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Development of drilling optimization strategies for CAM applications

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Abstract

The selection of economic cutting conditions in machining operations is becoming increasingly important in modern computer based-manufacturing. Using a generic deterministic approach, the optimization analyses, strategies and software for selecting the economic cutting conditions in drilling operations are presented based on the criteria typified by the maximum production rate (or minimum production time per hole) and incorporating a range of machine tool constraints. The deterministic optimization approach involving mathematical analyses and graphic presentation of economic characteristics provides clearly defined optimization strategies which guarantee the global optimum solution. Numerical simulation studies have verified the optimization strategies and demonstrated the economic benefits of using optimization in process planning as well as the suitability of the developed optimization strategies for on-line applications in Computer-Aided Manufacturing (CAM).

Keywords: Drilling, optimization strategies, process planning, software, machining.

1. Introduction

Machining is a versatile and accurate operation process of major importance to manufacturing industry. While the notion of an optimum speed for maximum material removal rate in single pass turning was recognized by Taylor [1] early this century, the progress in developing realistic optimization strategies for selecting the economic cutting conditions in process planning has been very slow [2]. As a result, the selection of cutting conditions in machining operations has often relied on experience, 'rules of thumb' and handbook recommendations. A survey by Kegg [3] has indicated that the cutting conditions set on CNC machine tools by such approximate practices are far from optimal. Furthermore, the fact that about 75% of total available production time was forecast to be spent on machining components in computer based manufacturing (compared to about 5% in conventional 'manual' machine tools) [4] has highlighted the considerable scope for cost savings through efficient and effective machining. The use of economic cutting conditions may indeed be essential to offset the high capital and operating costs in modern manufacturing involving high technology equipment and systems and to increase the competitiveness of manufacturing firms.

The lack of progress in developing realistic optimization strategies may be attributed to the complex nature of the economic machining problem and the lack of quantitatively reliable machining performance equations relating the tool-life, forces, power and surface finish to the many process variables. As such, there has been a tendency by some researchers to use the available mathematical programming and numerical search algorithms in the optimization of cutting conditions in machining operations [5-7]. These computer packaged ‘strategies’ neither guarantee global optimum solutions nor provide clearly defined economic characteristics and solution strategies which highlight the effects of the various constraints and machining performance data. Moreover, these strategies are not suitable for on-line application in Computer-Aided Manufacturing (CAM) due to the required long computer processing time.

In contrast, the development of realistic optimization strategies and CAM software based on a generic deterministic optimization approach has been possible in recent years for single and multi-pass turning [8,9] and various major milling operations [10-12] on CNC and conventional machine tools while incorporating a wide range of machine tool constraints as well as component surface finish. These strategies provide both optimal and feasible solutions provided comprehensive machining performance information and equations as well as machine tool specifications are known. Such information is available in one of the very few machining data handbooks [13], although the need for continually updating and improving the reliability of the information and allowing for the new development of tool and work materials are re-emphasized in an international survey conducted by the International Institution of Production Engineering Research (CIRP) [14].

In this paper, the economic analysis, strategies and software module for drilling operations on CNC machine tools are developed using the generic deterministic optimization approach. The analysis allowing for the many constraints of relevance to practical drilling operations is based on the minimum production time per hole criterion while the strategy and software developed apply for the minimum cost per hole criterion due to the proven mathematical similarity of the two objective functions. Numerical studies are finally carried out to verify the optimization strategies and show the importance of using optimization in process planning.

2. Objective function and characteristics

Based on the minimum production time and cost per hole criteria, the objective functions for drilling operations can be formulated in the usual forms as

$$T_T = T_L + T_c + T_R \frac{T_{ac}}{T} \tag{1}$$

and

$$C_T = x\left(T_L + T_c + T_R' \frac{T_{ac}}{T} \right) \tag{2}$$

where $T_R' = (T_R + y/x)$ and other symbols are as defined in the nomenclature. In the economics of machining analysis, it is common to assume that the non-productive loading/unloading time T_L and tool replacement time T_R have been optimized using work study techniques, ingenious loading and unloading devices and jigs and fixture designs. Likewise, the labour and overhead cost rate, x, and tool cost per failure, y, have been minimized through good management and purchasing policy. Thus it is apparent that equations (1) and (2) are mathematically similar and the same optimization strategy can be used to determine the optimum cutting conditions for the two equations although the numerical values of the optimum cutting conditions can be different. Therefore, only the production time per hole equation (1) will be analyzed in this paper.

