-making [11,12].

Optimization of cutting conditions (cutting depth, feed and cutting speed) should be assessed together with optimization of tool life. The optimization is preceded according to specific optimization criteria within a set of restrictive conditions (restrictions). These restrictions are given by for e.g., technical parameters of the machine, tool, machined material, by the requirements, etc.

Dependency of production costs on the cutting speed, which has its local minimum, has steeper character/progress; or more precisely curve progress at capital intensive manufacturing equipment compared with machining on conventional machines [1,2]. A similar differentiation of cutting speed to optimum cutting speed has different economic effects on both types of production facilities. The higher the initial costs of machinery, the grater the increase in production costs for the given differentiation of cutting speed compared to minimal cost.[5,6,7] Failure to respect this fact is often the cause of high production costs for capital-intensive equipment (e.g., CNC machines), as in Figure 1.

Fig. 1.: The total production costs per unit related to the tool's cutting edge durability, where: T_{opt} is optimum tool's cutting edge durability, N_{Cjmin} is the minimum total cost per unit of production, N_V are costs of clamping and workpiece measurement (labour cost per machine), N_N is tooling cost.[1,2]

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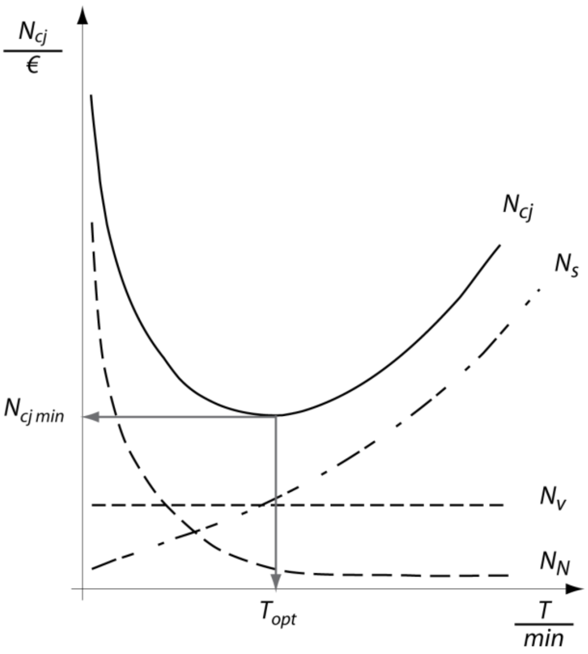

Figure 1. The dependence of production cost on cutting speed

If one considers machining process in terms of productivity, production costs are not taken into account. It is therefore appropriate to use the criterion in exceptional cases only.
Optimization of cutting conditions can be purposefully carried out by complex calculations that result in optimum values of cutting conditions and cutting edge durability. Due to complexity of the problem, a solution or the complex optimization can be practically done by the use of computer aided software/application.[3,4,5]
The less suitable solution is the optimization of cutting conditions in a gradual manner. However, this procedure can only be used under certain conditions.

In this context, it is necessary to point out that there are commercially available „universal" software solutions for such optimization, without having to enter specific data of an enterprise. But in this case it is impossible to talk about optimization. Optimization depends on specific circumstances of every company. Such software represents only basic recommendations for the deployment of cutting conditions. The actual optimum values can then be significantly different from these data.

Setup of cutting conditions is mostly done by the implementation of norms for cutting conditions. Often, the interpretation of the norm data for the optimization is not provided correctly and does not lead to truly optimum cutting conditions (to correspond to the gradual optimization method) [13].

2. Criterion of minimal production costs

The criterion of minimum production costs can be expressed in different ways. Currently, the following method is often used:

If not considering the cost items that are not dependent on the cutting conditions, the production costs for processing of a single operational section can be formulated in the following form:

$$N = N_s + N_n + N_{vn}, \tag{1}$$

where:

N – production costs for the desired operating section in €,

N_s – the cost of machine work for operating section in €,

N_n – tooling costs related to operating segment in €,

N_{vn} – replacement costs, e.g., restoration of worn tool or replacement of cutting plate (edge) related to operating section in €.

Production costs can be expressed by the following equations. The cost of machine work can be expressed as:

$$N_s = t_{As}\left[k_c \frac{M_o}{60}\left(1 + \frac{RNS_{PL}}{100}\right) + \frac{N_{hs}}{60}\right] = t_{As} N_{sm}, \tag{2}$$

where:

N_{sm} – the cost of machine work in €/min,

N_{hs} – hourly cost of machine operation in €/min,

M_o – wage of operator (worker), including social and health insurance in €/min,

RNS_{PL} – planned overhead costs of the department in %,

k_c – coefficient for shift time (typically from 1.11 to 1.15),

t_{As} – machine time in mins.

