

A computer aid in the optimization of turning conditions in multi-cut operations

Citation for published version (APA):

Kals, H. J. J., Hijink, J. A. W., & van der Wolf, A. C. H. (1978). A computer aid in the optimization of turning conditions in multi-cut operations. *CIRP Annals*, 27(1), 465-469.

Document status and date:

Published: 01/01/1978

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

A Computer Aid in the Optimization of Turning Conditions in Multi-Cut Operations

H.J.J. Kals, TH Twente/NL (2); J.A.W. Hijink, TH Eindhoven/NL; submitted by A.C.H. van der Wolf, TH Eindhoven/NL (1).

Summary: This paper reports on the development of a computer program for the calculations of optimum values of the machining variables in "multi-cut" turning operations. An optimization criterion can be selected for minimum production costs and maximum production rate. The limits in the use of both the lathe and the tool are taken into account. This also applies to the constraints imposed by the requirements with regard to product accuracy and surface finish. The computer program has been used for determining the influence of lathe specifications and accuracy demands on machining costs.

INTRODUCTION

In metal cutting there has always been a tendency to increase productivity by automation, aiming at an increase in the ratio of actual cutting time and total machining time. Compared with conventional machine tools, automatic and numerical controlled machine tools require higher investments, which have led to an increasing need for machining under economic acceptable cutting conditions. This applies in particular to turning where the nature of the machining process imposes a relatively high ratio of actual cutting time and total machining time. Automatic lathes are generally applied and the demands for numerically controlled lathes has never been as high as during the last few years. The computation of optimum turning conditions in terms of cutting speed, feed and depth of cut and regarding the constraints which are imposed by both the lathe and the tool - is quite complex and virtually impossible in cases where a single cutting edge is subjected to cutting under different conditions. A computer aid is indispensable here. Moreover, a computer offers an enormous advantage in the possibility of storing and handling the large data files as required for the calculation of cutting forces, tool life, stability of the cutting process, deflections etc.

1. THE CALCULATION OF ECONOMIC CUTTING CONDITIONS

1.1. Optimization for uniform cutting conditions.

In the case of a single cutting operation, the actual cutting time t_c is a function of the machined length l , the diameter d , the cutting speed v and the feed s :

$$t_c = \frac{\pi d l}{s v} \quad (1)$$

When taking t_a as the auxiliary and idle time (set-up, tool traverse time, etc.), t_s as the tool changing time and T as the tool life, the total machining time t of one product can be expressed as:

$$t = t_a + t_c + t_s \frac{t_c}{T} \quad (2)$$

or

$$t = t_a + \frac{\pi d l}{s v} \left(1 + \frac{t_s}{T} \right) \quad (3)$$

For a given combination of workpiece material and tool, the tool life is:

$$T = T(v, s, a, V_0) \quad (4)$$

where V_0 represents the generalised wear criterion (either the admissible width of flank wear VB_0 or the admissible crater width KB_0).

Putting c_{lm} as the costs of labour and equipment per minute and c_s as the tool costs per edge, the total machining costs C per product yield from the equation:

$$C = c_{lm} \left(t_a + t_c + t_s \frac{t_c}{T} \right) + c_s \frac{t_c}{T} \quad (5)$$

$$= c_{lm} t_a + c_{lm} \frac{\pi d l}{s v} + (c_{lm} t_s + c_s) \frac{\pi d l}{s v T} \quad (6)$$

$$= C_a + C_c + C_s \quad (7)$$

where

C = total machining costs per product;
 C_a = costs of auxiliary and idle times per product (independent of v);

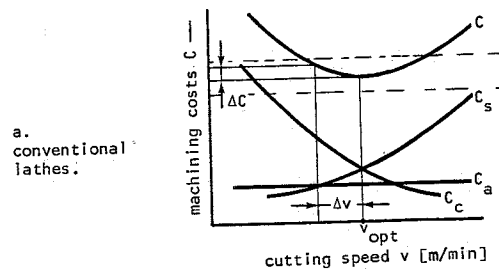
C_c = costs of actual cutting time per product;
 C_s = costs of tool and tool changing time per product.

Fig. 1a shows a typical relation between the machining costs per product C and the cutting speed v .