The tool-life T is taken from the comprehensive machining data handbook [13] and given by

$$T = \frac{K\, D^{1/n_2}}{V^{1/n}\, f^{\,1/n_1}} \tag{3}$$

The cutting time T_c for drilling a hole of depth h can be approximately expressed as

$$T_c \approx T_{ac} = \frac{h\, D}{\mu\ V\ f} \tag{4}$$

Substituting equations (3) and (4) into equation (1) gives

$$T_T = T_L + \frac{h\,D}{\mu V f} + \frac{h\,T_R}{\mu K} V^{1/n-1} f^{1/n_1-1} D^{1-1/n_2} \tag{5}$$

For drilling operations, it can be assumed that the drill (i.e. *D*) is pre-selected according to the process need, the depth of the hole *h* and the tool-workpiece material combination are know and constant. The two independent cutting variables, the feed *f* and cutting speed *V*, should be selected such that the production time per hole T_T is minimized. A study of the numerical values of the empirical tool-life equation exponents in the handbook [13] has found that for all the tool-workpiece material combinations presented for drilling operations, $1/n > 1/n_1 > 1$. Thus, if T_L is minimized and constant, an increase in the cutting speed *V* or feed per revolution *f* will result in a decrease in the second term in equation (5) but an increase in the third term. Consequently, equation (5) exhibits a local minimum turning point with respect to *V* for any given *f*. A similar trend with respect to *f* exists which corresponds to a local minimum time per hole T_T.

A global minimum time per hole production requires that $\partial T_T/\partial V=0$ and $\partial T_T/\partial f=0$ from which the so-called economic tool-life equations with respect to the cutting speed *V* and feed *f* can be found to be

$$T_V = \frac{K\,D^{1/n_2}}{V^{1/n}\,f^{1/n_1}} = T_R\left(\frac{1}{n} - 1\right) \tag{6}$$

$$T_f = \frac{K\,D^{1/n_2}}{V^{1/n}\,f^{1/n_1}} = T_R\left(\frac{1}{n_1} - 1\right) \tag{7}$$

These two equations represent the loci of *V* and *f* which satisfy $\partial T_T/\partial V=0$ and $\partial T_T/\partial f=0$, respectively. Since $n \neq n_1$, equations (6) and (7) cannot be simultaneously satisfied and a global minimum at a unique pair of *V* and *f* does not exist. However, a local minimum T_T with respect to *V* (at a given *f*) exists which will lie on the curve described by equation (6). Similarly, for a given *V*, an optimum *f* can be found from equation (7) which yields a local minimum T_T. These characteristics are illustrated in Figure 1.

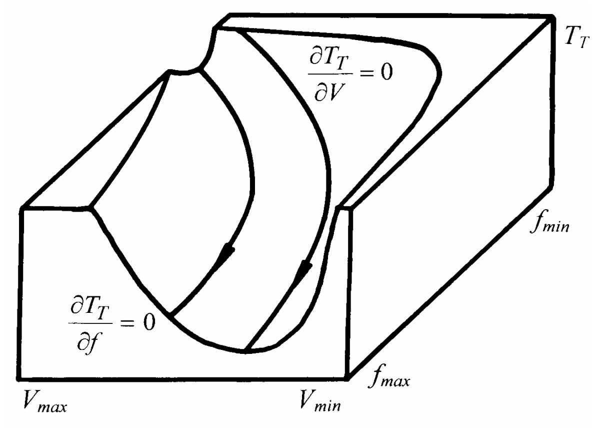

Fig. 1. T_T characteristics with respect to the feed and cutting speed.