Hourly cost of machine operation can be expressed by the relation:

$$N_{hs} = O_s k_{us} + C_E \tag{3}$$

$$O_s = \frac{C_s}{Z_s CFS_{EFPL} . SM . k_{vs}} \tag{4}$$

where:

O_s – depreciation of machine €/hour,

C_s – machine price in €,

C_E – price of electricity (mean long-term average, or qualified estimation) in €/hour,

Z_s – machine's life in years,

CFS_{EFPL} - planned time machine resources in hour/year and shift,

SM – shift work (nr. of shifts),

k_{us} – machine's repair and maintenance coefficient,

k_{vs} – machine's time utilization coefficient.

Machine's time utilization coefficient (rate of the time when the machine is operating in a given number of changes to the total time of considered changes) is derived from a long-term average, eventually from the estimation of machine's capacity utilization.[17] Different types of production environment show approximate values of the coefficients (as seen in Tab. 1. for the time utilization coefficients). In some companies, the values of coefficients are lower than the values in Tab. 1.below. This fact contributes significantly to the production costs. Machine's repair and maintenance coefficient is given by the rate of sums of machine's price, estimated costs of repairs and/or maintenance over the machine lifetime, to price of the machine.

Table 1. Table of machine's time utilization coefficients

Type of production	Machine's time utilization coefficient k_{vs}
Mass and large-batch production	0,8
Programmable machine control, Machining centres	0,65 to 0,75
Conventional short-batch production	0,50 to 0,65

Tooling costs (depreciation, maintenance, eventually sharpening the tools) can be expressed in the form:

$$N_n = z_v N_{nT} \tag{5}$$

where:

N_{nT}– cost of operation related to single (one) edge durability in €,

z_v – number of tool changes related to one operating segment (mostly, the value is higher than one).

The number of tool changes z_v can be expressed as follows:

$$z_v = \frac{t_{As}}{T} k_r \, , \tag{6}$$

where:

T – cutting edge durability in minutes,

k_r – rate of actual time or the duration of machining, respectively (when the edge wear appears) and machine time or the duration of machine's automatic operation, respectively.[16]

Tooling costs related to single (one) edge durability can be expressed for different types of a tool.

For solid (single-piece sharpened) tools, the following formula is applicable:

$$N_{nT} = \frac{C_n - C_m}{z_0 + 1} + t_{os} k_c \frac{M_{os}}{60}\left(1 + \frac{RNO_{PL}}{100}\right)\frac{z_0}{z_0 + 1}\, , \tag{7}$$

where:

C_n – is price of tool in €,
C_m - redundant tool's price in €,
M_{os} – salary of the tool sharpener, including social and health insurance in €/hour,

RNO_{PL} – overhead costs of the tool sharpening department, planned yearly in %,

z_0 – number of possible tool sharpening,
t_{os}- tool's sharpening time.

For the tool with a replaceable cutting plate (plate not to be sharpened), the following formula can be applied:

$$N_{nT} = \frac{C_d z_d}{z_b s_b} + \left(1 + k_{ut}\right)\frac{C_m}{z_u}\, , \tag{8}$$

where:

C_d – is price of the edge cutting plate in €,
C_m – price of the tool body in €,
z_d – number of the edge cutting plates on the tool,
z_b – number of edges on the plate,
z_u – assumed number of cutting plate's fixing over the tool body lifetime,
s_b – utilisation factor of the edge cutting plates,
k_{ut} – tool body maintenance coefficient,

Approximate values of the empirical constants from the Equation (8) can be found in Tab. 2.for a number of fixings, factors for the utilisation of an edge cutting plates and tool body maintenance. The utilisation factor of edge cutting plates is influenced by the technological principles, cutting plate brittleness, damage of a new edge which is not in contact (by leaving chip, etc.). Assumed number of cutting plate's fixings depends on the usually accidental destruction of a tool body and on the tool body maintenance coefficient and includes mainly spare parts of the tool.

Table 2. Tabular values of coefficients for number of fixings, factors for the utilisation of edge cutting plates and tool body maintenance.

Cutting conditions	z_u	s_b	k_{ut}
Light	400 to 600 (even more)	0,95	0,05
Moderate	200 to 400	0,90	0,025
Hard	200	0,80	0,40
Very hard	100	0,70	0,60

For the tool with changeable edge cutting plates that can be sharpened, the following equation is valid:

$$N_{nT} = \frac{C_d z_d z_0}{z_b s_b (z_0+1)} + (1+k_{ut})\frac{C_m}{z_u} + t_{0s} k_c \frac{M_{0s}}{60}\left(1+\frac{RNO_{PL0}}{100}\right)\frac{z_0}{z_0+1} \quad (9)$$

where:

z_0 is the number of possible plate's sharpening.