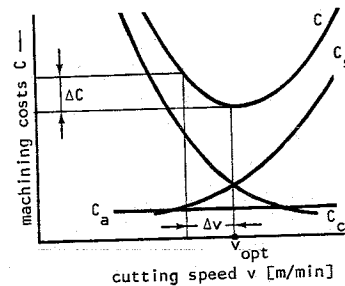
An increase of the cutting speed v results in a decrease of the actual cutting costs C_c but causes simultaneously a progressive increase in tool wear ($T \sim v^{-1/n}$, $n < 1$; see equation (12)) and thus an increase in the costs C_s . Keeping in mind that C_a is not influenced by v , the machining costs C are affected by two opposing influences and as a result C shows a minimum as a

function of v .

The adjacent Figs. 1a and 1b are given to demonstrate the difference between conventional and for instance numerical controlled lathes. For the latter the non productive costs C_a are lower, pointing to the key of automation. The curve representing the total machining costs C in Fig. 1b is steeper and more narrow. This is caused by the higher cost of labour and equipment as well as the costs of tool changing.



a. conventional lathes.



b. automated lathes.

Fig. 1. Machining costs per product versus cutting speed.

As a result the optimum cutting conditions for NC lathes should be chosen between more narrow limits than for conventional lathes.

The optimum value of the cutting speed v_{opt} or the feed s_{opt} is, dependent on the applied criterion, derived from the partial differential equations of either the machining costs C or the machining time t .

1.2. Optimization for varying cutting conditions.

In the case of one cutting edge being subjected to different cutting conditions, the tool wear will develop according to the wear rate characteristics belonging to these different cutting conditions.

Each cutting operation being characterised by its length l_j , the diameter d_j , the cutting speed v_j and the feed s_j , the total machining time t of m cutting operations can be expressed as [2]:

$$t = t_a + \sum_{j=1}^m \frac{\pi d_j l_j}{s_j v_j} \left(1 + \frac{t_s}{T} \right) \quad (8)$$

and the total machining costs C yield from:

$$C = c_{lm} t_a + c_{lm} \sum_{j=1}^m \frac{\pi d_j l_j}{s_j v_j} + (c_{lm} t_s + c_s) \sum_{j=1}^m \frac{\pi d_j l_j}{s_j v_j T} \quad (9)$$

The derivation of the equations (8) and (9) is given in reference [3]. The optimum values of the cutting speed $v_{opt j}$ and the feed $s_{opt j}$ are derived from the partial differential equations:

- in the case of minimum costs: $\partial C / \partial v_j = 0$ and $\partial C / \partial s_j = 0$,
- in the case of maximum production rate: $\partial t / \partial v_j = 0$ and $\partial t / \partial s_j = 0$ ($T_j = T_j(v_j, s_j, a_j, V_0)$).

Remarks:

- As a rule the calculated optimum cutting speed cannot be obtained. Both lathe and tool are setting limits to the attainable values of feed, speed and depth of cut. Additional limitations must be set with regard to the stability of the cutting process (chatter) and the quality specifications of the product. Last but not least there are constraints for proper chip removal; certain combinations of feed, speed and depth of cut have to be preferred.
- The use of each tool grade is limited with respect to both cutting speed and feed. A maximum cutting speed v_{max} has to be set to prevent plastic failure of the tool. In particular for cemented carbide and ceramic tools, the observance of a minimum value of the cutting speed v_{min} will protect the tool from being damaged by fluctuations in the cutting force due to the occurrence of an instable build up edge as well as discontinuous chip formation. The adoption of a maximum feed rate s_{max} must prevent breakage of the tool wedge and a minimum value of the feed s_{min} must be observed to prevent premature failure of the cutting edge. Another limitation of a cutting tool is found in the useful length of the major cutting edge L_s .
- Regarding the lathe, in general the setting of the spindle speed n is only possible in discrete steps. This may also apply to the setting of the feed rate s . Both the maximum available power P_d and the maximum allowable torque M_d at the spindle depend on the specifications of the main drive. When tolerances for cylindricity or measure are required, a lack of static stiffness of the machining system will set a limit to the depth of cut a . Another limitation of the depth (width) of cut may be found in a lack of dynamic stiffness of the system lathe - tool - workpiece. The critical width of cut b_{cr} is the width of cut below which the cutting process will be stable. As the lathe is comparatively rigid, the dynamic compliance of the tool, the toolholder, the workpiece and - if applicable - the tailstock, are the main constraining factors in this respect.
- Cutting speed and feed additionally have to be subjected to limitations imposed by requirements concerning the surface roughness of the product and chip removal. As to the latter, the allowable value of the chip slenderness ratio δ is limited by a maximum value, mainly dependent on the type of workpiece material.

