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An integrated cost model for metal cutting operations based on engagement time and a cost breakdown approach

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Abstract: In all manufacturing processes, it is important to determine the costs and their distribution between different sequential processing steps. A cost equation based directly on the losses during manufacturing, such as rejection rate, stops and waste of workpiece materials, also provides a valuable aid in giving priority to various development activities and investments. The present work concerns how a cost model presented earlier for calculating part costs can be developed to describe part costs as a function of the cutting data and tool life time T selected. This enables a tool life model to be a directly integrated into the cost model by use of tool engagement time. The model presented also takes into account the part costs for scrap incurred in connection with forced tool changes. Examples are also given of how the model developed can be used in the economic evaluation of various cutting tools and workpiece materials.

Keywords: cost model; cost breakdown approach; metal cutting; Colding equation; tool life; cutting data.

Biographical notes: Jan-Eric Ståhl received his PhD from Lund University Sweden in 1986 in Metal Cutting. He was appointed as an Associate Professor and Full Professor at the Department of Mechanical Engineering, Lund University, Sweden in 1987 and 1990, respectively. He has been working in education and research in the area of production and materials engineering for more than 30 years. He was the Director of Educational Programs at the Faculty of Engineering and Vice Dean at the respective faculty responsible for the industrial connection. He initiated and started up the Swedish Production Academy in 2006.

1 Introduction

In discrete production, part costs are inversely related to the firm's ability to compete. Models for computing the costs of a part can be described for different hierarchic levels and in differing detail. Macroeconomic models used at a system level for determining retrospectively what the costs of manufacturing a given component have been can be rather exact. It is much more difficult to predict the costs in advance, particularly when different variables or parameters of relevance are unknown or vary statistically. Precise cost computations are also more difficult to achieve when variables of central importance, such as cycle time, rejection level and downtime rate, are partly dependent upon one another. Comprehensive economic models usually make use of aggregated data, without distinguishing between the value-added and non-value-added time consumed. Economic models can also involve detailed cost computations regarding the processing carried out. Such models, referred to as microeconomic or cost-breakdown models, tend to be concerned directly with the manufacturing process in question. Differences between microeconomic and macroeconomic models in the account they provide of the production of a component have been dealt with earlier by Tipnis et al. (1981). The present author (Ståhl, 2005; Ståhl et al., 2007) has also presented a cost-breakdown model of this at a system level, one that has been employed and implemented by many others, such as Jönsson (2012), who also analysed a number of other cost models described in the literature, the results he arrived at being shown in Table 1. Microeconomic models have also been presented, for example, by Colding (1978), Alberti et al. (1985) and Ravignani and Semeraro (1980). Such models can be used, in connection with metal cutting, to describe the relationship between cutting data, tool lifetime, and processing costs. Models of this sort usually do not include costs of rejections and downtimes, but do include costs of changing the tool or workpiece. In the present study, an integrated cost model including both loss terms (so-called q-parameters) and a complete model of the lifetime of metal-cutting tools is introduced, one that is restricted to cutting operations and concerns primarily turning operations. It is based upon the same principles as those of a model developed by the author earlier (Ståhl, 2005). A comparable model concerning the costs a given surface requirement concerning the R_a-values would entail has been reported by Schultheiss et al. (2016).

In the present study, the Swedish currency (SEK) is used in all examples, but the model is generic and is independent of the currency unit selected.

Table 1 A summary of models presented in the literature

	Present study	*Ståhl, (2016), Ståhl et al., (2007)*	*Ravignani et al. (1980)*	*Alberti et al. (1985)*	*Colding (1978)*	*Koltai et al. (2000)*	*Özbayrak et al. (2004)*	*Aderoba (1997)*	*Dhavale (1990)*	*Yamashina and Kubo (2002)*	*Son (1991)*	*Chiadamrong (2003)*	*Cauchick-Miguel et al. (1996)*	*Branker et al. (2011)*	*Noto La Diega et al. (1993)*	*Needy et al. (1998)*
Parameters								*System level*								
Material	x	x	x	x	x		x		x	x	x	x	x	x		
Labor	x	x		x	x		x	x	x^1	x	x	x	x	x		x
Machine depreciation						x^1	x^1	x	x	x	x		x	x^1	x^1	x^3
Machine cost	x	x	x	x	x											
Floor space	x	x					x^1	x	x		x		x			
Utilities (e.g., energy)	x	x					x^1	x	x^1	x	x	x	x^1	x		
Tool cost	x	x	x		x	x	x	x^1	x^1	x	x		x	x	x	
Maintenance	x	x				x^1	x^1	x^1	x^1	x	x	x	x^1	x^1		
Repairs	x	x						x^1			x	x^1				
Material handling	x	x				x	x		x^1			x		x	x^1	x
Computer							x^1		x^1		x			x^1	x^1	
Inventory	x	x	x		x	x	x		x^1		x					
Quality: prevention												x^2				
Quality: appraisal						x^1				x	x	x	x			
Quality: failure (scrap)	x	x			x		x^2			x	x	x				
Reworking	x	x	x				x^2				x	x	x^1			
Downtime	x	x					x^2			x		x^1				
Speed loss	x	x								x						
Setup	x	x			x	x	x			x	x	x	x	x		x
Waiting	x	x					x	x^1			x	x				
Idling	x	x									x	x			x	
Environmental														x		
Parameters			*Process level*													
Cycle time	x	x	x	x	x											
Tool engagement time	x		x	x	x											
Idling in cycle	x			x	x											
Cutting data	x		x	x	x											
Tool life	x		x	x	x											

Note: [1]Included, but not as a separate parameter. [2]Mentioned as considered, but the equation is not presented in the paper. [3]The cost is expressed as a leasing cost.

Source: As modified by Jönsson (2012)

2 The metal-cutting process and how the cycle time is produced

A particular cycle time is needed in order to process a component in the manner shown in Figure 1. The cycle time t_0 can be obtained as the sum of the engagement time t_e, of the remaining time t_{rem}, the latter concerning the movement of the tool associated with non-value-added time, and of the time needed for change of the workpiece and of the tool T_{tct}.

$$t_0 = t_e + t_{rem} + t_{tct} = t_e + t_{rem} + \frac{t_e}{T} \cdot t_{tct} \quad (1)$$

where T is the tool lifetime selected and T_{tct} is the time taken for tool change, t_{tct} being the contribution of the workpiece to the time required for tool change. An alternative way of describing the time needed for tool change is to treat it as being a downtime. It can nevertheless be practical, if the time per workpiece needed for tool change is short, to consider it to be part of the added-value time. The engagement time t_e is then the added-value time, and the remaining time t_{rem} can be regarded as the loss in time that occurs in processing, a loss that is unavoidable due to the nature of added-value processing.