The costs of tool replacement can be expressed in the following form:

$$N_{vn} = t_{vn}\left[k_c \frac{M_s}{60}\left(1+\frac{RNS_{PL}}{100}\right)+\frac{O_s}{60}\right] = t_{vn} N_{vnm} z_v, \quad (10)$$

where:

N_{vnm} is the cost of tool replacement in €/min,

M_s – salary of the machining worker including social and health insurance in €/hour,

t_{vn} – duration of the tool replacement in minutes.

The criterion of minimum production costs (production costs per operating section should be minimal) can be expressed from the previous Equation (10).

Substituting the above Equations (9) and (10) into the criterion of the minimum production cost, we obtain the optimization criterion in terms of minimum production costs in the following form:

$$N = t_{As} N_{sm} + \frac{t_{As}}{T} k_r N_{nT} + t_{vn} N_{vnm} \frac{t_{As}}{T} k_r = \min \quad (11)$$

$$N = t_{As} N_{sm} + \frac{t_{As}}{T} k_r \left(N_{nT} + t_{vn} N_{vnm}\right) = \min \quad (12)$$

Machine operating time is expressed as:

$$t_{As} = \frac{L}{n.f}, \quad (13)$$

where:

L - is the length of the automatic tool's path in mm,

n – rounds per minute (rpm),

f – feed rate in mm per round.

Substituting the variables into the Equation (13) and criterion from Equation (12), we obtain a criterial equation in the following form:

$$N = \frac{L}{n.f} N_{ns} + \frac{L.k_r}{n.f.T}\left(N_{nT} + t_{vn} N_{vnm}\right) = \min \quad (14)$$

After the modifications, we obtain the following equation:

$$\frac{K_1}{n.f} + \frac{K_2}{n.f.T} = \min, \quad (15)$$

where:

$$K_1 = L.N_{sm}, \quad (16)$$

$$K_2 = L.k_r\left(N_{nT} + t_{vn} N_{vnm}\right) \quad (17)$$

In milling operations, the variable parameter is considered as feed per tooth f_n instead of the feed per round f.

The overall manufacturing costs of a product can be expressed by the following equation:

$$N_c = \sum_{1}^{uu} N_i + N_v + \frac{N_b}{d} + \frac{N_{sz}}{d} \quad (18)$$

where:

N_c- is the total production costs of a workpiece in €,

N_i - production costs of the *i*-th operating section in €,

N_v – the cost of ancillary works in €,

N_b – batch costs in €,

N_{SZ} – the cost of special equipment necessary to produce aworkpiece in €,

d – number of units produced,

uu – number of operating units on the workpiece.

The cost of ancillary works can be calculated using the following equation:

$$N_v = t_{Av}\left[k_c \frac{M_o}{60}\left(1+\frac{RNS_{PL}}{100}\right)+\frac{O_s}{60}\right] = t_{Av} N_{vm}, \qquad (19)$$

where:

N_{vm} - the costs on ancillary works in €/min,

t_{Av} ancillary unit time in min.

Batch costs:

$$N_B = t_{BC}\left[k_c \frac{M_s}{60}\left(1+\frac{RNS_{PL}}{100}\right)+\frac{O_s}{60}\right] = t_{BC} N_{Bm}, \qquad (20)$$

where:

N_{Bm}- batch costs v €/min,

t_{Bc}-batch time with an extra short time in mins.

The criterion of minimum costs can be expressed the other way also. The above expression of the cost items may not be the best under the special circumstances of individual companies. The method of hourly overhead costs seems to be the most suitable.

Then alternatively, it is possible to express minute costs of machine work (operation) as follows:

$$N_{sm} = k_c \frac{M_o}{60} + \frac{HRP_{SP}}{60} + \frac{HRP_{PRA}}{60} \qquad (21)$$

where:

HRP_{SP} – hour overhead cost of common costs €/hour, €/Nh (Hh – standard hour),

HRP_{PRA} – hour overhead flat rate of a production unit (machine) in €/hour, €/Nh.

Analogically, for the minute costs on the tool replacement, the following relation can be applied:

$$N_{vmn} = k_c \frac{M_s}{60} + \frac{HRP_{SP}}{60} + \frac{HRP_{PRA}}{60} \qquad (22)$$

Presented method to express cost items requires analysis of overhead costs related to the calculation unit. This applies to the lowest organizational levels, i.e. working cell, workplace, machine, unit.