2. THE SELECTION OF TECHNOLOGICAL RELATIONSHIPS

2.1. The equivalent chip thickness.

The significance of the equivalent chip thickness h_e as a generalising parameter, expressing the influence of the cutting geometry, has empirically been demonstrated [4,5]. According to Fig. 2, h_e can be defined as follows:

$$h_e = a \cdot s / b_e \quad (10)$$

A commonly applied approximation for the equivalent chip width b_e is given by:

$$b_e = \frac{a - r_e (1 - \cos \kappa_r)}{\sin \kappa_r} + \frac{\kappa_r \pi r_e}{180} + \frac{s}{2} \quad (11)$$

Actually three different geometrical conditions must be distinguished for the calculation of the equivalent chip width b_e [4]. The corresponding exact formulae are used in the computer program.

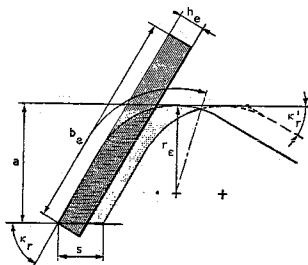


Fig. 2. Chip geometry.

The following consideration lead to the choice of the equivalent chip thickness as a cutting variable.

- Together with the cutting speed v and the material properties of the workpiece, h_e determines the tool face temperature θ .
- Because tool wear is predominantly dependent on θ , the equivalent chip thickness h_e can be considered as a fundamental parameter in the tool life relationship, replacing the geometric variables s , a , κ_r and r_e .

The so called reduced main cutting force F_v/b_e , i.e. the main cutting force per unit length of the tool active cutting edge, appears to be a linear function of the equivalent chip thickness h_e . The same holds for the feed force and the thrust force.

2.2. The tool-life equation.

The relationship between tool life T , the machining variables v , h_e and the wear criterion V_0 can be expressed by the empirical formula:

$$vT^n = \frac{K_1 K_2 V_0^m}{h_e} \quad (12)$$

$K_1 K_2$ represents the extrapolated cutting speed for $T=1$ minute, $h_e=V_0=1$ mm and K_1 is a rating factor depending on the shape of the carbide tip (for square inserts $K_1=1$). The exponents n , m and i are fixed for one tool-workpiece material combination. They all have values smaller than one. The recommended tool life data as given in [6] and which suit the generalized Taylor equation have been elaborated to calculate the constants according to equation (12). Reference [6] provided the data covering a number of common workpiece material/carbide grade combinations. The introduction of the shape rating factor K_1 clearly results in a reduction of scatter between the computed and the actual tool life. For a number of additional combinations of workpiece material and carbide tool grade, constants have been experimentally determined in the Laboratory of the Division of Production Engineering at the Eindhoven University of Technology. The results have been used to predict tool wear in turning under workshop conditions. Verification in the case of six different products, the machining of which included three to six cuts, respectively to be done with a single cutting edge and under different cutting conditions, showed an overestimation of the calculation (crater) wear up to a maximum of 32%. However, a close estimation of the results yielded that this deviation is systematically related to the number of interruptions. Correcting for the systematic deviation resulted in a scatter between the actual and the calculated results of a few percent only.

2.3. The cutting force relationship.

The cutting force is decomposed into three mutually perpendicular components: the main cutting force F_v , the feed force F_f and the thrust force F_p . For the different cutting force components the following formulae have been adopted [5]:

$$F_v/b_e = \alpha_v + \beta_v h_e \quad (13)$$

$$F_f/b_e = \alpha_f + \beta_f h_e \quad (14)$$

$$F_p/b_e = \alpha_p + \beta_p h_e \quad (15)$$

where $\alpha_v, \beta_v, \alpha_f, \beta_f, \alpha_p$ and β_p are constants belonging to a given cutting speed.

The recommended cutting force data given in [7] have been elaborated to determine the constants of the equations (13), (14) and (15). The influence of the cutting speed v on the various constants is effectuated by the use of polynomial expressions in v .

