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Integrated approach for optimising machining parameters, tool wear and surface quality in multi-pass turning operations

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A B S T R A C T

This paper implements a holistic decision approach for determining tool wear and surface quality together with machining parameters such as cutting speed, feed rate, depth of cut, and cutting passes during turning operations. As a consequence, two machining optimisation models are formulated with the objectives of maximising the material removal rate and minimising the production cost so that the decisions regarding machining parameters can be determined as well as the status of tool wear and surface quality between intermediate cutting passes. The feasibility and applicability of the formulated models have been tested through computational analyses, and a comparison made between the two performance objectives. The results show that the integrated decisions of machining parameters, tool wear and surface quality can be made and thus avoid the application of expensive on-line equipment for measuring tool wear and surface quality. Furthermore, the feasible removal of material during turning operations can be achieved through proper selection of depths of cut and number of cutting passes. The proposed optimisation models can also be used to provide tool replacement schedules based on the number of processing parts and cutting passes.

A R T I C L E I N F O

Keywords:
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1. Introduction

Machining parameters, tool wear and surface quality are three metal cutting conditions that are strongly interrelated. While machining parameters contribute to tool wear, the quality of surface finish is affected by tool wear. At higher cutting speed, tool wear increases causing shorter tool life. On the other hand, due to tool wear, the width of tool nose increases leading to inferior quality of part surface. In order to achieve effective and efficient machining operation, better tool usage as well as improved product quality, it is essential to integrate the decisions of machining parameters, tool wear and surface quality altogether. The optimisation of machining parameters such as cutting speed, feed rate, and depth of cut is a critical step in the planning of machining operations to achieve higher machining efficiency. Researchers have studied the optimisation of machining parameters extensively. The approach to solving these problems involves the use of various techniques including mathematical programming, fuzzy logic, genetic algorithm, simulated annealing, expert systems and the commercially available software.

Problems of multi-pass machining operations have been investigated. Traditionally, the depth of cut and the number of passes needed for machining a stock material to the final dimension of a part are either selected by operators or from handbooks. However, the depth of cut and the number of passes so selected are often either too conservative leading to low productivity or too aggressive causing unnecessary tool breakages and part defects. To avoid these problems, the study of [1] included the decision of depth of cut in a multi-pass machining problem. In practice, a single operation may not necessarily be the most economic choice. Findings in [2-5] illustrated that multi-pass operations have shown to be more economical than single-pass operations when practical machining constraints such as cutting force and cutting power are incorporated in the machining optimisation model.

Other studies have tried to find possible trade-offs among the machining parameters, tool replacement policies, tool allocation, tool availability and tool adjustment. The calculation for the optimal cutting speeds and tool replacement policies of a two-stage machining problem was reported by [6] while the optimisation of machining conditions in conjunction with tool allocation to minimise production cost of multiple cutting operations with alternative tools for each operation was studied by [7]. A research presented in [8] dwelt in an integrated approach to simultaneous optimising the machining parameters, including machining speed, feed rate and depth of cut, number of passes, tool adjustment intervals, and the amounts of tool adjustments for multi-pass turning operations. Further research by [9] described a procedure to obtain optimum machining parameters in turning operation using dynamic programming for minimum unit cost of production. A Taguchi method was used to determine better machining parameters and achieve superior surface finish.

More recent investigations in [10-16] have attempted to work on the optimisation of turning process parameters for determination of optimal machining parameters incorporating various cutting conditions such as surface roughness, geometric tolerances, surface temperature, constrained machining parameters, workpiece hardness and high-pressurised cutting fluid in turning operations. However, these studies lack comprehensive decisions of machining parameters, tool wear and part surface quality as they rely on local spectrum of machining decisions which can be difficult to adopt in the machining shop floor. For example, it has been always assumed that a tool can be used up to its life limit specified by the maximum allowable wear leaving the amounts of tool wear between successive cutting passes not known. On-line tool wear and part quality measurements are not common practices in shop floor because they involve higher investment, and as such, most of reported machining studies lack decisions on either surface quality or tool wear for intermediate cutting passes. To avoid such deficiencies and obtain more realistic process plans for application on machining shop floor, this study proposed an integrated decision approach for the determination of optimal machining parameters, tool wear and surface quality in a global continuum.