Figure 1 Longitudinal turning in principle

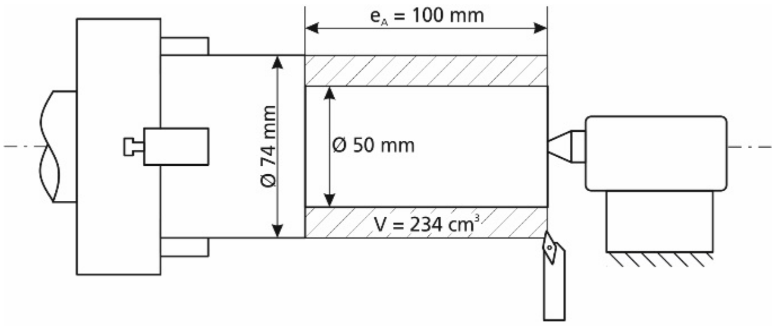
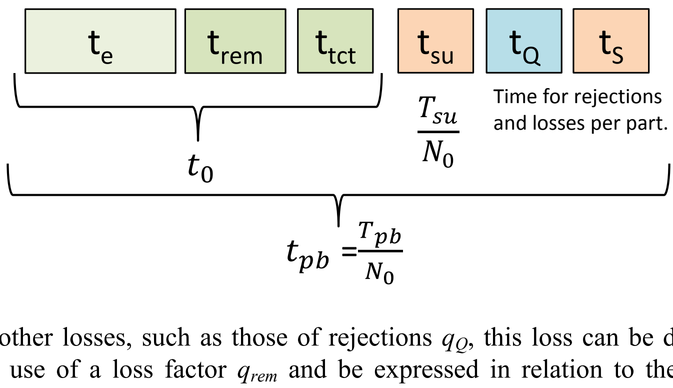


Figure 2 The individual times that lead to the total manufacturing time per part



Just as with other losses, such as those of rejections q_Q, this loss can be dealt with and described by use of a loss factor q_{rem} and be expressed in relation to the value-added engagement time t_i as shown in equation (2).

$$q_{rem} = \frac{t_{rem}}{t_e + t_{rem}} \tag{2}$$

The loss term q_{tct} for tool change can be described in a similar way in regard to the engagement time and the additional time that tool change brings about as:

$$q_{tct} = \frac{t_{tct}}{t_e + t_{rem} + t_{tct}} \tag{3}$$

where the average tool change time t_{tct} per part can be computed as:

$$t_{tct} = \frac{t_e}{T} \cdot T_{tct} \tag{4}$$

The cycle time t_0 can then be expressed, with the help of the loss terms q_{rem} and q_{tct}, as:

$$t_0 = \frac{t_e}{\left(1 - q_{rem}\right) \cdot \left(1 - q_{tct}\right)} \tag{5}$$

The additional time t_{rem} is strongly dependent upon the preparations made, whereas the tool change time T_{tct} depends more upon the manner of working and the machine characteristics. The production time T_{pb} for a batch of N_0 parts, as shown in Ståhl (2005), can be computed using equation (6), which takes account of the rejection rate q_Q and the downtime rate q_S.

$$T_{pb} = T_{su} + \frac{t_0 \cdot N_0}{\left(1 - q_Q\right) \cdot \left(1 - q_s\right)} \tag{6}$$

Use of the loss terms in equation (5) enables the cycle times in equation (6) to be expressed, in equation (7), with the help of the engagement time t_e.

$$T_{pb} = T_{su} + \frac{t_e \cdot N_0}{\left(1 - q_{rem}\right) \cdot \left(1 - q_{tct}\right) \cdot \left(1 - q_Q\right) \cdot \left(1 - q_s\right)} \tag{7}$$

The formalism above agrees with the principle developed by the author earlier (Ståhl, 2005; Ståhl et al., 2007) for dealing with losses (q-parameters) associated with the cycle time.

The engagement time t_e is determined by the cutting data selected (v_c, f, a_p) and by the volume of work material V to be removed. It can be computed using equation (8) or equation (9), where e_A is the axial distance involved.

$$t_e = \frac{V}{v_c \cdot f \cdot a_p} \tag{8}$$

$$t_{e,A} = \frac{e_A}{f \cdot N} = \frac{e_A \cdot \pi \cdot D \cdot 10^{-3}}{f \cdot v_c} \tag{9}$$

The time per part produced t_{pb} can be computed by dividing equation (7) by the series length N_0 using equation (10).

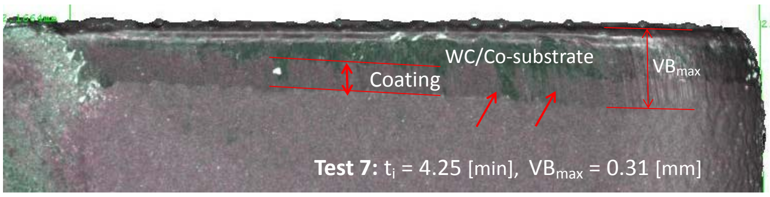
$$t_{pb} = \frac{t_{pb}}{N_0} = \frac{t_{su}}{N_0} + \frac{t_e}{\left(1-q_{rem}\right)\cdot\left(1-q_{tct}\right)\cdot\left(1-q_Q\right)\cdot\left(1-q_s\right)} \tag{10}$$

In this case the engagement time t_e rather than the cycle time t_0 serves as the primary basis for the computations carried out.

3 Tool life and tool life models

The lifetime T of a cutting tool is determined by the tool's characteristics, as well as by the work material, the cutting data and the types of operations involved, as well as by the tool lifetime criterion employed. One tends to distinguish between a wear-based model and a lifetime model. A wear-based model describes how the speed with which the tool is worn down changes as a function of time and of other process data. A tool lifetime model describes the total engagement time t_i up to a predetermined total tool lifetime, for example such that VB = 0.30 mm under the processing conditions present (cutting data).

Figure 3 Example of a tool lifetime criterion of VB = 0.3 mm



3.1 Colding equation

The tool lifetime T can be modelled in a variety of ways. The model most frequently employed is an extension of the Taylor model, an 'extended Taylor'. It involves use of four constants. Colding's equation usually functions somewhat better than an 'Extended Taylor', which in its most usual form has five constants. Colding's equation describes, for an application having a predetermined tool lifetime criterion, the relationship between the cutting speed v_c and both the equivalent chip thickness he and the tool lifetime T. It is based on Woxén's (1932) assumption that for a given equivalent chip thickness he the tool lifetime T is always the same. Colding's (1982) equation is presented here as equation (11).

$$v_c = \exp\left[K - \frac{\left(\ln\left(h_e\right)-H\right)^2}{4\cdot M} - \left(N0 - L\cdot ln\left(h_e\right)\cdot\right)ln(T)\right] \tag{11}$$

where K, H, M, N_0 and L are Colding's constants. The equivalent chip thickness h_e can be computed in terms of Woxén's approximation using equation (12).

$$h_e = \frac{A_W}{l_W} = \frac{a_p\cdot f}{\frac{a_p - r_\varepsilon(1-\cos\kappa)}{\sin\kappa} + \kappa\cdot r_\varepsilon + \frac{f}{2}} \tag{12}$$

Use of the equivalent chip thickness h_e is advantageous in its combining four separate parameters to form a single one. According to Woxén (1932) and as also shown in many practical cases, a given equivalent chip thickness is associated with a given tool lifetime T. It is also possible to express Colding's equation in a way such that the tool lifetime T is obtained as a function of v_c and h_e in a given application.

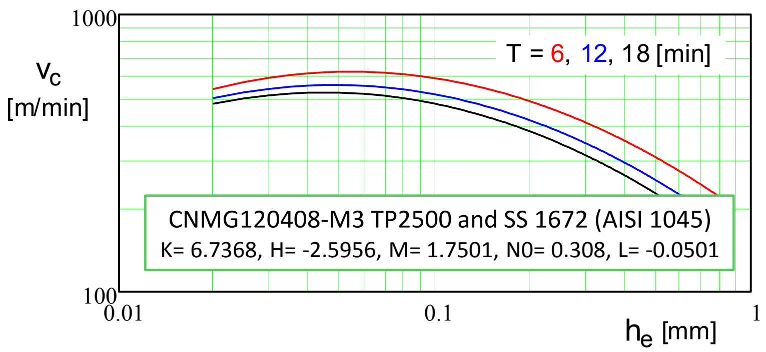
$$T = e - \frac{H^2 - 2 \cdot H \cdot ln(h_e) + ln(h_e)^2 - 4 \cdot K \cdot M + 4 \cdot M(v_c)}{4 \cdot M(N_0 - L \cdot ln(h_e))} \tag{13}$$

The engagement time t_e, and thus the associated loss terms as well, are dependent upon the parameters T, v_c and h_e. The additional parameters needed to compute h_e are the indirect variables, as they are called.