2.4. Product quality.

If requirements must be set with respect to the surface roughness or if the shape of the (slender) workpiece has to meet given tolerances regarding cylindricity or the diameter, during finish turning the feed s has to be subjected to a maximum value. In turning, the roughness profile is mainly a function of the corner radius of the tool r_e and the feed s . But also the chip flow, substantially dependent on the cutting speed v , has influence on the geometrical quality. For a given R_a -value, the limit value of the feed s follows from the equation:

$$R_a = \frac{s^2}{31.2 r_e} \cdot 10^{-3} + f(v) \quad (16)$$

The first part of equation (16) represents the theoretical surface profile. The value of the empirical term $f(v)$ has to be determined experimentally for each combination of tool and workpiece material. In the case that a tolerance (c) of either cylindricity or of the diameter is required, the thrust force F_p has to be restricted to limit the deflection between workpiece and tool. The limit thrust $F_{p,max}$ is a function of the tolerance and the stiffness of both the workpiece (f_w) and the tool including the tool holder:

$$F_{p,max} = F(f_w, f_t, c) \quad (17)$$

For finish turning, the limit value of the feed takes the lower value following from equation (16) and the equations (17), (11) and (10).

2.5. Dynamic instability.

During machining, self-induced vibrations may occur in the machining system. This type of vibrations is attendant with periodic deflections of the tool relative to the workpiece and can result in damage of the workpiece surface. In most cases the vibrations also will decrease tool life. The most important variable in self-excited vibrations is the width of cut b .

The critical width of cut b_{cr} is defined as the width of cut at which the cutting process starts to become unstable. As an example Fig. 3 shows the critical width of cut b_{cr} as a function of cutting speed and feed (compliant shaft). The value of b_{cr} is largely dependent on the dynamic transfer function of the machining system, which may be decomposed in an in-phase component (Re) and an out-of-phase component (Im). In general, the dynamic stiffness of the lathe itself is high enough to have no significant influence on self-induced vibrations for the practical values of cutting speed and feed. This leaves the dynamic properties of the tool, the toolholder and the (slender) workpiece as the main influencing structural factors. The dynamic response of the cutting force to periodic variations in the feed can be decomposed into a stiffness coefficient k_i and a damping coefficient c_i . Both k_i and c_i are functions of cutting speed and feed.

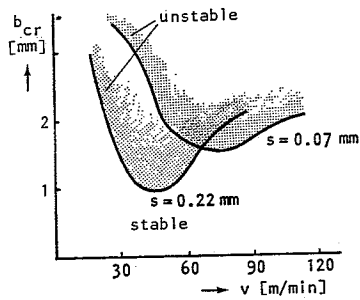


Fig. 3. The critical width of cut b_{cr} as a function of cutting speed v (slender shaft). Ref. [9].

Their values are highly dependent on the type of workpiece material and tool and they have to be experimentally determined using a special test rig. For the calculation of the critical width of cut b_{cr} the following equation is adopted [8,9]

$$b_{cr} = \frac{-1}{2Re k_i} \frac{1}{1 - \frac{\omega c_i}{k_i} \frac{lm}{Re}} \quad (18)$$

2.6. Optimum cutting speed and feed.

An analysis of the differential equations $\partial C/\partial h_{e_j} = 0$ and $\partial t/\partial h_{e_j} = 0$ did lead to the conclusion that for both criteria: either minimum costs or maximum production rate, the optimum cutting conditions are being met when h_{e_j} takes the maximum possible value and the value of v_j answers the differential equation $\partial C/\partial v_j = 0$ or $\partial t/\partial v_j = 0$ [3]. The respective cutting speed values yield from the corresponding equation [3]:

$$v_{opt j} = \frac{K_1 K V_0^n}{h_{e_j}^n} \left[\frac{1}{(t_s + c_{1m}/c_s)(1/n-1)} \right]^n \quad (19)$$

or

$$v_{opt j} = \frac{K_1 K V_0^n}{h_{e_j}^n} \left[\frac{1}{t_s(1/n-1)} \right]^n \quad (20)$$