2. Theoretical concepts

Prior to the formulation of the two machining optimisation models, theoretical concepts are derived to provide meaningful relationship between the performance objectives and decision variables. The relational base of material removal rate, production cost, machining parameters, tool wear, tool life, and surface quality is presented below.

2.1 Material removal rate

The rate of material to be removed from the workpiece depends mainly on machining parameters including cutting speed, feed rate and depth of cut. For instance, as cutting speed increases, the tool life is reduced rapidly but the rate at which material is removed increases. The volume of material removed is directly proportional to the workpiece diameter, depth of cut and the distance the tool has travelled and can be calculated as:

$$v_r = \pi D d L \tag{1}$$

The machining time is given by:

$$t_m = \frac{\pi D L}{1000 v f} \tag{2}$$

where D is the diameter of the workpiece (mm), L is the length of the workpiece (mm), v is the cutting speed (m/min), f is the feed rate (mm/rev) and d is the depth of cut (mm). The material removal rate (MRR) is thus obtained when the volume of the material to be removed in Eq. 1 is divided by the machining time in Eq. 2 and can be written as [17]:

$$MRR = 1000vfd \tag{3}$$

2.2 Production cost

In this study, the components of total production cost include machining cost, tool cost, tool replacement cost, and quality loss. Machining cost is the cost incurred during the actual cutting process that depends on machining time. Machining time is given as a function of cutting speed v and feed rate f in Eq. 2. Machining cost per piece is then the product of machining time t_m (min) and the operating cost C_o ($) given as:

$$C_m = \frac{\pi DLC_o}{1000vf} \tag{4}$$

Denoting C_e as the tool cost per cutting edge and N the number of parts, then the tool cost of machining a single part is represented as:

$$C_t = \frac{C_e}{N} \tag{5}$$

If t_r is the time required to replace the tool, then the tool replacement cost distributed in each part will be:

$$C_r = \frac{C_o t_r}{N} \tag{6}$$

Quality loss is defined as the cost incurred when the quality characteristic of the part deviates from its nominal or target value. According to [18], quality loss function can be expressed as a quadratic function of quality deviation from the target quality value, i.e.,

$$L(s) = \frac{A}{S_{max}^2}(s - S_o)^2 \tag{7}$$

where A is rework or scrap cost, S_{max} is the quality limit, s quality characteristic of the part, and S_o is the quality target value. The quality loss and deviation from the target value is depicted in Fig. 1.

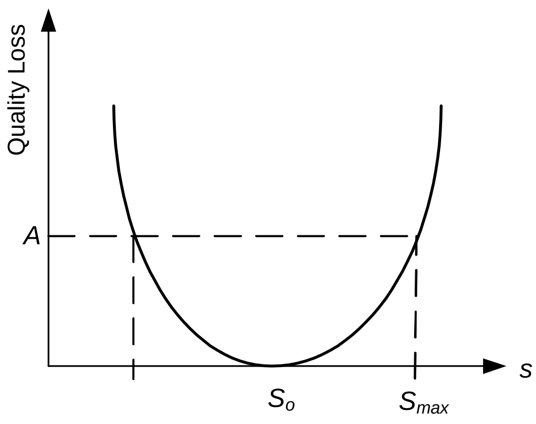

Fig. 1 Quality loss and deviation from the target value

The total production cost is the sum of machining cost, tool cost, tool replacement cost and quality loss:

$$C_p = \frac{\pi DLC_o}{1000vf} + \frac{C_e + C_o t_r}{N} + \frac{A}{S_{max}^2}(s - S_o)^2 \tag{8}$$

2.3 Tool wear and tool life

Tool life depends on machining parameters in that at higher cutting speeds, the life of the cutting tool becomes shorter because of higher friction between the tool and machined surface. In order to form a basis for optimising machining parameters, it is necessary to understand the nature of tool wear. For gradual or progressive tool wear, certain regions of tool face and flank are worn. Wear on the tool face is characterised by the formation of a crater, a result from the action of chips flowing along the face. Wear on the flank of the tool is caused by friction between newly machined surface and the contact area on the tool flank and is widely used as a measure of tool life. Due to tool wear, the width of tool nose increases thus affecting the quality of part surface. The interrelationship among the machining parameters, tool wear and surface quality can be depicted in Fig. 2.

