Flexible machining environments – tests on the shop floor in order to minimize setup times

Ambiente de fabricação flexível – testes em chão de fábrica para redução do tempo de setup

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Abstract

In previous work the authors proposed a model suitable for reducing the number of cutting tools required for machining in factory environments, where production lots consisting of a small number of pieces of different materials and geometries were optimized. The model, although yielding good results in simulations, lacked a practical application. The purpose of this paper is to analyze and provide any needed modifications of the optimization model and then validate the more recent one using data obtained from its practical implementation in the shop floor of an industry that operates using flexible machining practices. This implementation is important to allow the identification of other situations that were not perceived in simulation, such as the variation in cutting tool life. The results show that the model can be successfully applied to flexible manufacturing environments.

Key words: Flexible Machining. Optimization. Presetting.

Resumo

Em trabalhos anteriores, os autores propuseram um modelo de otimização adequado para a redução do número de ferramentas de corte exigida para usinagem de pequenos lotes de peças de diferentes materiais e geometrias. O modelo, apesar de dar bons resultados nas simulações realizadas, carecia de uma aplicação prática. O objetivo deste trabalho é analisar e fornecer quaisquer modificações necessárias do referido modelo de otimização e depois validar o mais recente com dados obtidos em sua aplicação prática no chão de fábrica. Para isso, foi selecionada uma indústria que opera com usinagem flexível. Tal aplicação é importante para permitir a identificação de outras situações que eventualmente não foram percebidas nas simulações feitas, tais como variações no tempo de vida da ferramenta. Os resultados mostram que o modelo pode ser aplicado com sucesso em ambientes de manufatura flexível.

Palavras-chave: Otimização. Presetting. Usinagem flexível.

1 Introduction

Studying the optimization of a cutting process is not as easy as it sounds. Along the years, the authors have noted that tool manufacturers are called upon by their customers to optimize their machining processes. However, usually this optimization procedure occurs in manufacturing plants based on actual data. Unfortunately, in these cases, commercial interests negatively influences the results, because the tool manufacturer is interested in selling products, not in continuing to seek further optimization of process parameters. Actually, this procedure is not incorrect, because industries have to earn profits. Fortunately, there are researchers who examine these issues without the need to be concerned about the immediate financial aspects, except when this is actually part of the research objectives.

Inspired by the cited tool manufacturers' behavior, the authors opted to develop models for optimizing cutting processes using data extracted from the shop floor in real time in the production of machined parts.

In the particular case of flexible machining, the development of optimization models is even more challenging and has been studied by other researchers (MUKHERJEE, RAY, 2006). Boyle and Scherrer-Rathje (2009) proposed an empirical way to better examine the problems related with flexible manufacturing. This is because, to obtain statistically reliable data directly from the shop floor requires production of a reasonable number of identical parts, representing an adequate sampling (COPPINI, BAPTISTA, 2002).

It is almost impossible for this situation to occur, because during the planning of a typical flexible machining workday, normally several batches of only a small number of parts each are scheduled. In extreme cases, it can be just one.

To work in this type of setting, the authors identified the following possible situations:

- optimize the cutting parameters that influence the cutting time. Try to reduce non-productive time by applying concepts of lean manufacturing. This option would require tests to determine each tool's life and its respective size in each lot. This would be impossible to be applied in the field, because it would require the shop floor to operate as a laboratory. When the number of parts per batch is large, the authors have developed models and operational support systems which are already presenting good solutions (COPPINI, BAPTISTA, 2002);
- reduce the presetting time: in this case it will be necessary to find solutions with greater flexibility to reduce the presetting time. This is because, to use specific selected tools to cut different batches, innumerous presettings will be necessary (GUILHERME et al., 2008; VIEIRA JÚNIOR et al. 2006; VIEIRA JÚNIOR et al. 2007; MENG et al. 2000);
- reduce the presetting time as proposed and detailed later in this paper;
- explore all the above proposals at the same time after analyzing the characteristic background of each industry.