The tool lifetime in terms of Colding's equation can be expressed indirectly as a function of the variables connected with the equivalent chip thickness, i.e., $h_e = h_e(f, a_p, r_\varepsilon, \kappa)$. In Figure 4, the tool lifetime T is shown as a function of the cutting speed v_c as computed for various feeding levels f or h_e levels when the remaining parameters are held constant ($a_p = 4$ [mm], $r_\varepsilon = 0.8$ [mm] och $\kappa = 95^o$), which true as well in the additional examples taken up.

Examples of the use of Coldings equation, which describes the relationship between the cutting speed v_c and the equivalent chip thickness h_e for a given tool lifetime are shown in Figure 4.

Figure 4 An example of a graph describing the Colding-plane for a particular application, that of the combination of v_c and h_e for a given tool lifetime T



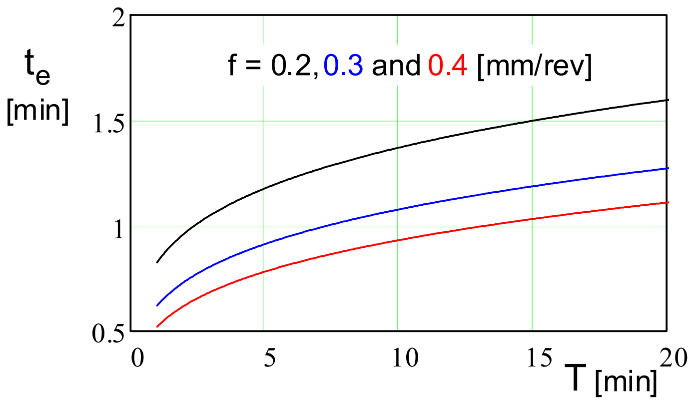
3.2 *Number of workpieces per edge*

The number of workpieces N_{wt} that the edge of a cutting tool is able to process can be computed by dividing the lifetime T of the tool by the total intervention t_e.

$$N_{wt} = \frac{T}{t_e} \tag{14}$$

One often attempts to select the cutting data in such a way that a change in the cutting tool and in the workpiece take place at the same time, i.e., that the next-lower whole number N_{wt} for the latter is selected. In Figure 5, the relationship between the intervention time t_e in equation (8) and the tool lifetime T for each of three different feeding rates f for a given chip volume V = 500 cm^3 is shown.

Figure 5 Examples of the relationship between intervention time t_e and tool lifetime T for three different feeding rates f selected, for a chip removal volume of V = 500 cm^3

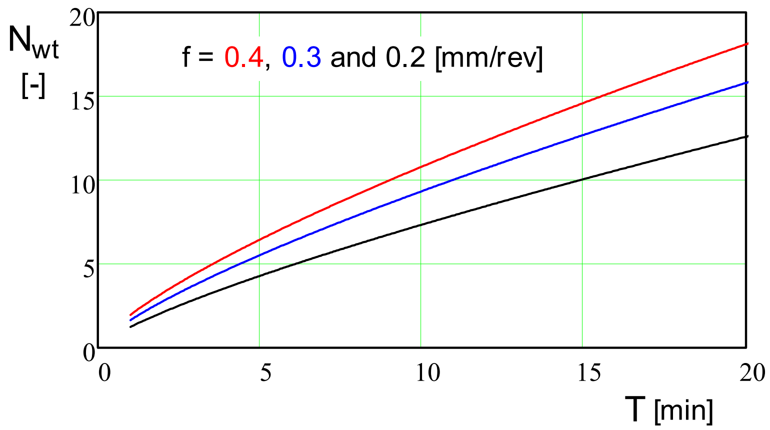


The number of tool changes needed for processing a batch of size N_0 can be computed as:

$$n_{tcb} = \frac{t_e \cdot N_0}{T} \tag{15}$$

where N_0 is the batch size. This is not to be confused with Colding's constant *N*0.

Figure 6 Examples of the numbers of parts N_{wt} able to be produced with use of cutting edges of differing tool lifetime T for each of three different feeding rates f at V = 500 cm^3



3.3 *Rejections related to tool changes*

A non-negligible rejection rate can often be noted in conjunction with tool change. It is not unusual for some 50% of the rejections to occur when the switchover takes place, the remainder of them occurring soon after the new tool has been installed. The reasons for rejection vary, some of the primary reasons being the following:

- Locational errors due to varying degrees of wear, to the cutting forces thus produced, and to difficulties in finding the correct reference position in the coordinate system. Problems of this sort are accentuated in connection with non-stiff fixturing
- Changes in size and form of the cutting tool and the edge radius of it, a problem that is accentuated when little variation in this respect can be tolerated.
- Inadequate routines for tool change.

In a linear model the number of parts rejected in connection with a tool change can be computed as:

$$N_{Qtcb} = P_{Qtc} \frac{t_e \cdot N_0}{T} \tag{16}$$

where p_{Qtc} is the number of parts rejected, or the probability of rejection of a given part, when tool change takes place. For p_{Qtc} = 1.0 a part is rejected at each tool change, whereas for p_{Qtc} = 0.25 a part is rejected when 4 tool changes take place, etc. The value of p_{Qtc} can thus be greater than 1.0.

Figure 7 Number of parts in a batch rejected in connection with tool change N_{Qtcb}, shown for differing probabilities p_{Qtc} as a function of the tool lifetime selected

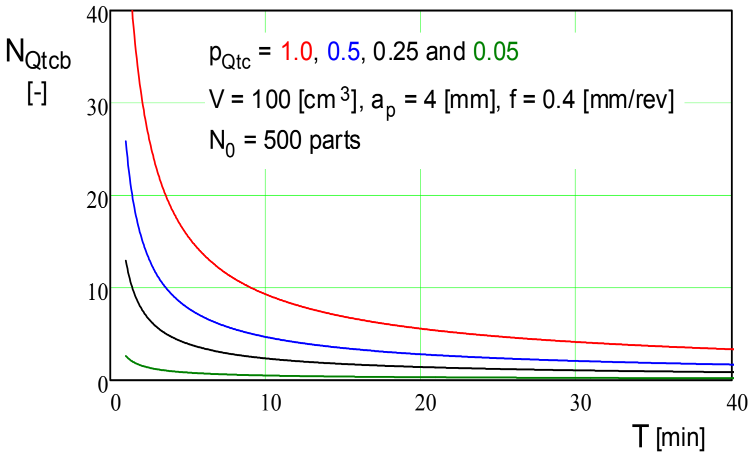
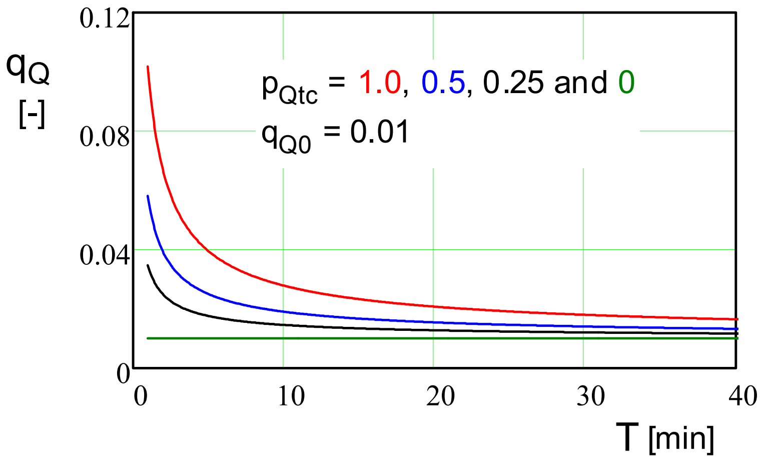


Figure 8 exemplifies how the rejection level q_Q is affected by the tool lifetime T selected, shown for different rejection rates in connection with tool change p_{Qtc}.