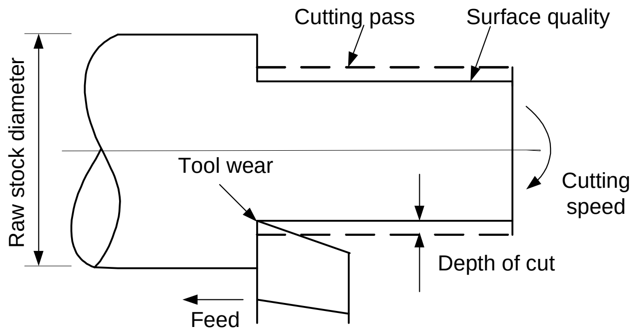

Fig. 2 Machining conditions of a rotational part

The average flank wear land width of 0.3-0.4 mm is often used as an indicator of the end of the tool life depending on the tool material. The extended Taylor's tool life is a function of cutting speed, feed rate and depth of cut expressed as [17]:

$$T_L = \frac{E_T}{v^{\alpha_T} f^{\beta_T} d^{\gamma_T}} \tag{9}$$

where α_T, β_T, γ_T, and E_T are empirical constants and v (m/min), f (mm/rev), and d (mm) are cutting speed, feed rate, and depth of cut, respectively. When tool wear is assumed to be linear, the amount of tool wear can be written in terms of the machining time and tool life as given in [19]:

$$w = \frac{t_m}{T_L} W_{max} \tag{10}$$

Substituting Eq. 2 and Eq. 9 into Eq. 10 and rearranging the terms, the amount of tool wear can be represented by:

$$w = \frac{\pi DLW_{max}}{1000E_T} v^{\alpha_T - 1} f^{\beta_T - 1} d^{\gamma_T}, \tag{11}$$

where W_{max} is the maximum allowable tool wear (mm).

3. Formulation of machining optimisation models

Practically, machining parameters, tool wear and surface quality are three interrelated machining conditions. However, the common theoretical analyses in machining studies have been to isolate the decisions of these machining conditions causing unrealistic process plans. For more effective turning operations, two machining optimisation models are proposed in this section. The first is the maximum material removal rate model and the other is the minimum production cost model.

3.1 Integrated model for maximum material removal rate

In order to remove as much material from the raw stock material to the finished part size and in a shorter period, the maximum volume of material to be removed becomes an important machining concern. In this case, it is necessary to maximise the material removal rate (MRR) in the following model:

$$\text{Maximise } MRR = \frac{1000\sum_{i=1}^{I} v_i\, f_i d_i}{\sum_{i=1}^{I} p_i} \tag{12}$$

Subject to:

(a) Limits of cutting speed, feed rate and depth of cut:

$$v_i^L \le v_i \le v_i^U, \forall i \tag{13}$$

$$f_i^L \le f_i \le f_i^U, \forall i \tag{14}$$

$$d_i \le d_i^U, i = 1,2,\dots,I-1 \tag{15}$$

$$d_I^L \le d_I \le d_I^U \tag{16}$$

(b) Constraints of material removal and pass selection:

$$\sum_{i=1}^{I} d_i = d_T \tag{17}$$

$$\sum_{i=1}^{I} d_i\, p_i = d_T \tag{18}$$

$$0 \le p_i \le 1, i = 1,2,\dots,I-1 \tag{19}$$

$$d_i \le d_i^U p_i, i = 1,2,\dots,I-1 \tag{20}$$

$$p_I = 1 \tag{21}$$

(c) Tool wear constraints:

$$w_i = \frac{\pi D_{i-1} L W_{max}}{1000 E_T} v_i^{\alpha_T - 1} f_i^{\beta_T - 1} d_i^{\gamma_T} p_i, \forall i \tag{22}$$

$$N\sum_{i=1}^{I} w_i = W_{max} \tag{23}$$

$$w_i \leq W_{max}, \forall i \tag{24}$$

(d) Constraints of cutting force and cutting power:

$$E_F v_i^{\alpha_F} f_i^{\beta_F} d_i^{\gamma_F} \leq F_{max,} \forall i \tag{25}$$

$$E_P v_i^{\alpha_P} f_i^{\beta_P} d_i^{\gamma_p} \leq P_{max,} \forall i \tag{26}$$