The purpose of this paper is to analyze and eventually provide any necessary modification of the optimization model already developed by the authors in previous work and then validate the more recent one using data taken from its practical application in the shop floor of an industry that works in an environment of flexible machining.

2 Theoretical foundations

The theoretical foundations used in this paper are based on the author's previous work (GUILHERME, et al., 2008). The concept of cutting tool edge life was applied in a different way from how it is traditionally done. The same cutting tool will be used to cut parts with different materials and geometries. Each batch will use a percentage of the cutting edge life, according to the hardness of the pieces and their number. Thus, supposing that (n) batches are scheduled for a fraction of a workday. For batch (i) it is possible to write down Equation (1):

$$Z_{ti} = \frac{T_i}{t_{ci}} \tag{1}$$

where
Z_{ti} = number of pieces per cutting edge life of batch (i);
T_i = life of the cutting edge for batch (i) and workpiece material (previously determined or obtained from the manufacturer's tool catalog) [min];
t_{ci} = cutting time to cut one piece of batch (i) [min].

Thus, for a number of machined parts (Z_i) less then (Z_{ti}), only a percentage (PT_{ai}) of its life is used up. Then, the same cutting edge can continue mounted in the machine, cutting new parts of the same batch or parts of the next new batch. (PT_{ai}) is given by Equation (2).

$$PT_{ai} = \sum_{i=1}^{n} \left(\frac{Z_i}{Z_{ti}} \right) * 100 \tag{2}$$

where the relationship (Z_i/Z_{ti}) is the percentage of cutting edge life used up to cut a number of pieces of batch (i).

When the predefined life criterion is reached, the same cutting edge accumulates percentages of tool life used up to cut different parts of different batches. Then, it can be considered that, when the (PT_a) value, calculated as showed in Equation (3), is close or equal to 100%, the cutting edge has had its life completely used up, and must be exchanged for a new one. Values close to 100% are considered, because, it is unlike that (PT_a) results equal exactly 100%. The (PT_a) value could be 100% when cutting pieces from one or different batches. Summarizing, the cutting edge should always be changed when

$$PT_a = \sum_{j}^{m} PT_{aj} \cong 100\% \tag{3}$$

where
(PT_a) reaches approximately 100% of cutting edge life used up for cutting (m) parts from (j) different batches [%].

A second aspect pursued in the author's previous work was the method used for calculating the cutting edge life. It was based on the toolmaker's catalog. More specifically, the theoretical foundations developed by Sandvik Coromant (2009) were adopted. This tool maker supplies a catalog that allows selecting the cutting parameters; and, for these, the foreseen cutting edge life is supposed to be 15 minutes. The catalog does not inform what the cutting edge's life criterion is.

If, for an actual application, the workpiece material presents a different hardness from that for which the catalog was created, it will be necessary to introduce a factor correction to calculate the new cutting edge life. For this purpose the user will find inside the catalog a table giving the appropriate correction factors for different hardness levels. Another correction must be used in the case where the cutting speed must be modified to adjust for the actual application: in this case, it will be necessary to calculate the new edge life using a factor also obtained from a catalog table.

3 Theoretical simulation of the model

Based on the author's previous work, a new version of Table 1 is presented that represents the simulated theoretical scheduling to cut three different parts – A, B and C.

Table 1 summarizes the essence of the proposed model, which is to reduce the presetting time in flexible cutting process situations.

For the users, it is recommended that the following steps be applied:

a) each work day must be organized to identify batches of parts that will be cut with the same tool material and geometry;
b) select the holder and insert geometry so that the tool can cut profiles of all the different parts of the scheduled batches, without interferences in its trajectories during the cutting process evolution;
c) select in the tool maker's catalog all the cutting conditions as they normally occur and also determine the respective cutting edge lives, strictly following the catalog recommendations;
d) a batch must be considered a group of parts with the same geometries and materials. In an extreme case, the number of parts per batch could be just one;
e) the optimization model is proposed for making operations in CNC lathes highly flexible. However, the model could be applied also to other types of cutting operations and machines;
f) the cutting edges will be changed at each one's life end, based on a pre-fixed tool edge life criterion. In the case of Table 1, this is when the life of the cutting edge is reached;
g) the cutting edge exchange should be made the moment it reaches approximately 100% of its life, determined according the tool maker's catalog. This could occur for a number of pieces of one or more batches;
h) when the Table for the theoretical model is ready, it will be the moment to verify its performance in practice;
i) for the proposed model, the setup time between batches will only include running each batch's CNC program, providing the machine settings, possibly exchanging holders for the new parts to be cut and cutting the first workpiece just to check if everything is set according to the desired part quality. It is no longer necessary to spend time cleaning the work area, doing maintenance or presetting before starting to cut a new batch of parts.