3. THE CONSTRUCTION OF THE COMPUTER PROGRAM

The construction of the computer program will be discussed with help of the flow chart in Fig. 4. First the geometrical data of the workpiece are fed in. These data represent one or more cutting operations with appropriate tools. The required technological input data concern the type of workpiece material, the chosen lathe and the applied tools. The related property specifications are present in the data bank of the computer program. Lastly the cumulative auxiliary and idle times t_a and the costs of labour and machine tool are entered. The computation automatically includes every cutting operation i ($1, \dots, M_j$ = total number of cutting operations with tool j) of each of the tools j ($1, \dots, L$ = total number of tools). In the first procedure called "NUMBER OF CUTS" the cutting operations are divided into m different cuts. The procedure develops as follows. First, the chip slenderness ratio δ (= ratio of the width of cut b and the undeformed chip thickness: $b/h = a/(s \sin^2 \kappa_r)$) is determined in order to prevent unmanageable chip flow. In the case of finish turning, the feed s of the last cut of the cutting operation is determined according to equation (16) or (17). The value of the depth of cut follows from $a = \delta s \sin^2 \kappa_r$. For the remaining rough-turning operation, the maximum feed s_{max} , its limitation being imposed by the strength of the tool, is the starting point for the computation of the number of cuts. The workpiece oversize is divided by the value of $(\delta s_{max}/\sin^2 \kappa_r)$ and then rounded off to render the number of rough turning cuts. It is taken that the feed is continuously adjustable.

Then for every cut ($1, \dots, q$), according to equation (19) or (20) the optimum cutting speed v_{opt} is determined in the procedure "CALCULATION v_{opt} ". In "R.P.M." the best fitting number of revolutions per minute n available is selected and the cutting speed v calculated.

In the procedure "CALCULATION OF COSTS AND TIME", the machining costs and time for the single cut under the conditions a , h_{e_j} max, and v are calculated (see equations (3) and (6)). So are the additional machining costs and time with reference to the machining costs and time when cutting under optimum conditions. Consequently, the cutting variables s (h_{e_j}) and v are checked for the additional constraints imposed by the tool. If necessary v and/or s are adjusted. The resulting increase in machining costs and time are calculated or another tool grade is advised. The cutting force F_v is determined according to equation (13)

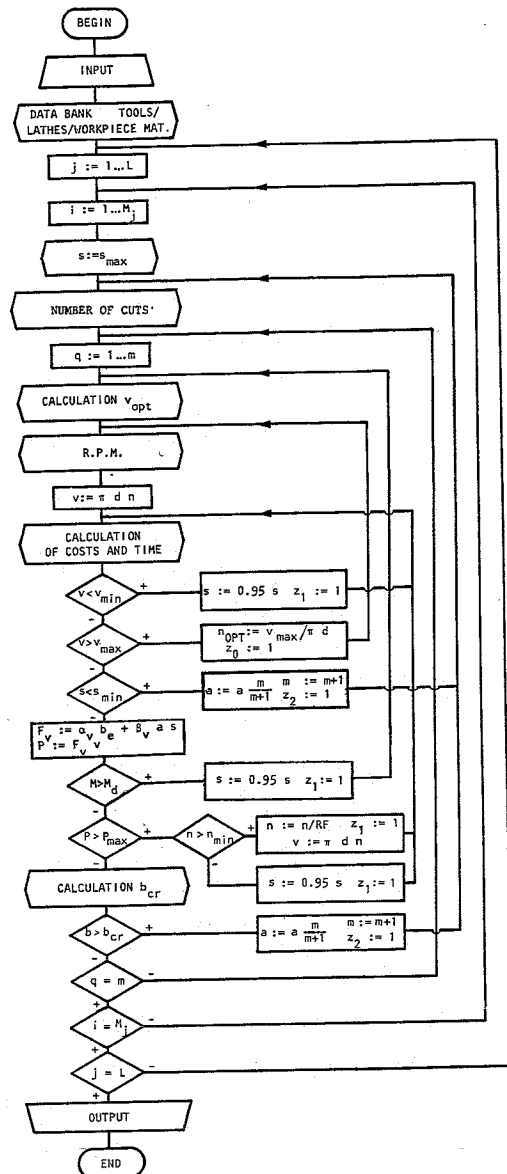


Fig. 4. Simplified flow chart of the computer program

and the machining operation is checked for maximum allowable torque. The required power is $P = F_v v$. When $P > P_d$ (= power capacity of the main drive of the lathe), first it is examined whether lowering the number of revolutions is possible (the impact of v on costs is smaller than that of h_{e_j}). If in this way the required power P cannot be lowered sufficiently, the feed is lowered stepwise by 0.05 s until the requirement is met.

Next, in "CALCULATION b_{cr} " the critical width of cut b_{cr} is calculated. If the width of cut ($b = a/\sin \kappa_r$) exceeds b_{cr} , the number of cuts of the machining operation is increased to meet the requirement $b < b_{cr}$ and the computer program proceeds after the procedure "NUMBER OF CUTS". Finally the total machining costs and time of all cuts are computed, as well as the differences with the costs and time when cutting under the primary optimum conditions a , h_{e_j} max and v_{opt} . This gives insight into the rise of costs and time which result from transgressing the different constraints. The tool changing frequency is obtained by totalling the quotients t_c/T_j of all the cuts to be done with one single cutting edge.