(e) Surface quality requirements and restrictions:

$$E_S v_I^{\alpha_S} f_I^{\beta_S} r^{\eta} BHN^{\theta} = s_I \tag{27}$$

$$S_o \leq s_I \leq= S_{max} \tag{28}$$

The objective function in Eq. 12 is intended to maximise the average rate of material removed from the workpiece. Constraints in Eq. 13 and Eq. 14 specify the limits of cutting speed and feed rate respectively while constraints in Eq. 15 and Eq. 16 set the limits of depth of cut. Constraint in Eq. 17 equates the sum of depths of cut of all cutting passes to total material to be removed. Constraints in Eq. 17, Eq. 18 and Eq. 19 altogether guarantee p_i to take the binary value 0 or 1. Constraint in Eq. 20 satisfies the condition that $d_i = 0$ when $p_i = 0$, and $d_i > 0$ when $p_i = 1$.

Constraint in Eq. 21 justifies a finish pass since otherwise the finish surface quality of the part cannot be considered. The tool wear for each cutting pass is specified by constraint in Eq. 22 while constraint in Eq. 23 states that the sum of tool wear of cutting passes for all parts should be equal to the maximum allowable tool wear. Constraint in Eq. 24 ensures that the tool wear for each cutting pass never exceeds the maximum allowable tool wear. The limiting cutting force and cutting power are given in constraints in Eq. 25 and Eq. 26, respectively, where α_F, β_F, γ_F, and E_F are empirical constants for cutting force and, α_P, β_P, γ_P, and E_P are empirical constants for cutting power. The surface requirement for the finish cutting pass is defined by constraint in Eq. 27 where α_S, β_S, γ_S, and E_S are empirical constants for surface finish. The restriction for the finish surface quality is imposed by the constraint in Eq. 28.

3.2 Integrated model for minimum production cost

When the production economics is a major concern, a cost model can become indispensable for the purpose of minimising the total production cost. The general formulation of the production-cost model which is to be minimised is:

$$\text{Minimise } COST = \sum_{i=1}^{I} \frac{\pi D_{i-1} L C_o}{1000 v_i f_i} + \frac{1}{N}\left((C_e + C_o t_r) + \sum_{n=1}^{N} \frac{A_n}{S_{max}^2} (s_I - S_o)^2 \right) \tag{29}$$

subject to all constraints from Eq. 13 to Eq. 28, where

$$D_{i-1} = D_0 - 2\sum_{q=1}^{i-1} d_q \tag{30}$$

The objective function in Eq. 29 minimises the total production cost, and all constraints used for this model are the same as those used in the integrated model for maximum material removal rate (refer to subsection 3.1).

4. Results and discussion

The formulated models are tested with a numerical example where a batch of mild steel raw stock is to be machined on a CNC lathe using carbide tools. The diameter of the stock D_o is 200 mm and the length L is 225 mm. The total depth of cut to be removed from the stock d_T is 5 mm and the maximum number of cutting passes is set to 8. Other data are given in Table 1.

The Extended LINGO nonlinear software was implemented to solve the models based on the input data given in Table 1. LINGO has the capability to solve nonlinear programming problems with unlimited number of linear and nonlinear constraints as well as unlimited number of integer, nonlinear and global variables [20]. The results of the MRR model are as follows: The number of parts N = 5 each processed with two cutting passes at average rate of removed material MRR = 255325 mm^3/min. It means that, the tool can be replaced after processing five parts at two cutting passes each. The quality of surface finish s_2 = 0.95 μm. The optimal cutting speeds v_1 = 150 m/min, v_2 = 250 m/min; feed rates f_1 = 0.7 mm/rev, f_2 = 0.19 mm/rev; depths of cut d_1 = 4.75 mm, d_2 = 0.25 mm; and amounts of tool wear w_1 = 0.03 mm, w_2 = 0.05 mm. The results of production cost model are as follows. The number of parts N = 5 each processed with two cutting passes at total production cost equal to $2.5. It means that, the tool can be replaced after processing five parts at two cutting passes each. The quality of surface finish s_2 = 1.25 μm. The optimal cutting speeds v_1 = 150 m/min, v_2 = 250 m/min; feed rates f_1 = 0.7 mm/rev, f_2 = 0.25 mm/rev; depths of cut d_1 = 4.48 mm, d_2 = 0.52 mm; and amounts of tool wear w_1 = 0.03 mm, w_2 = 0.05 mm.