Figure 8 Examples of different rejection levels q_Q, account being taken of rejections in connection with tool changes



The value of N_{Qtcb} represents a portion of the traditional q_Q rejection rate value. If one assumes that q_{Q0} represents causes of rejection in addition to that of tool change (Ståhl, 2005; Ståhl et al., 2007), the rate of tool rejection as a whole can be described as:

$$q_Q = \frac{N_{Qctb} + \frac{qQ_0}{1 - qQ_0} \cdot N_0}{N_{Qctb} + \frac{N_0}{1 - qQ_0}} \tag{17}$$

The part rejection rate q_Q is directly or indirectly dependent upon the number of different parameters as follows:

$$q_Q = q_Q\big(\underbrace{f, a_p, r_\varepsilon, \kappa,}_{h_e} \underbrace{T, V,}_{t_e \rightarrow} \underbrace{N_0, P_{Qtc}}_{N_{Qtcb}}\big) \tag{18}$$

3.4 *Time for manufacturing a batch of size N_0*

For a particular rejection rate, as specified in equation (17), the production time per component t_{pb} can be computed with use of equation (10) shown earlier. Figure 9 illustrates that when rejection occurs in connection with tool change the effect of tool lifetime upon the time needed to produce a component is reduced. The minimal production time per part, or the maximal production rate, is then no longer as extreme compared to the microeconomic models.

Figure 9 Production time for a component t_{pb} in batch production involving a series size of N_0, shown as a function of the tool lifetime T selected

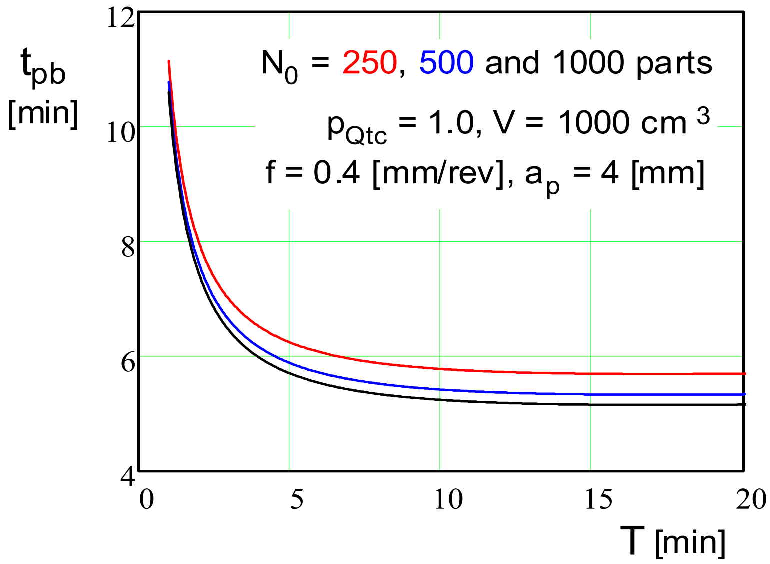
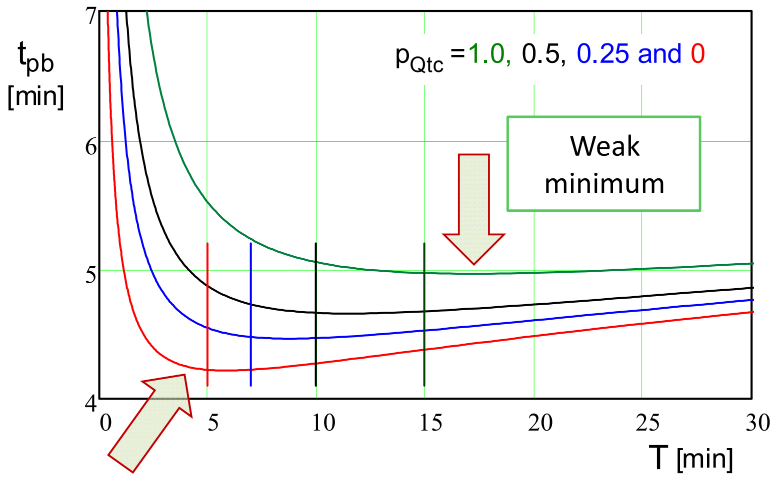


Figure 10 The production times t_{pb} associated with different rejection rates p_{Qtc} during tool change, which results in the minimal part-manufacturing time being displaced in the direction of higher values of T



4 Integrated part cost model

The costs per part can be described, as shown below, in a manner similar to that involved in the standard model (Ståhl, 2005; Ståhl et al., 2007). The difference is that here the technical cutting arrangements are fully integrated, i.e., that the macro-model takes account of all the loss terms associated with the cycle time t_0, account also being taken of relations between the cutting process and the overall rejection rate q_Q.

The cost of producing a component consists of a variety of different elements:

- tool costs per component K_A
- alongside the cost for the workpiece material k_B, the costs of workpiece material per rejected part, K_{BQ}
- machine costs during production per component, K_{CP}
- machine costs during downtimes per component, K_{CS}
- Direct costs for personnel per component, K_D.

4.1 Tool costs per part

Tool costs per component can be computed using equation (19) below.

$$K_A = \frac{K_A}{z} \cdot \frac{t_e}{T \cdot (1 - q_Q)} \tag{19}$$

where k_A is the tool costs and z is the number of cutting edges that can be used in the cutting tool, z not needing to be a whole number, since it can represent an expected average over a given period of time. It is important to also consider the tool cost for manufacturing of rejected parts by included the term for quality utilisation ($1–q_Q$).

4.2 Costs of workpiece material in rejected parts

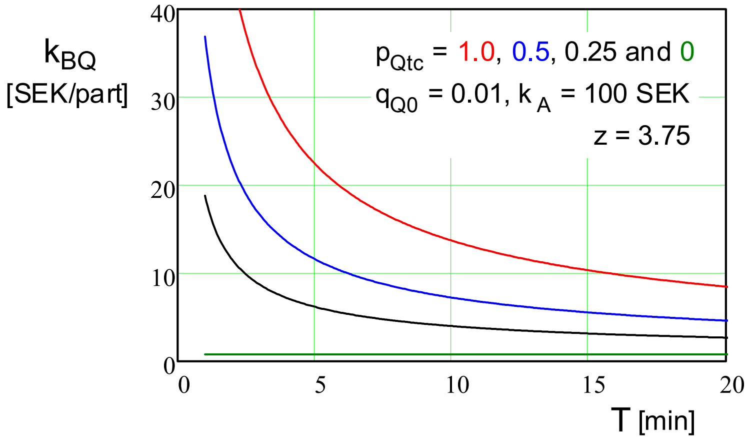
The costs of workpiece material for rejected parts can be computed using equation (20) below.

$$K_{BQ} = \frac{k_B}{(1 - q_Q)(1 - q_B)} - k_B \tag{20}$$

Since k_B is the cost of work material, subtraction of it enables the rejection costs of it (for $q_Q \neq 0$) and the material waste (for $q_B \neq 0$) to be computed. That approach is appropriate for following changes in added value over a series of production steps or operations. Otherwise, if k_B is not subtracted, the material costs computed at a later processing stage can turn out to be far too high, so that the precision of the results is lost. If rejection occurs in connection with tool change, the value of q_Q can be computed by use of the earlier equation (17).

In view of the rejection rate q_Q being dependent upon the number of tool changes that occur, the rejection costs can be seen to also be dependent upon the tool lifetime T selected, and in this way to also be indirectly dependent upon the cutting data selected. This relationship is exemplified in Figure 11.

Figure 11 Examples of the rejection costs k_{BQ} in connection with tool change being a function of the tool lifetime T selected, shown for different rejection rates p_{Qtc}



4.3 Machine costs per part

Machine costs per component can be computed using equation (21) below, provided the machine costs per hour kCP are known.

$$K_{CP} = \frac{k_{CP}}{60} \cdot \frac{t_e}{(1-q_{rem}) \cdot (1-q_{tct}) \cdot (1-q_Q)} \qquad (21)$$

where k_{CP} are the machine costs per hour during production, expressed as SEK/hr, which can be computed with use of the annuity method (Ståhl, 2005; Ståhl et al., 2007).