4. RESULTS OF THE COMPUTER PROGRAM

The programming language used is BEA (Burroughs Extended Algol). At present the program can be used interactively with the input given in a conversational mode. The user can immediately respond to the computed results and proceed with another lathe and/or tool grade.

4.1. The data bank.

At present the data bank includes the following data:

- Specifications of the lathes present in the laboratories of the Division of Production Technology at the Eindhoven University of Technology. The data are extended with the dynamic properties of the toolholders.
- The constraints for the various tool grades.

- The data of various combinations of workpiece material and carbide grade, required for the calculation of cutting forces, tool life and the critical width of cut. The data cover the usually applied carbon steels and cast iron as well as a number of alloy steels such as 20 Cr Mo 3, 42 Cr Mo 4, X 22 Cr Ni 17.

4.2. Example of the computation of cutting conditions.

An obvious application of the described computer program is to determine the most economical values of the cutting conditions for the machining of a given product on a given lathe.

As an example the computed results of the machining of a simple product as shown in Fig. 5, taking four cutting operations, are given.

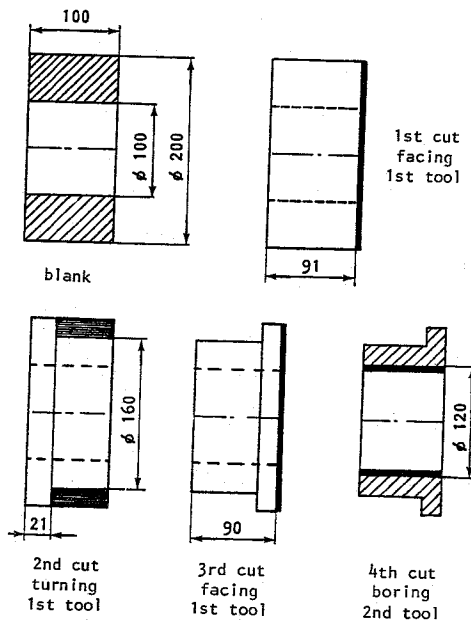


Fig. 5. The machining of a product taking four cutting operations with two different tools.

The complete product (See Fig. 5)
 MACHINING COSTS ----- 7.33 Dfl
 - TIME ----- 315 sec
 Difference of machining costs and -time as compared with optimum conditions.

z_0	z_1	z_2	Δ COSTS		Δ TIME	
			Dfl	%	sec	%
0	0	0	0.07	1.0	13.3	4.2
1	0	0	1.87	25.6	77.2	24.5
1	0	1	0.34	4.7	13.9	4.4
1	1	1	0.91	12.5	49.9	15.8

column

A B₁ B₂ C₁ C₂
 Tool NR. 1: change after 5 products.
 Tool NR. 2: change after 28 products.

Table 1. Constraints and their influence on machining costs and -time.

Cut nr.	a	h_e	s	v_{opt}	n	v	b_{cr}	costs	time	transgr. constr.		
										Dfl	sec	z_0
1	5.90	.60	.70	248	219	137	-	0.60	27.8	1	1	0
2	5.90	.60	.70	248	219	129	-	0.59	27.7	1	1	0
3	5.90	.60	.70	248	219	121	-	0.59	27.6	1	1	0
4	2.31	.27	.35	309	534	276	-	0.58	24.0	0	0	0
								2.36	107.1			

z_0 : application area of the tool; z_1 : power main drive; z_2 : critical width of cut.

Table 2. Output per machining operation.

The output, which can be partly suppressed, is concluded with a survey like the one in Table 1. In Table 1, the columns B₁, B₂, C₁ and C₂ show the rise of machining costs and -time as a result of running up against constraints. The three-figure code in column A indicates which constraints are concerned; 0 0 0 means that none of three limitations (of the tool (z_0), of the available main drive power (z_1) and of the critical width of cut b_{cr} (z_2)) are reached. However, also in this case there is a rise in machining costs because of the lathe having only discrete steps to establish the spindle speed n . The character 1 indicates that a limitation has come in, followed by the increase in costs and time. Also is shown the number of products after which the different cutting edges have to be changed. For each cutting operation an output can be obtained as shown in Table 2, giving both the optimum and the applicable value of each of the cutting conditions n , s and a , as well as the required machining costs and time for each cut.