A sensitivity analysis was conducted through additional computations in order to examine how the material removal rate and production cost would change with variations in total depths of cut. This helps to test out the range of validity of the formulated models and data used in the models. The sensitivity results of material removal rate and production cost with associated machining parameters, tool wear, surface quality, number of parts and number of passes are summarised in Table 2 and Table 3. As seen in the two tables, the decisions of optimal machining parameters, tool wear and surface quality can be concurrently made while the material removal rate is maximised and production cost minimised. As expected, different machining parameters could lead to different tool wear and surface quality. Nevertheless, it can be observed that the same machining parameters may provide different tool wears. This is because of differences in workpiece diameters at respective cutting passes whose amounts also contribute to tool wear.

Table 1 Input data for the two machining optimisation models

Symbol	Value
C_e, C_o, t_r	\$3/edge, \$0.5/min, 1 min
v_i^L, v_i^U	60 m/min, 150 m/min for rough turning; 160 m/min, 250 m/min for finish turning
f_i^L, f_i^U	0.3 mm/rev, 0.7 mm/rev for rough turning; 0.15 mm/rev, 0.25 mm/rev for finish turning
d_i^L, d_i^U	2.5 mm, 7.6 mm for rough turning; 0.25 mm, 2.5 mm for finish turning
S_o, S_{max}, A	0.4 μm, 6.3 μm, \$2 for each part
α_T, β_T, γ_T, E_T, W_{max}	1.41, 0.35, 0.25, 17795, 0.4 mm
α_F, β_F, γ_F, E_F, F_{max}	–0.15, 0.75, 1, 2.65, 2 kN
α_P, β_P, γ_P, E_P, P_{max}	0.85, 0.75, 1, 0.059, 10 kW
α_S, β_S, η, θ, r, BHN	–1.52, 1.004, –0.714, –0.323, 1 mm, 195

Table 2 Results of MRR model for different total depth of cut with tool cost $3/edge

Depth of cut d_T (mm)	MRR (mm³/min)	Machining parameters v_i (m/min), f_i (mm/rev), d_i (mm)	Tool wear w_i (mm)	Surface quality s_I (μm)	Parts N	Passes p_i
10	463603	$v_1 = 150$, $v_2 = 215$ $f_1 = 0.7$, $f_2 = 0.25$ $d_1 = 7.6$, $d_2 = 2.4$	$w_1 = 0.04$, $w_2 = 0.06$	1.6	4	2
15	511581	$v_1 = v_2 = 150$, $v_3 = 250$ $f_1 = f_2 = 0.7$, $f_3 = 0.15$ $d_1 = 6.8$, $d_2 = 7.6$, $d_3 = 0.6$	$w_1 = 0.04$, $w_2 = 0.03$ $w_3 = 0.06$	0.75	3	3
20	521605	$v_1 = v_2 = v_3 = 150$, $v_4 = 203$ $f_1 = f_2 = f_3 = 0.7$, $f_4 = 0.25$ $d_1 = d_2 = 7.6$, $d_3 = 4.55$, $d_4 = 0.25$	$w_1 = 0.04$, $w_2 = 0.03$ $w_3 = 0.03$, $w_4 = 0.03$	1.7	3	4
25	536140	$v_1 = v_2 = v_3 = 150$, $v_4 = 250$ $f_1 = 0.42$, $f_2 = f_3 = 0.7$, $f_4 = 0.15$ $d_1 = 7.3$, $d_2 = d_3 = 7.6$, $d_4 = 2.5$	$w_1 = 0.05$, $w_2 = 0.04$ $w_3 = 0.03$, $w_4 = 0.08$	0.75	2	4
30	609427	$v_1 = v_2 = v_3 = v_4 = 150$, $v_5 = 250$ $f_1 = f_2 = f_3 = f_4 = 0.7$, $f_5 = 0.15$ $d_1 = 5.7$, $d_2 = d_3 = d_4 = 7.6$, $d_5 = 1.5$	$w_1 = 0.04$, $w_2 = 0.04$ $w_3 = 0.03$, $w_4 = 0.03$ $w_5 = 0.06$	0.75	2	5
35	609792	$v_1 = v_2 = v_3 = v_4 = v_5 = 150$, $v_6 = 250$ $f_1 = f_2 = f_3 = f_4 = f_5 = 0.7$, $f_6 = 0.16$ $d_1 = 5.2$, $d_2 = 6.8$, $d_3 = d_4 = d_5 = 7.6$, $d_6 = 0.25$	$w_1 = 0.04$, $w_2 = 0.04$ $w_3 = 0.03$, $w_4 = 0.03$ $w_5 = 0.03$, $w_6 = 0.03$	0.8	2	6
40	678596	$v_1 = v_2 = v_3 = v_4 = v_5 = 150$, $v_6 = 163$ $f_1 = f_2 = f_3 = f_4 = f_5 = 0.7$, $f_6 = 0.25$ $d_1 = d_2 = d_3 = d_4 = d_5 = 7.6$, $d_6 = 2.0$	$w_1 = 0.04$, $w_2 = 0.04$ $w_3 = 0.03$, $w_4 = 0.03$ $w_5 = 0.03$, $w_6 = 0.03$	2.4	2	6