4.4 Costs per part of time losses

The downtime costs per purchased and approved part can be computed using equation (22). If the hourly machine costs during the downtime K_{CS} are known, k_{cs} can be computed through use of an annuity method (Ståhl, 2005; Ståhl et al., 2007).

$$K_{cs} = \frac{k_{cs}}{60} \cdot \left(\frac{t_e \cdot q_s}{(1-q_{rem}) \cdot (1-q_{tct}) \cdot (1-q_Q) \cdot (1-q_s)} + \frac{T_{su}}{N_0} \right) \qquad (22)$$

4.5 Personnel costs per part

Direct costs for personnel can be computed using equation (23) below. It is assumed here that the operator who adjusts the machine is the same one who normally drives it.

$$K_D = \frac{K_D \cdot n_{op}}{60} \cdot \left(\frac{t_e}{(1-q_{rem}) \cdot (1-q_{tct}) \cdot (1-q_Q) \cdot (1-q_s)} + \frac{T_{su}}{N_0} \right) \qquad (23)$$

where k_D is the salary costs in SEK/hr and n_{op} is the number of operators connected with the production segment in question. Dividing the result obtained by 60 is done to harmonise salary k_D per hr. with the cycle time t_0 in minutes.

4.6 Total direct costs per part

Summing the results for equation (19)–equation (23) enables the direct costs per component to be computed using equation (24).

$$k = K_A + K_B + K_{CP} + K_{CS} + K_D \tag{24}$$

One can note that a large number of parameters or variables are involved in computing the part costs as a whole using equation (24). There are more than 35 parameters altogether that influence in a direct or indirect way the costs of manufacturing a component. The list below presents the most important parameters. The bottom row presents the parameters that are indirectly involved.

In Figure 12, one can note that an increase in the probability of rejection P_{Qct} during tool change leads to a reduction in the clarity of what tool lifetime is optimal and to an ever higher value for the tool lifetime T appearing best.

If both the production costs k in terms of equation (24) and the production time t_{pb} in terms of equation (10) are known, cost graph Hägglund (2013) can be constructed in line with Figure 14. Hägglunds original graph takes account of the q-parameters q_{rem} and q_{tct} but not of loss terms for rejections or downtimes.

In Figure 14, a linear rise in equipment and personnel costs (blue line) can be noted, that can be computed using equation (25).

$$k_c = \frac{\left(k_{cp} \cdot (1 - q_s) + k_{cs} \cdot q_s + n_{op} \cdot k_D\right) \cdot t}{60} \tag{25}$$

Figure 15 illustrates how costs of producing a component vary with cutting speed for different values of p_{Qtc} during tool change.

Figure 12 Examples of the part costs k involved in SEK/part for different values of p_{Qct}, shown as a function of tool lifetime T

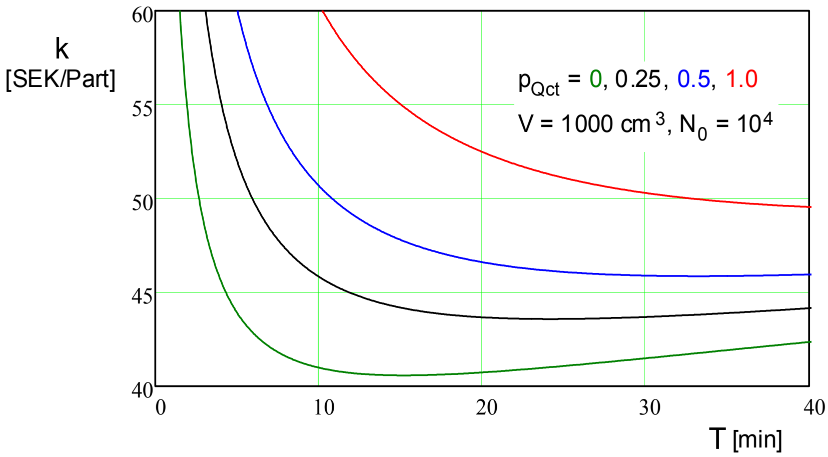


Figure 13 Production time t_{pb} shown as a function of cutting speed v_c for different rejection rates p_{Qtc} during tool changes, where the point of minimum t_{pb} value is displaced toward lower v_c values as P_{Qtc} increases

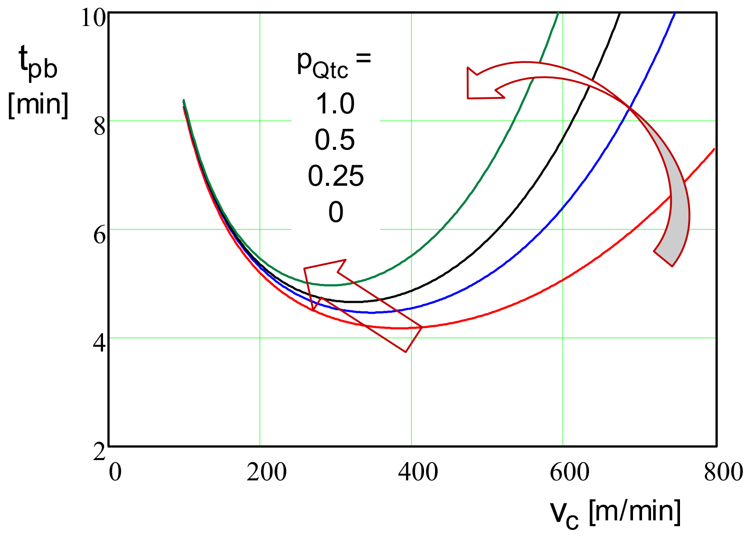


Figure 14 Part costs and tool costs shown as a function of production time t_{pb}, increasing the feeding rate, if conditions permit, leading to shorter production times and lower costs

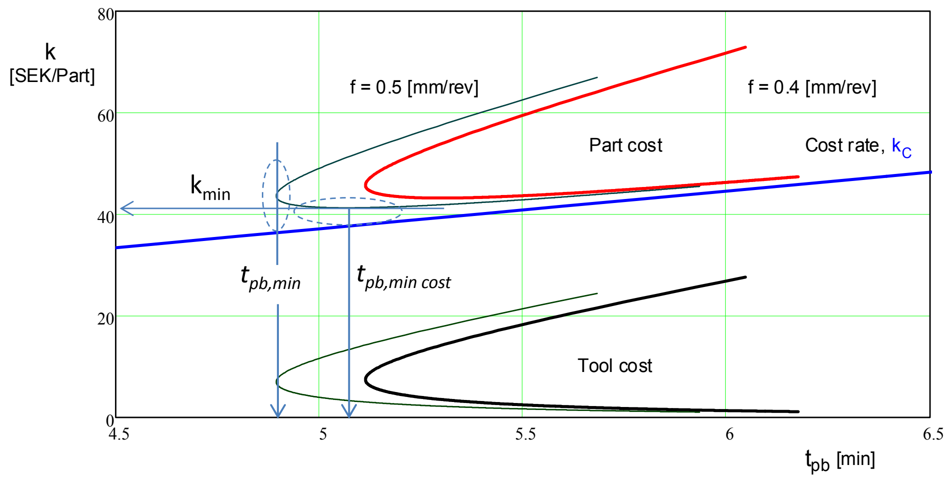


Figure 15 Examples of part costs k shown as a function of cutting speed v_c for different rejection rates p_{Qtc} during tool change