For the usual tool-life exponent values $1/n > 1/n_1 > 1$, it can be proved that the relative position of the $\partial T_T/\partial V=0$ and $\partial T_T/\partial f=0$ loci is as shown in Fig. 1, e.g. for a given f the cutting speed from equation (6) (representing $\partial T_T/\partial V=0$) is less than that from equation (7) representing $\partial T_T/\partial f=0$ locus. The time per hole T_T trend along the $\partial T_T/\partial V=0$ and $\partial T_T/\partial f=0$ loci can be found by substituting V (or f) from equations (6) and (7) into equation (5), respectively. This results in the trends whereby T_T will decrease along the $\partial T_T/\partial V=0$ and $\partial T_T/\partial f=0$ curves as V decreases or f increases, as shown by the arrowheads in Fig. 1, for the common tool-life exponent values considered. These T_T characteristics have led to the popular strategy of selecting V and f in the 'high feed-low speed' region in the vicinity of the $\partial T_T/\partial V=0$ and $\partial T_T/\partial f=0$ loci. However, this strategy is not always valid in selecting the optimum feed and speed since in practice a number of constraints have to be satisfied. The influence of groups of related constraints on the selection of optimum cutting conditions are considered below before developing the overall strategy allowing for the combined effects of all the constraints relevant to drilling operations.

3. Constraints and characteristics

3.1 Effect of machine tool feed and speed boundary constraints

In practice, the machine tool maximum and minimum feed and cutting speed (for a given drill diameter) boundaries will act as constraints. In order to establish an optimization strategy for selecting the feed and cutting speed which allows for these constraints, it is necessary to consider the T_T characteristics along the feed and cutting speed boundaries together with the unconstrained T_T characteristics developed above to identify the various optimal solutions.

Figure 2 provides a graphical representation of the feed and cutting speed boundary constraints as well as the $\partial T_T/\partial V=0$ and $\partial T_T/\partial f=0$ loci in an f-V diagram where the T_T trends along the constant maximum and minimum feed and speed lines can be readily found using the above analysis, as shown by the arrowheads for the decreasing direction. It is apparent that the T_T trends on each segment of the maximum and minimum feed and speed boundaries are dependent on the relative position of these segments with respect to the $\partial T_T/\partial V=0$ and $\partial T_T/\partial f=0$ loci. For CNC machine tools considered in this paper, the machine tool feed and speed boundaries represent the feed and speed constraints. Depending on the relative position of $\partial T_T/\partial V=0$ and $\partial T_T/\partial f=0$ loci with these boundaries, five different possible optimum solutions have been identified together with the corresponding limiting conditions, Fig. 2 showing one of them where the dot highlights the optimum solution.

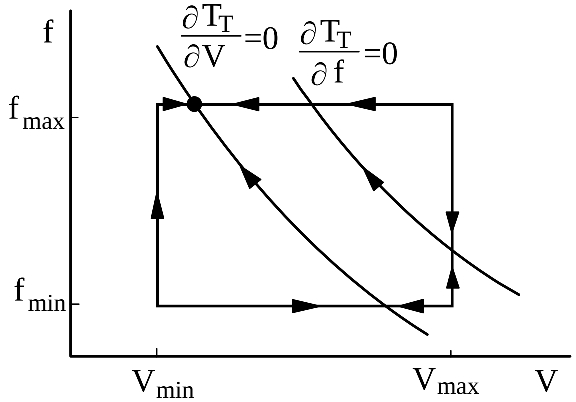

Fig. 2. Machine tool feed and speed constraints and T_T characteristics.

3.2 Effect of machine tool thrust force, torque and power and drill bit strength constraints

The thrust force needed to obtain or maintain the predetermined feed in drilling acts on the feed mechanism and the spindle of the machine tool and has to be constrained to within the machine tool maximum permissible loading. Using the empirical thrust force equation in the machining handbook [13], this condition can be expressed as

$$F = E\ f^{\alpha_1} D^{\beta_1} \le F_{\max} \tag{8}$$

Thus, the maximum thrust force constraint F_{max} will result in a feed limit, i.e.

$$f \le f_F = \left(\frac{F_{\max}}{E\ D^{\beta_1}} \right)^{1/\alpha_1} \tag{9}$$

In the low speed region of a machine tool operating range, the machine tool maximum power P_{max} may not be permitted since this would involve an excessive spindle torque. In this region, the 'low' speed power constraint P_a due to the limiting spindle torque must be considered. This low speed power usually increases linearly with speed V until a critical speed V_a where the machine tool maximum power constraint P_{max} becomes relevant. Hence the combined torque (or low speed power P_a) and maximum power constraints can be expressed as

$$P = W\ f^{\alpha_2} D^{\beta_2} V \le P_a = A' N = A\ V \qquad \text{for } V \le V_a \tag{10}$$

$$P = W\ f^{\alpha_2} D^{\beta_2} V \le P_{\max} \qquad \text{for } V > V_a \tag{11}$$