The importance of proper selection of cutting passes is due to the fact that a single pass will not be feasible because it should be a finish cutting which will not satisfy the total depth of cut to be removed. On the other hand, a single pass with a very heavy depth of cut may also be infeasible due to excessive cutting force and power which may lead to tool breakage.

Table 3 Results of cost model for different total depth of cut with tool cost $3/edge

Depth of cut d_T (mm)	$COST$ ($)	Machining parameters v_i (m/min), f_i (mm/rev), d_i (mm)	Tool wear w_i (mm)	Surface quality s_I (μm)	Parts N	Passes p_i
10	3.2	$v_1 = 139$, $v_2 = 150$, $v_3 = 250$ $f_1 = f_2 = 0.7$, $f_3 = 0.25$ $d_1 = 7.6$, $d_2 = 2.15$, $d_3 = 0.25$	$w_1 = 0.04$, $w_2 = 0.02$ $w_3 = 0.04$	1.25	4	3
15	3.5	$v_1 = v_2 = 150$, $v_3 = 250$ $f_1 = f_2 = 0.7$, $f_3 = 0.25$ $d_1 = 7.5$, $d_2 = 5.0$, $d_3 = 2.5$	$w_1 = 0.04$, $w_2 = 0.03$ $w_3 = 0.06$	1.25	3	3
20	4.1	$v_1 = v_2 = 137$, $v_3 = 150$, $v_4 = 250$ $f_1 = f_2 = f_3 = 0.7$, $f_4 = 0.25$ $d_1 = d_2 = 7.6$, $d_3 = 4.55$, $d_4 = 0.25$	$w_1 = 0.04$, $w_2 = 0.03$ $w_3 = 0.03$, $w_4 = 0.03$	1.25	3	4
25	5.4	$v_1 = v_2 = v_3 = v_4 = 150$, $v_5 = 250$ $f_1 = f_2 = f_3 = f_4 = 0.7$, $f_5 = 0.182$ $d_1 = 5.4$, $d_2 = 5.5$, $d_3 = 5.7$, $d_4 = 5.9$, $d_5 = 2.5$	$w_1 = 0.04$, $w_2 = 0.03$ $w_3 = 0.03$, $w_4 = 0.03$ $w_5 = 0.07$	0.9	2	5
30	5.3	$v_1 = v_2 = v_3 = v_4 = 150$, $v_5 = 250$ $f_1 = f_2 = f_3 = 0.7$, $f_4 = 0.66$, $f_5 = 0.187$ $d_1 = 6.39$, $d_2 = 6.61$, $d_3 = 6.89$, $d_4 = 7.6$, $d_5 = 2.5$	$w_1 = 0.04$, $w_2 = 0.04$ $w_3 = 0.03$, $w_4 = 0.03$ $w_5 = 0.06$	0.9	2	5
35	5.4	$v_1 = v_2 = v_3 = v_4 = v_5 = 150$, $v_6 = 250$ $f_1 = f_2 = f_3 = 0.7$, $f_4 = 0.66$, $f_5 = 0.7$, $f_6 = 0.25$ $d_1 = d_2 = d_3 = d_4 = 7.6$, $d_5 = 3.3$, $d_6 = 1.3$	$w_1 = 0.04$, $w_2 = 0.04$ $w_3 = 0.03$, $w_4 = 0.03$ $w_5 = 0.02$, $w_6 = 0.04$	1.25	2	6
40	6.0	$v_1 = v_2 = v_3 = v_4 = v_5 = v_6 = 137$, $v_7 = 250$ $f_1 = f_2 = f_3 = f_4 = f_5 = f_6 = 0.7$, $f_7 = 0.25$ $d_1 = d_2 = d_3 = d_4 = d_5 = d_6 = 7.6$, $d_7 = 2.5$	$w_1 = 0.04$, $w_2 = 0.03$ $w_3 = 0.03$, $w_4 = 0.03$ $w_5 = 0.03$, $w_6 = 0.02$ $w_7 = 0.02$	1.25	2	7