4.3. The prospects of the computer program.

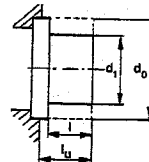
There is no need to emphasize that a computer program like this can be valuable in the planning of turning operations. The need for this is, for instance, increasingly being recognized during the last years by the management of small workshops in the United States and particularly in the case of NC-lathes. The program can assist in choosing the most suitable tool and the best available lathe to machine a given product. With respect to the buying of new machine tools, the program can be applied as an aid in comparing lathes for machining costs per product and as such provide directives for the buying of lathes.

Workpiece material C45N.
 "Standard tool"
 Carbide P20, $\alpha = 5^\circ$, $\gamma = 6^\circ$, $\kappa_r = 90^\circ$,
 $\lambda = 0^\circ$, $r_e = 0.4$
 Wear criterion $VB_D = 0.4$ mm.
 Tool changing time = 0.5 min.
 Costs per cutting edge = Hfl 2.-
 "Standard lathe"
 Max power = 10 kW,
 Max torque = 1.6×10^5 Nm,
 Spindle speeds 10 - 3000 rev./min
 (continuously variable)
 Feed 0.2 - 10 mm/rev.
 (continuously variable)
 Rapid traverse 10.2 m/min.
 Costs of labour and equipment Hfl 50.-/hr.

All results refer to long turning; non productive time 1 min.

Table 3

As an example, computations have been carried out for a product, the specifications of which are given in Table 2. The results, expressed in machining costs per product, covering the influence of both available power and available number of steps in the feed drive as well as the spindle drive, are given in the Figs. 6 and 7. Additionally, the influences of non-productive time and tool changing time as well the influence of surface roughness on machining costs per product are shown in the Figs. 8 and 9. The results do not need further comments.



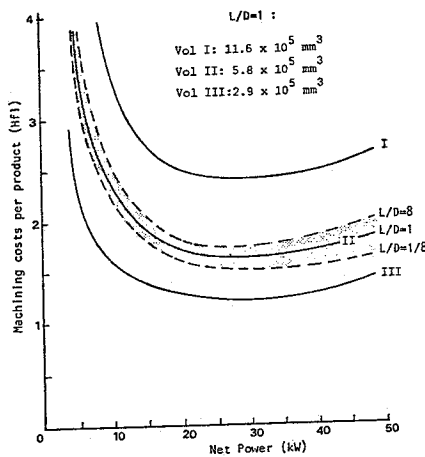


Fig. 6. Machining costs as a function of available power.

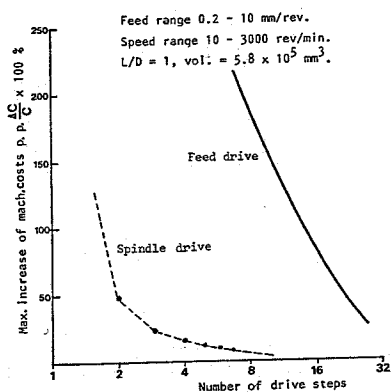


Fig. 7. Increase in machining costs as a function of the number of steps in feed- and spindle drive.

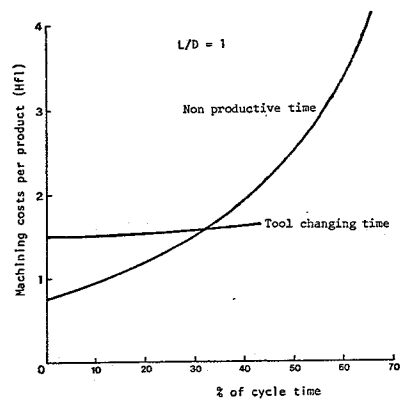


Fig. 8. The influence of the non productive- and tool changing-time on the machining costs.

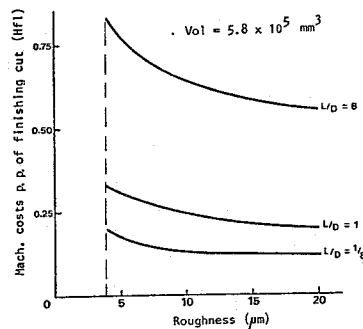


Fig. 9. The machining costs of the finishing cut.