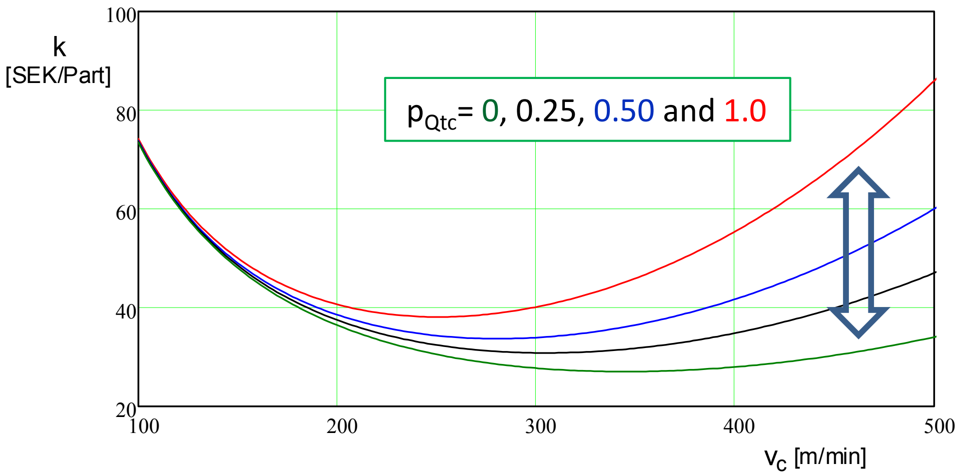
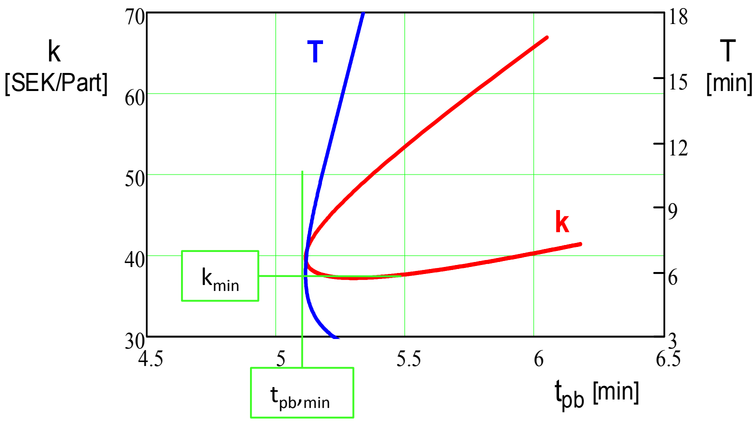


Figure 16 Part costs k and tool lifetime T shown as a function of production time t_{pb}



5 Machining costs per cubic centimetre of workpiece material

Dividing the part costs k by V, the volume of material removed, enables the material removal costs kcm^3 to be computed in terms of SEK/cm^3 using equation (26).

$$kcm^3 = \frac{k}{V} \tag{26}$$

Figure 17 Material removal costs k_{dm3} expressed as SEK/dm^3 for V = 1.0 dm^3, shown as a function of tool lifetime T for each of three different feeding rates

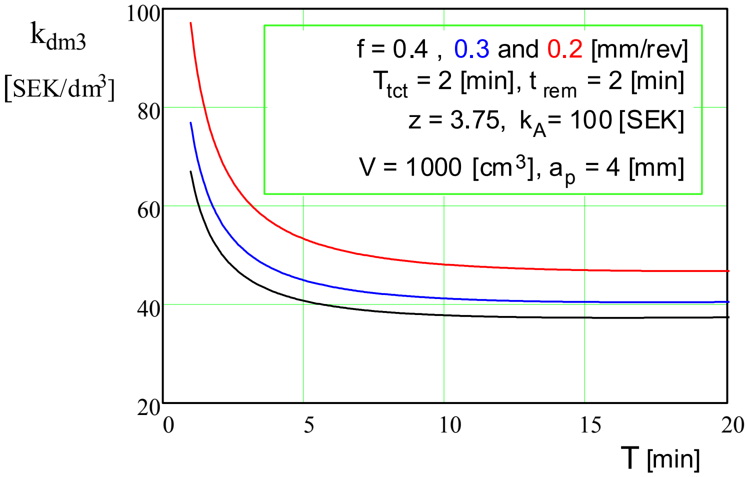
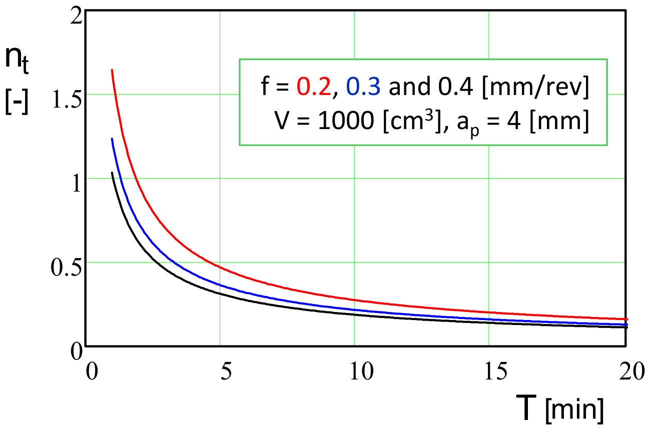


Figure 18 The number of cutting tools (cutting edges) needed for the removal of V = 1.0 dm^3, shown as a function of the tool lifetime T selected



The number of cutting edges or the parts of these consumed in the removal of a given volume of material can be computed using equation (27), The number of components that can be produced per cutting edge N_{wt} can be computed using equation (14).

$$n_t = \frac{1}{N_{wt}} = \frac{t_e}{T} \quad (27)$$

Results obtained by use of equation (26) and equation (27) are exemplified in Figure 17 and Figure 18, respectively.

6 Relations of part costs to variations in machinability

Cutting data that appear promising do not always result in the tool lifetime T that was aimed at. This can lead to a loss in tempo q_P, involving a discrepancy between the nominal or recommended data and the actual cutting data used in the application at hand.

6.1 Differentiation of the Colding equation

One possibility for describing such a situation is to differentiate Colding's equation with regard to the relatively strong constant K that the equation contains. This enables one to create a new and more adequate tool lifetime model.

Such a differentiation of Colding's model can be based on use of equation (28).

$$\Delta T = \frac{dT}{dK} \cdot \Delta K \tag{28}$$

where ΔK is the change in Colding's constant K corresponding to the error in the tool lifetime ΔT. If the tool lifetime turns out to be 3 minutes shorter than was expected, one lets $\Delta T = -3$ minutes.

Rewriting equation (28) results in ΔK having the value of

$$\Delta K = \frac{\Delta T}{\frac{dT}{dK}} \tag{29}$$

A derivation of Colding's equation (13) with regard to K results in:

$$\frac{dT}{dK} = e - \frac{H^2 - 2 \cdot H \cdot ln(h_e) + ln(h_e)^2 - 4 \cdot K \cdot M + 4 \cdot M \cdot ln(v_C)}{\frac{4 \cdot M \left(N0 - L \cdot ln(h_e)\right)}{N0 - L \cdot ln(h_e)}} \tag{30}$$

Use of the differentiation that equation (30) provides enables ΔK to be computed. Inserting it in equation (13) yields the following:

$$T = e - \frac{H^2 - 2 \cdot H \cdot ln(h_e) + ln(h_e)^2 - 4 \cdot (K + \Delta K) \cdot M + 4 \cdot M \cdot ln(v_c)}{4 \cdot M \cdot \left(N0 - L \cdot ln(h_e)\right)} \tag{31}$$

In the present case, in which ΔT = –3 minutes and dT/dK = 48.67, one obtains ΔK = –0.062. This results in a reduction in the cutting speed v_c of abt. 20 m/min in connection with obtaining a tool lifetime of T = 12 minutes. Changes in machinability, described as ΔK, are reported in Figure 19.