When optimizing cutting conditions, it is possible, under certain circumstances, to determine tool's edge optimum durability according to a certain optimization criteria independently from the optimization of cutting conditions.

Optimal cutting edge durability in terms of minimum production costs can be also express by other relation, as follows:

$$T_{optN} = \frac{\left(N_{nT} + t_{vn} N_{vmn}\right)}{N_{sm}} k_r (m-1) \qquad (23)$$

where:

T_{optN} – optimum durability of the edge in terms of production costs in mins.,

k_r- ratio of the relative tool path to the workpiece, while the cutting process is operating during the whole automatic tool's path,

m – Taylor's empirical constant.

Determining the optimal durability regardless of the cutting conditions leads to a simplification of cutting conditions' optimization. However, this procedure does not always lead to optimal values.

3. The criterion of maximum productivity

These days, the basic criterion for the optimization of the machining process is the economic criterion of minimum production costs. But there are also other useful criteria under special circumstances.[18]

Machining according to the criterion of maximum productivity means producing the maximum possible volumes, number of units in a defined period of time, regardless of production costs. This criterion is acceptable in exceptional cases, particularly in the case when a manufacturer is bound by a deadline from the customer with a risk of financial penalties [7,8].
Such situation however, can be solved more appropriately, for example working overtime or in cooperation with other company.
The criterion of maximum productivity can be formulated as the minimum time required for

processing a single operating section using this relation:

$$t_u = t_{As} + t_{vn} z_v, (23)$$

where:

t_u – is a duration of operating segment in mins.

After substitution of z_v and t_{As}, the criterion of maximum productivity is derived as follows:

$$t_u = \frac{L}{n.f} + \frac{L.k_r t_{vn}}{n.s.T} = \min \qquad (24)$$

After modifications are performed, the criterion ofmaximum productivity can be adjusted or expressed as the criterion of minimum production costs as follows:

$$t_u = \frac{K_3}{n.f} + \frac{K_4}{n.f.T} = \min \qquad (25)$$

where:

$K_3 = L,$ (26)

$K_4 = L.k_r.t_{vn}.$ (27)

From the mathematical point of view, the criterion of maximum productivity is consistent with the criterion of minimum production costs. This allows optimization of cutting conditions from a mathematical point of view using both criteria the same way.

4. Criterion of the maximum material removal

Criterion of maximum material removal is often confused with the criterion of maximum productivity. But these two are completely different in principle.
When optimizing cutting conditions under special circumstances, it is possible to determine tool's edge optimum durability according to special optimization criterion independently from optimization of cutting conditions. Thus, for example when the optimization of cutting conditions is based on the optimum edge durability determined for maximum productivity criterion, then the criterion of maximum material removal is consistent with the criterion of maximum productivity.[9,10]
These facts can be used to simplify the optimization of cutting conditions by the criterion of minimum production costs and maximum productivity while assuring specific conditions. Here we are using gradual method for setting optimum cutting conditions.
The criterion of maximum material removal can be mathematically expressed in the following form:

$$U = a_p.f.v_c = \min , \qquad (28)$$

where:

U – is material removal in cm^3/min.,
v_c– cutting speed v cm/min.,
a_p – cutting depth v mm.

Cutting speed can then be expressed as a function of rounds:

$$v_c = \frac{\pi.D_n.n}{10^3}, \qquad (29)$$

where:

D_n– is a diameter of the workpiece or tool v *mm.*

Substituting this relation into Equation (28), the criterion of maximum material removal can be expressed in the following form:

$$U = 10^3 D_n \pi.a_p.f.n = \min \qquad (30)$$

As optimization of cutting conditions is usually based on the given cutting depth, the criterion of maximum material removal can then be expressed in the following form:

$$n.f = \min \qquad (31)$$

Incorrect view that the criterion of maximum material removal is consistent with the criterion of maximum productivity can be seen by comparison of the two criterial Equations (25) and (31). The criterion of maximum productivity includes duration of the tool replacement procedure. If the criterion of maximum material removal without restrictions is fulfilled, it is clear that production would be practically zero (0), taking in mind that e.g. in high cutting speeds (theoretically infinitely large), the tool's edge is destroyed immediately after the cutting starts and needs to be replaced many times [14,15].

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5. Conclusion

Economics and optimization of the production, new modern industrial machinery equipment, new manufacturing fixtures and new technologies have nowadays increasingly wider application in the manufacturing and the industry. All the relatively new technologies appeared in the second half of 20. century, however, new technologies appear every day. This fact demonstrates that their potential is far from being exhausted. The technologies are becoming dominant where there are high requirements on dimensional accuracy as well as satisfying the requirements on modern automation, energy, environmental and especially economic requirements.

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