It is common that V_a has a constant value between the minimum and maximum machine tool speed limits and at $V=V_a$, $P_a=P_{max}$ so that V_a can be found to be

$$V_a = \frac{P_{\max}}{A} \tag{12}$$

In addition, the low speed power constraint can be represented by a feed limit f_a which can be found by re-arranging equation (10), i.e.

$$f \le f_a = \left(\frac{A}{W\,D^{\beta_2}} \right)^{1/\alpha_2} \tag{13}$$

In contrast, the maximum power constraint P_{max} will limit both the feed and speed when equation (11) is satisfied.

The drill bit strength constraint considered is to ensure that the cutting conditions selected will result in cutting force and torque that are not only within the machine tool limits but also within the limit that the drill can sustain. According to the comprehensive handbook [13], the cutting force and torque are independent of cutting speed so that the drill bit strength constraint will in fact result in a feed limit, f_d, for a selected drill diameter and drill-workpiece material combination. This handbook also recommends a series of feed limits (f_d) imposed by drill strength for different drill diameters when drilling different workpiece materials and mechanical properties with high speed steel (HSS) drills. This data base may be incorporated into the optimization analysis and the optimization software as constraints.

A study of the machining performance data in drilling from the handbook [13] has shown that the exponents in the thrust force and power equations are of the relationships $\beta_2>\beta_1\ge 1>\alpha_2\ge\alpha_1$ and $1>\{\alpha_1,\alpha_2\}>n/n_1>0$, while E and W are constant and greater than zero for a given tool-workpiece material combination. In addition, it is noted that the low speed power (or torque), thrust force and drill strength constraints are mutually exclusive, since each is represented by a limiting feed where the more restricted one will be effective. Therefore, the three equivalent feed limits can be generalized by

$$f \le f_x = \min\{f_F, f_a, f_d\} \tag{14}$$

Thus the maximum power constraint will combine with f_x to limit the feed and speed domain in the selection of optimum cutting conditions, as shown in Figure 3. The cutting speed at the intersection of the limiting feed f_x and P_{max} locus can be found from equation (11) (with P=P_{max}) and is given by

$$V_x = \frac{P_{\max}}{W f_x^{\alpha_2} D^{\beta_2}} \tag{15}$$

It should be noted that when f_x=f_a, V_x=V_a so that V_x is between V_{min} and V_{max} due to the normal range of V_a value mentioned earlier. If f_x is equal to f_F or f_d, then V_x is greater than V_a. Consequently, V_x is greater than the machine tool minimum cutting speed limit V_{min}.

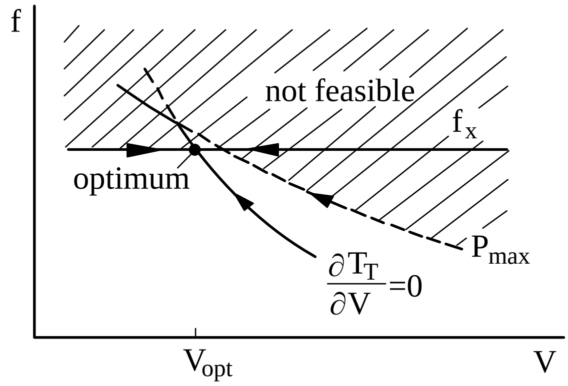

Fig. 3. Machine tool force, torque and power and drill strength constraints and T_T characteristics.

As shown in Fig. 3, the maximum power and the $\partial T_T/\partial V$=0 curves intersect, such that for the usual set of exponents, $\alpha_2 > n/n_1$, the slope of the P_{max} curve is less than that of the $\partial T_T/\partial V$=0 locus at the point of intersection and so the curves cross in the way shown in the figure. It can also be shown that the power constraint curve intersects the $\partial T_T/\partial f$=0 curve in the same manner as the $\partial T_T/\partial V$=0 curve on the f-V diagram.