Figure 19 Adjusting the cutting speed by ΔK in order to obtain a tool lifetime of 12 minutes

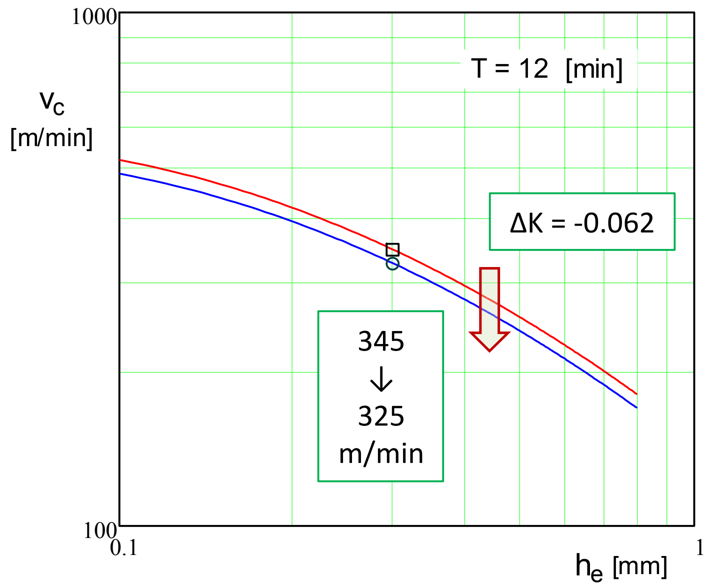
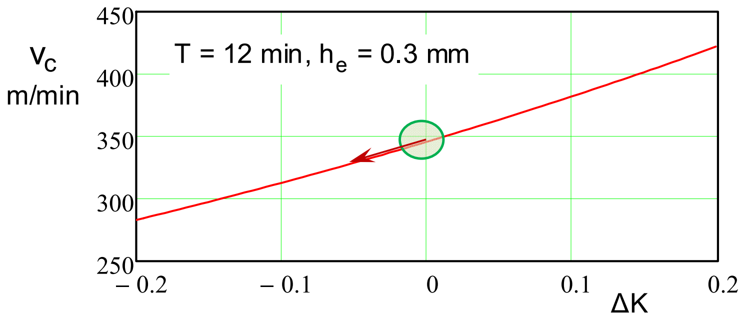


Figure 20 An example of the relationship between the cutting speed and ΔK used for obtaining a tool lifetime of $T = 12$ min



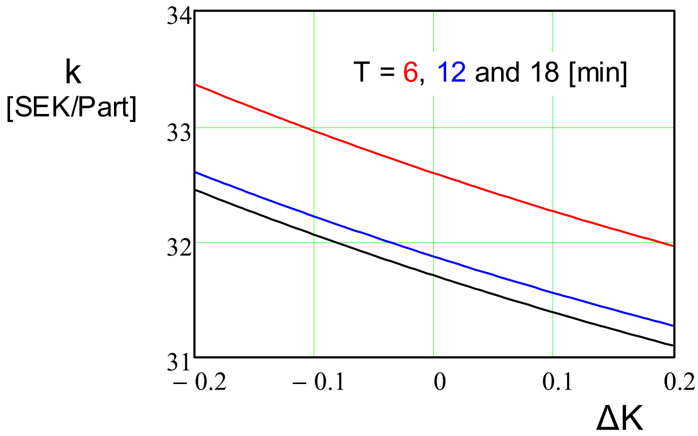
6.2 Relations of part costs to variations in machinability

Manufacturing costs are affected by variations in machinability. Calibration of the lifetime of a tool by use of particular cutting data can be achieved by introducing the parameter ΔK through use of equation (29). The example above, linked to Figure 19 and Figure 20, involved correcting the value of the cutting speed v_c, which is done quite frequently in cases in which there is wear without such further complications as tool failure or damage to the cutting edge. It is also possible to correct other constants in Colding's equation, such as the H-constant or $N0$.

Faced with a case like that described above, there are two differing experimentally anchored approaches that can be used, the one involving changes in cutting speed and the other changes in the equivalent chip thickness he (primarily through changes in the feeding rate *f*) with the aim of achieving a particular tool lifetime. It could be appropriate here to use ΔK in combination with ΔH, for example.

Measuring machinability while taking account of the tool lifetime though use of the parameter ΔK enables *k*, the costs per component, to be computed. At the same time, a cost increase Δk due to a reduction in machinability would be independent of the tool lifetime *T* selected, since *T* is a variable in Colding's equation and both *K* and $K + \Delta K$ are constants. Figure 21 exemplifies how the costs of producing a component can vary as a function of changes in machinability, ΔK.

Figure 21 Examples of part costs shown as a function of ΔK

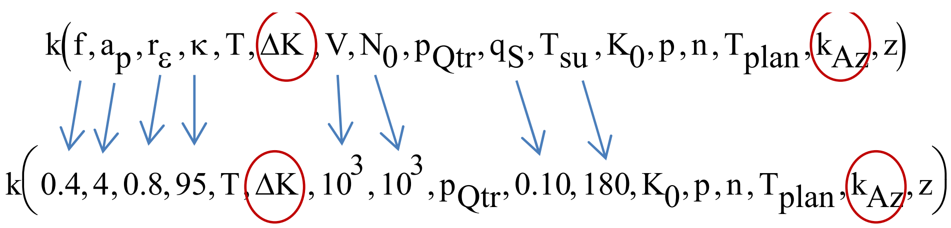


7 Relations of part costs to tool costs and tool performance

The effects of a wide variety of parameters and variables, some of them included in Figure 22 or in the symbol list below, can be studied by use of the cost model described here.

The effects of tool costs on the cost of producing a given component are exemplified in Figure 23 and Figure 24.

Figure 22 Parameters and variables that contribute to the costs k of producing a particular component



Note: The machinability of the work material ΔK and the tool costs k_{Az}, both of which are marked here, are particularly important.

Figure 23 Examples of the effects of tool costs k_A on part costs, shown as a function of T

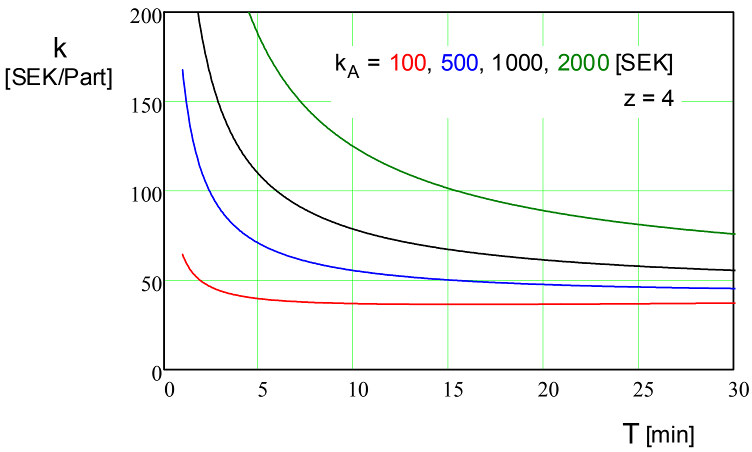
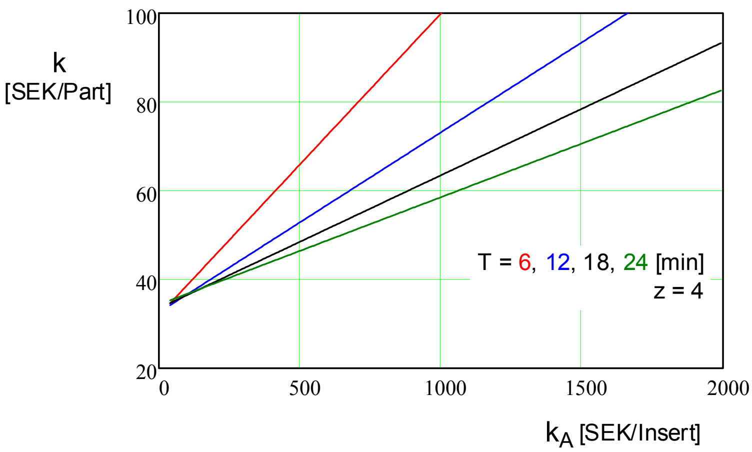