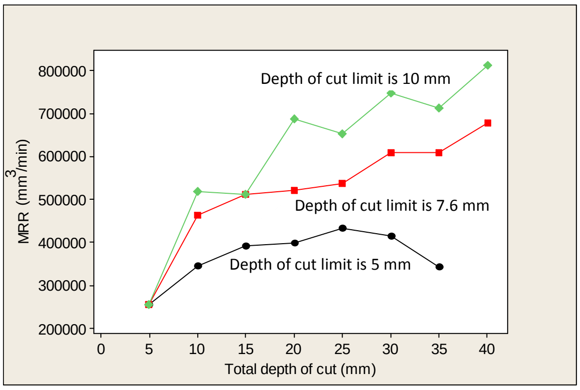

Fig. 3 The effect of total depth of cut on average material removal rate

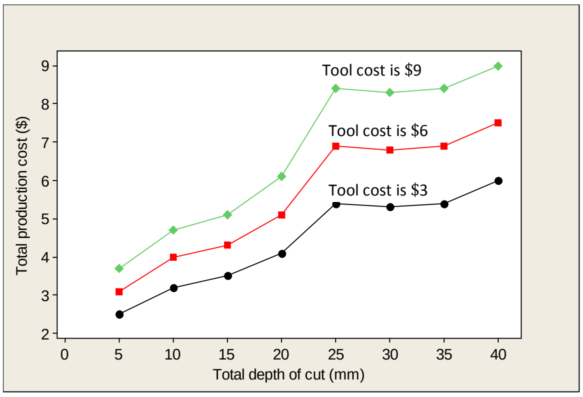

Fig. 4 The effect of total depth of cut on total production cost

By comparing the number of cutting passes in Tables 2 and 3, there is a reality that maximum removal of material may cause reduced number of cutting passes because a significant amount of material is removed out of the workpiece.

Fig. 3 depicts the fact that when the total depth of cut is increased, the average material removal rate will also increase. Moreover, the increase in the depth of cut limits could lead to increased average material removal rate. As the study in [4] pointed out, the maximum depth-of-cut constraint may have great influence on the production cost and the selected number of passes. However, with smaller depth of cut limits, the average material rate may drop as the total depth of cut increases. The reason might be that, attaining total removed material with smaller cutting depths requires more number of cutting passes. Accordingly, many number of cutting passes may reduce the average material removal rate. In Fig. 4, it is shown that by increasing the total depth of cut, the total production cost also increases. However, there is a zone where production cost becomes slightly constant despite the increase in total depth of cut. This zone gives a cost advantage of operating at higher material removal rate. It is also revealed that increasing tool cost results in increased total production cost.

5. Conclusion

This study have attempted to develop and compute two machining optimisation models in order to provide inclusive decisions of machining parameters, tool wear and surface quality while meeting maximum material rate and minimum production cost objectives. It has added up some theoretical concepts of machining optimisation analyses bridging the gap of suboptimal solutions mostly obtained in machining optimisation problems. The formulated models can easily be adopted on the machining shop floor since the sensitivity analysis has supported their applicability over a wide range of total depths of cut. A new fact has been revealed whereby tool wear for each cutting pass and surface finish can be determined and known in the process planning stage even before the actual turning operation. In this case, the task of taking measurements of amounts of tool wear during the operations or the use of expensive on-line measurement for tool wear and surface finish can be avoided. The study has shown that the total depth of cut and the average material removal rate as well as the total depth of cut and production cost are well correlated. It can also be deduced that proper selection of number of cutting passes may exhibit feasible removal of material and thus avoid unnecessary conservative or aggressive depths of cut. Finally, the tool replacement can be scheduled based on the number of processing parts and cutting passes.

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