The T_T trend along the maximum power locus may be found by substituting V from equation (11) (with P=P_{max}) into equation (5). This shows that for the common ranges of machining performance data of $1 > \alpha_2 > n/n_1$ and $1/n > 1/n_1 > 1$, T_T decreases along the P_{max} locus as the feed f increases. Fig. 3 illustrates the decreasing T_T trends by arrowheads on the curves. The portions of the P_{max} and $\partial T_T/\partial V$=0 curves on which the optimum point is likely to lie are shown by the solid lines.

When both the machine tool maximum power P_{max} constraint and the generalized feed f_x constraint are considered jointly, the T_T characteristics can be found by superimposing the two constraints on the f-V diagram as in Fig. 3. This shows that when the thrust force, torque (or low speed power) and maximum power constraints are considered as a group, the optimum cutting conditions will be at the intersection of the generalized f_x constraint with either the maximum power curve or the $\partial T_T/\partial V$=0 curve, depending on which intersection is at lower speed. Fig. 3 shows the latter case.

4. Optimization strategy for CNC machine tools

In the above analyses, practical constraints have been considered individually and in related groups. In these cases the optimum solution depends on the economic trends of the objective function and the effective constraints considered. In practical situations, however, the economic trends and the combined effects of all the constraints have to be considered. This results in more complex strategy which benefits greatly from computer assistance for its implementation.

The economic trends can be found by superimposing the equivalent feed limit, f_x, and P_{max} limiting speed-feed curve together with the feed and cutting speed boundaries and the $\partial T_T/\partial V=0$ and $\partial T_T/\partial f=0$ loci on the f-V diagram. To establish the optimization strategy, it is necessary to identify the various constrained optimum solutions on the 'active' constraints, and the associated limiting cutting speed and/or feed for each solution.