Figure 24 Examples of the costs of producing a given component, shown as a function of the tool costs k_A and the tool lifetime T



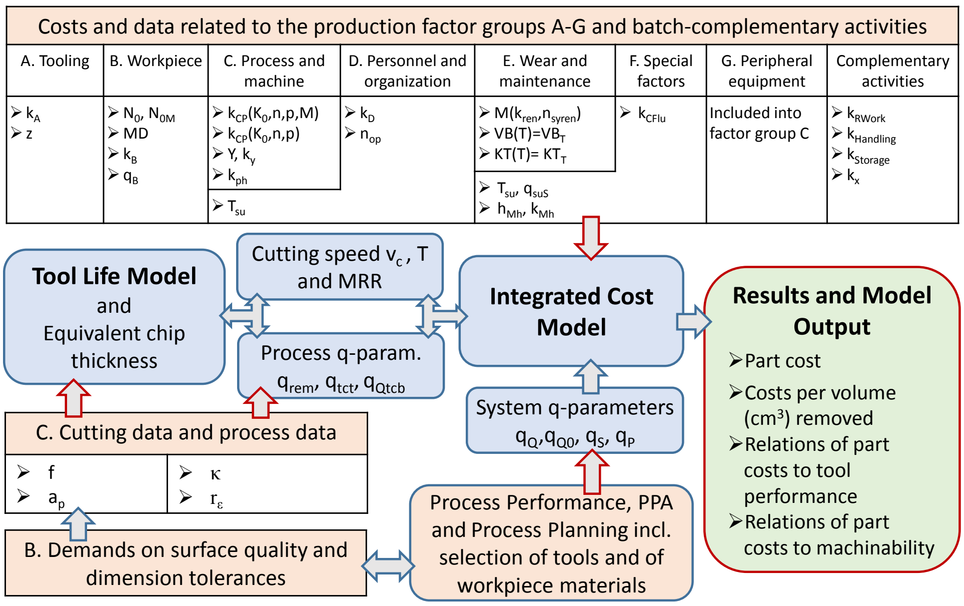
Just as the machinability of a work material can be calibrated in the form of ΔK, calibration can also be carried out in connection with tool change or a change in supplier. Calibration of the type ΔK can be sensible to perform when two tools of the same type, or designed for applications of the same type, are involved. The approximations this involves are based on the principle that it is simply the K-constant that distinguishes two tools of the same type and that a given work material does not vary in terms machinability.

If two tools differ in cost, this can be thought to be attributable at least in part to their performance, e.g., in terms of tool lifetime T, with use of the same cutting data in both cases, or in the form of metal removal rate (MRR) at a given tool lifetime level.

8 Summary and conclusions

A cost model of cutting processes that was developed in which process and system parameters are integrated is reported on here. The model's overall structure is described in Figure 25. The model stems from a model developed by the author earlier Ståhl (2005) referred to here as the standard model. A positive characteristic of the standard model, one retained in the present model, is its taking account of important loss terms (q-terms) concerned with rejections (q_Q), time losses (q_S), and material waste (q_B). The fact that tool lifetime T could be included in both models has also meant that appropriate models for relating it to cutting tool data and to tool lifetime criteria could be employed. Basing the present model on the engagement time t_e of the cutting tool, rather than on the cycle time t_0, enables a direct relationship to be established between process parameters (cutting data), cycle time t_0, and tool lifetime T. To be able in the present model to express cycle time t_0 with the help of engagement time, two new q-terms were defined and introduced: q_{rem}, or time losses associated with non-value-added time being included in cycle time, and q_{tct}, or time losses brought about by tool changes. In the present case, Colding's equation was used to describe the relationship between tool lifetime T and cutting data in the form of cutting speed v_c and equivalent chip thickness h_e.

Figure 25 Structure of the model developed for the analysis of integrated manufacturing costs



Other tool lifetime models, such as some variant of the Extended Taylor model, can also be included in the present model. Johansson et al. (2016) have shown that a model of the latter type can provide comparable results when Colding's equation is employed. Using Colding's equation to estimate tool lifetime also makes it possible to assess costs of varying degrees of machinability by differentiating Colding's equation and adjusting the constant K to $K + \Delta K$.

The model as described encompasses a large number of parameters and variables, making it possible to carry out a wide variety of analyses in addition to those reported on here. These include the following:

- computing the costs per cm^3 of the material removed, i.e., assessing a work material's machinability as expressed in economic terms
- analysing the balance between a tool's cost and its performance (cost-performance ratio)
- computing the costs associated with limited tool utilisation

The present model is implemented in Mathcad and can be developed further, e.g., by use of a more advanced model for describing the tool lifetime, one taking account of further tool lifetime criteria. A user-friendly interface should be developed too so as to increase the model's use and industrial application.

Acknowledgements

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Nomenclature

Symbol, meaning and units		
a_p	Depth of cut	mm
e_A	Axial tool travel distance	mm
D	Workpiece diameter	mm
f	Feed	mm/rev
h_e	Equivalent chip thickness	mm
h_{eW}	Woxén equivalent chip thickness	mm
H	Colding constant	-
k	Part cost	SEK/unit
k_B	Material cost per part	SEK/unit
K_B	Material cost per part including material waste	SEK/unit
K_{BQ}	Material cost per part for material waste	SEK/unit
kcm^3	Cost per chip volume	SEK/cm^3
k_{CP}	Hourly cost of machines during production	SEK/hr
K_{CP}	Machine cost per part during production	SEK/part
k_{CS}	Hourly cost of machines during downtime and setup times	SEK/hr
K_{CS}	Machine cost per part during disturbances	SEK/part
k_D	Average personnel cost per operator	SEK/hr
K_D	Average personnel cost per part	SEK
K	Colding constant	-
K_0	Equipment original investment	SEK
K_A	Tool cost per part	SEK/part
k_{Az}	Tool cost per insert	SEK/unit
L	Colding constant	-
M	Colding constant	-
n	Technical life time for equipment	year
n_{op}	Number of operators	unit
nt	Portion of an edge to produce a part	-
N	Total amount of parts required to be able to produce N_0 parts	unit
N_{Qctb}	Number of rejections related to tool changes per batch of N_0 parts	unit
N_0	Colding constant	-
N_0	Nominal batch size	unit
N_{0M}	Nominal manufactured batch size	unit
N_{wt}	Number of workpieces per cutting edge	unit
p	Cost rate for capital (interest level)	%
p_{Qtc}	Average portion of rejected parts during tool changes	-
q_B	Material waste rate	-
q_Q	Scrap rate	-
q_{Q0}	Total scrap rate except rejections related to tool changes	-

Nomenclature (continued)

Symbol, meaning and units		
q_{Qtcb}	Scrap rate related to tool change	-
q_P	Production-rate loss	-
q_S	Downtime rate	-
q_{rem}	Time loss factor within t_0	-
q_{tct}	Time loss factor related to tool change	-
r_ε	Tool nose radius	mm
t	Time in general	min
T_0	Ideal cycle time	min
t_e	Engagement time	min
t_{rem}	Average process idle time within t_0	min
t_{tct}	Average tool change time per part	min
T	Tool life time	min
T_{su}	Setup time for a batch	min
T_{tct}	Average tool change time	min
T_{pb}	Production time for a batch with N_0 parts	min
T_{plan}	Planned production time per year	hr
v_c	Cutting speed	m/min
V	Workpiece volume to be removed	cm^3
V_B	Tool flank wear	mm
z	Average number of edges per insert	unit
Greek symbol		
κ	Major cutting edge angel	o