5. LITERATURE

- [1] Computation of cutting conditions in turning with the aid of a computer program (In Dutch). J. Hendriks van de Weem - Division of Production Technology, Eindhoven University of Technology, 1976.
- [2] The development of BIDCANDE a program system for the calculation of turning conditions (In Dutch). F.J.A.M. van Houten - Report PT 0398, Division of Production Technology, Eindhoven University of Technology, 1977.
- [3] Cutting technology (In Dutch). H. Kals - Monograph, Division of Production Technology, Eindhoven University of Technology, 1976.
- [4] A simplified approach to the optimum selection of machining parameters. R. Brewer, R. Rueda - Engineers Digest, September 1963.
- [5] On the significance of equivalent chip thickness. C. Bus, N. Touwen, P. Veenstra, A. van der Wolf - Annals of CIRP, 1971.
- [6] Recommended cutting data for turning steel and cast iron (In Dutch). M. Maris - Metaalbewerking, January 1975.
- [7] Spezifische Schnittkraftwerte für die Zerspaltung metallischer Werkstoffe. K. Essel, W. König - Verlag Stahleisen.
- [8] Stability of the cutting process (In Dutch). H. Kals, A. van der Wolf - Lecture Notes Nr. 4841, Eindhoven University of Technology, 1971.
- [9] Dynamic stability in cutting. H. Kals - Dissertation, Eindhoven University of Technology, 1972.
- [10] The influence of accuracy and specifications of the lathe on machining costs (In Dutch). F.J.A.M. van Houten - Report PT 0399, Division of Production Technology, Eindhoven University of Technology, 1977.

NOMENCLATURE

a	[mm]	depth of cut.
$\alpha_V, \alpha_F, \alpha_P$	[N/mm]	constant in cutting force equation.
b	[mm]	width of cut $b = a/\sin \kappa_r$.
b_e	[mm]	equivalent width of cut.
$\beta_V, \beta_F, \beta_P$	[N/mm]	constant in cutting force equation.
c_{lm}	[DfI/min]	costs of labour and machine tool per minute.
c_s	[DfI]	tool costs per edge.
c_i	[DfI]	specific process damping coefficient.
C_a	[DfI]	machining costs per product.
C_a	[DfI]	costs of auxiliary and idle times per product $C_a = c_{lm}t_a$.
C_c	[DfI]	costs of actual cutting time per product.
C_s	[DfI]	costs of tool and tool changing time per product $C_s = (c_{lm}t_s + c_s)(t_c:T)$.
c	[mm]	tolerance of cylindricity or of diameter.
d	[mm]	diameter.
δ	[-]	chip slenderness (b/h) .
F_V, F_F, F_P	[N]	cutting force, feed force, thrust force.
F_p	[N]	limit thrust force.
f_w, f_t	[mm]	deflection of workpiece, deflection of tool and toolholders.
h	[mm]	undeformed chip thickness $h = s \sin \kappa_r$.
h_e	[mm]	equivalent chip thickness.
$h_{e \max}$	[mm]	maximum equivalent chip thickness.
$l_{m,n}$	[mm]	exponent in the tool life equation.
Im	[m/N]	out-of-phase component of the dynamic transfer function of the machining system.
k_i	[N/mm ²]	specific dynamic process stiffness.
KB	[mm]	crater width.
K, K ₁		constant in tool life equation.
κ_r	[°]	cutting edge angle
κ_f	[°]	minor cutting edge angle
n	[-]	number of revolutions per minute.
Md	[Nm]	maximum allowable torque (main drive).
l	[mm]	cutting length.
l_s	[mm]	major cutting edge length.
P_d	[Nm/s]	power capacity of the main drive.
r_e	[mm]	corner radius of the tool.
Re	[m/N]	in-phase component of the dynamic transfer function of the machining system.
R_a	[μm]	surface roughness.
s	[mm]	feed per revolution.
s_{\min}, s_{\max}	[mm]	feed constraint imposed by the tool.
s_{opt}	[mm]	optimum feed.
t	[min]	machining time.
t_a	[min]	auxiliary and idle time (set-up, tool travers time, etc.).
t_c	[min]	actual cutting time.
t_s	[min]	tool changing time.
T	[min]	tool life.
θ	[°C]	tool face temperature.
v	[m/min]	cutting speed.
v_{\min}, v_{\max}	[m/min]	cutting speed constraint imposed by the tool.
v_{opt}	[m/min]	optimum cutting speed.
VB	[mm]	width of the flank wear land.
V_o	[mm]	generalised wear criterion $(KB_o \text{ or } VB_o)$.