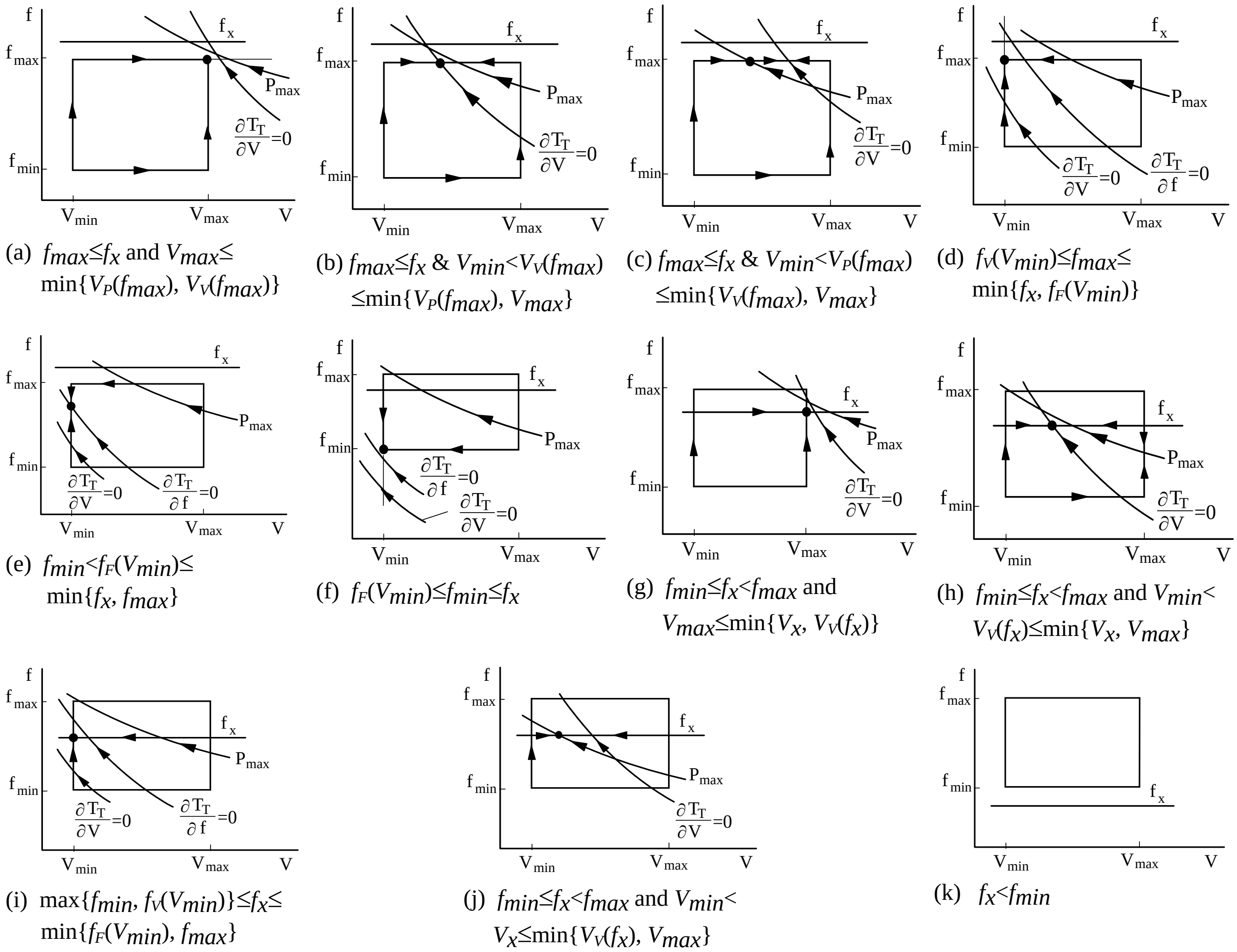

Fig. 4. The various possible optimum solutions in drilling operations.

For the common ranges of the tool-life, force and power equation exponents found in the comprehensive handbook being used [13], 11 different possible solutions have been identified together with the limiting feed and speed conditions, as depicted in Figure 4, where the arrowheads indicate the T_T reducing directions and the dot highlights the optimum feed and speed. It should be noted that in only two of the 11 different possible cases does the solution match with the popularly acclaimed strategy of selecting the largest possible feed with the speed being found from $\partial T_T/\partial V=0$ [2]. It is also interesting to note that when $f_x<f_{min}$ the intended drilling operation cannot be conducted on the selected machine tool as at least one constraint will be violated so that an alternative machine tool should be considered. A computer software module has been developed using the standard FORTRAN language to implement the optimization strategies.

This deterministic optimization approach assisted by the *f*-*V* graphical presentation has provided a mean of identifying explicitly every possible solution and guaranteeing the global optimum solution. For a given set of inputs there will be a unique pair of optimum feed and speed for a minimum production time per hole. In addition, while the overall optimization strategy is intricate, only a few comparisons are required to check progressively the limiting conditions and optimum solution, thus greatly reducing the computer processing time.

5. Assessment of the optimization model

Many machining handbooks (e.g. [15]) only provide initial recommendations for some of the cutting conditions, such as the feed and cutting speed in machining, leaving most of the problem to the process planner to solve. However, one metal cutting conditions handbook [13] provides not only complete tool-life, force, torque and power equations for a wide range of tool-work material combinations, but also detailed information and specifications for a number of machine tools. Furthermore, this handbook provides a methodology for selecting the feed and speed for drilling such that the machine tool constraints are not violated. A study of this methodology clearly indicated that the handbook solutions were feasible, but not necessarily optimal. Nevertheless, this handbook provides a unique opportunity to assess the developed optimization strategies and software for both T_T and C_T criteria, as the optimized times and costs should always be superior to those from the handbook. Further, the benefits of using optimization strategies over handbook recommendations can be evaluated.

For these purposes, a numerical simulation study has been carried out to assess the optimization strategy and software module when drilling a carbon steel of 650 MPa tensile strength with HSS general purpose twist drills on a 25 mm conventional vertical drilling machine found in the handbook [13]. The relevant constraint information of the machine tool are P_{max}=2.8 KW, transmission efficiency=81%, F_{max}=8830 N, N_a=97 rpm, N_{min}=97 rpm, N_{max}=1360 rpm, f_{min}=0.1 mm/r and f_{max}=0.81 mm/r. The feed and speed steps in the conventional machine were ignored to simulated a CNC machine tool.

Three drill diameters (10, 15 and 20 mm) were selected each drilling three different hole depths. In addition, three levels of average non-productive time per hole T_L (0.4, 0.7 and 1.0 min) and three levels of average tool replacement time per failure T_R (0.4, 0.7 and 1.0 min) were tested for all the ‘operations’. When the minimum cost per hole criterion was considered, the labour and overhead cost rate *x* at $0.60/min and the drill cost per failure *y* at $5.00, $7.50 and $10.00 for the three drill diameters, respectively, were selected. Thus 81 combinations were considered for each criterion in the simulation study.

Examining the optimum solutions has revealed that for all the cases the optimum feed and speed are feasible and the optimum times and costs per hole are superior to handbook recommended solutions [13]. While this was anticipated from the optimization analysis, it further confirms that the optimization strategies and software are correct. A sample of the optimized cutting conditions is shown in Table 1 where the handbook recommended feed and speed are also given for comparison purpose. It should be noted that for both minimum time and cost per hole criteria, the thrust force constraint is active for the cases in the table, which has resulted in the same optimum feed per revolution.

Table 1. Sample results of optimized and handbook recommended cutting conditions (D=10 mm, h=30 mm).

Drill	Optimization Strategies				Handbook Recommendation	
Replacement	Minimum T_T Criterion		Minimum C_T Criterion		Minimum T_T and C_T Criteria	
Time T_R (min)	V_o (m/min)	f_o (mm/r)	V_o (m/min)	f_o (mm/r)	V_r (m/min)	f_r (mm/r)
0.4	27.13	0.31	14.64	0.31	19.2	0.26
0.7	24.25	0.31	14.54	0.31	19.2	0.26
1.0	22.58	0.31	14.45	0.31	19.2	0.26

Quantitative comparisons between the optimized and handbook [13] recommended solutions have been carried out to assess the penalty of using handbook rather than the optimization strategies on the basis of percentage increase in the handbook time and cost per hole over the corresponding optimized solutions, i.e.

$$\frac{\Delta T_T}{T_{To}}100 = \left[\frac{T_{Tr} - T_{To}}{T_{To}}\right]100 = \left[\frac{T'_{Tr} - T'_{To}}{T'_{To}}\right]\left[1 - \frac{T_L}{T_{To}}\right]100 \tag{16}$$

$$\frac{\Delta C_T}{C_{To}}100 = \left[\frac{C_{Tr} - C_{To}}{C_{To}}\right]100 = \left[\frac{C'_{Tr} - C'_{To}}{C'_{To}}\right]\left[1 - \frac{xT_L}{C_{To}}\right]100 \tag{17}$$

where the T'_T and C'_T are the time and cost per hole when T_L is zero. It is apparent from the linearity of the two equations that the maximum penalties of using handbook recommendations (or maximum benefits of using optimization) will occur when the loading/unloading time T_L is as small as possible (ideally zero). Also these penalties reduce linearly to zero as T_L/T_{To} and xT_L/C_{To} increase to 1. Thus these equations highlight the need to continually reduce the non-productive times and costs. It also follows that in modern computer based manufacturing systems, where the non-productive times and costs are minimized and are small proportions of the total production times and costs, the use of optimization strategies becomes more important than in the past.

Based on the ideal loading/unloading time of zero, the overall results in this study show that the use of handbook recommendations will lead to an average increase of about 38% in T_T over the optimized times with a range of 18% to 66%. The corresponding values for the minimum C_T criterion are an average increase of 27% and a range of 13% to 50%. These penalties emphasize the need to use optimization for more efficient and economic production. The maximum overall penalties are depicted by the intercepts (at zero T_T/T_{To} and xT_L/C_{To}) in Figure 5, where the range and average penalties are shown to decrease linearly as the proportion of non-productive time T_L/T_{To} and cost xT_L/C_{To} increase according to equations (16) and (17).

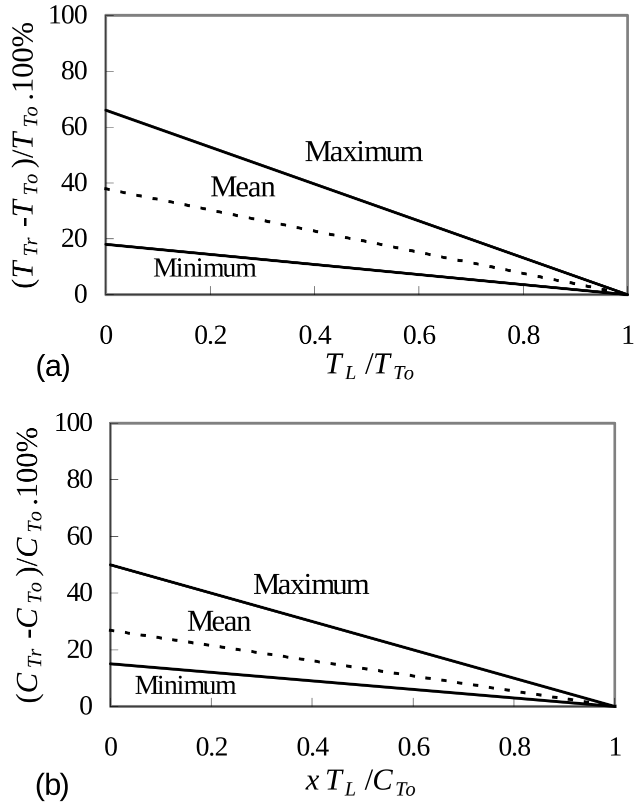

Fig. 5. Time and cost penalties for alternate non-productive loading/unloading times.

It is noted from equations (16) and (17) that the depth of hole drilled, h, will also affect the percentage increase in T_T and C_T. This effect stems from the terms ($1-T_L/T_{To}$) and ($1-xT_L/C_{To}$) in the two equations since either a decrease in T_L and/or an increase in h (which increases T_{To} or C_{To}) will result in increases in the two terms and in the final values of percentage T_T and C_T increases.

For the non-zero non-productive time T_L considered in this study, the penalties of using handbook recommendation are still considerable with up to 41% increases in T_T and 37% increase in C_T over the optimized results. Therefore, substantial economic benefits would be gained if these cutting conditions were optimized using the above strategies.

During the course of implementing the optimization strategies, attempts have been made to record the computer processing times in order to assess the software's suitability for on-line application. When the program was run on a Pentium 90 personal computer, the processing times for all the combinations of the selected conditions and for the time and cost criteria were less than 0.01 second. Thus, the developed deterministic, rather than numerical search, optimization strategies and software module are suitable for on-line applications in computer-aided manufacturing.

6. Conclusions

Realistic optimization strategies for selecting the economic cutting conditions in drilling operations has been developed based on the criteria typified by the maximum production rate and minimum cost per hole and incorporating constraints of relevance to drilling on computer numerically controlled machine tools. The analyses using the generic deterministic optimization approach with graphical assistance on the *f-V* diagram have provided an in-depth understanding of the economic characteristics and the influence of the practical constraints and machining performance data on the economic trends and optimum solutions, and resulted in clearly defined optimization strategies which guarantee the global optimum solution.

The numerical study has verified the optimization strategies and shown the economic benefits of using optimum cutting conditions over handbook recommendations in drilling operations. This study has also highlighted the increased benefits of using optimization in process planning in modern computer-based manufacturing where the proportions of non-productive times and costs are low and continually being improved. The short computer processing times required have made the developed strategies and the associated software suitable for on-line CAM applications.

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Nomenclature

A, A'	constants
C_T	average production cost per hole
D	drill diameter
f	feed per revolution
f_a	f limit from low speed power (or torque)
f_d	f limit from drill bit strength
f_F	f limit from thrust force
F	thrust cutting force
F_{max}	machine tool maximum thrust force limit
f_{max}, f_{min}	machine tool maximum and minimum f limits
f_x	generalized f limit from thrust force, low speed power and drill strength
h	depth of hole to be drilled

K, n, n_1, n_2, E	constants in tool-life equation
N	machine tool spindle speed
P	machining power
P_a	machine tool low speed power limit
P_{max}	machine tool maximum power limit
T	Tool (drill) life
T_{ac}	actual cutting time per hole
T_c	cutting time per hole
T_L	average loading/unloading, set-up and idle time per hole
T_R	average drill replacement time per failure
T_T	average production time per hole
V	cutting speed at drill outer corner
V_a	machine tool speed at which P_{max} limit becomes relevant
V_{max}, V_{min}	machine tool maximum and minimum V limits for a given D
V_x	V at the intersection of f_x and P_{max} loci
x	labor and overhead cost rate
y	tool cost per failure
$\alpha_1, \alpha_2, \beta_1, \beta_2, W$	constants in force and power equations
μ	constant of proportionality ($= 1/\pi$)