As mentioned before, Table 1 is a process planning simulation for three pieces, A, B and C, that illustrates the proposed model. The cost reduction of 28% was obtained by comparing the manufacturing cost calculated in the traditional way with the proposed model calculated in Table 1. On the other hand, Table 2 illustrates the simulation of a traditional process planning for the same parts of Table 1. The purpose of these simulations is to make it easier to understand the discussion of the proposed optimization model and its comparison with the traditional model.

Table 2 represents the planning process to machine the same three parts of Table 1, using the traditional cutting process routine. In this case, tool and part pairs are selected through the catalog; however, the cutting speed indicated is adopted, instead of using cutting data that, with the traditional method, could be completely different for each pair. The tool life is therefore always 15 minutes.

Each Table 2 column has the same meaning as in Table 1, but the final results are different because the values of cutting speed, tool life, cutting time and independent times are different too.

Table 1: Proposed optimization model application simulating three pieces A, B and C to be machined based on the proposed model (1 US$ = R$ 1,893)

1	2	3	4	5	6	7	8	9	10	11	
Parts	Z_{batch}	s_{cat} [m/min]	T_i [min]	t_{ci} [min]	t_{st} [min]	Z_{ti}	Z_i	PT_{ai} [%]	PT_a [%]	N_t	
A	16	216	12	1.5	3.0	8.2	8	97.3	97.3	1	
A		216	12	1.5	3.0	8.2	8	97.3	97.3	1	
B	10	216	15	1.7	3.0	8.6	8	92.8	92.8	1	
B		216	15	1.7	3.0	8.6	2	23.2	23.2		
C	30	216	20	0.9	3.0	22.2	17	76.5	99.7	1	
C		216	20	0.9	3.0	22.2	13	58.5	58.5	0.6	
Total value of t_c plus t_{st} multiplied by Z_i [min]											85.8
Passive time (piece load/unload, tool change time, etc...) [min]											34.2
Total number of cutting tool edges N_t to machine all batches											4.6
Total cost to machine all batches [$]											168.0
Cost reduction compared with the traditional cutting process routine [%]											28.8

where:
1st – is the part code;
2nd – is the batch size;
3rd – is the cutting speed selected strictly from the tool maker's catalog;
4th – cutting edge life is 15 minutes (according to the manufacturer). The simulation took material A to be the hardest to cut when compared with the others. Material B is easier than material A, and material C the easiest of all. In this way, the cutting speed of the material with an intermediate hardness was chosen. This same cutting speed was used for the other two materials and their cutting edge lives were recalculated based on their hardness;
5th – is the cutting time per part;
6th – is the suggested time that is supposed to be sufficient to take care of all necessary activities for adjusting the equipment to run the first workpiece;
7th – is the cutting edge life in number of machined parts;
8th – is the number of machined parts;
9th – is the edge life percentage used up per effective number of machined parts;
10th – is the cutting edge percentage of life accumulated until 100% of it is used up.
11th – is the number of tool cutting edges used up;

Table 2: Proposed optimization model application simulating three pieces A, B and C to be machined based on a traditional routine (1 US$ = R$ 1.893).

Piece	Z_{lot}	s_{cat}	T_i	t_{ci}	t_{st}	Z_{ti}	Z_i	PT_{ai}	PT_a	N_t	
A	16	179	15	1.8	15.0	8.3	8	96.0	96.0	1	
A		179	15	1.8	3.0	8.3	8	96.0	96.0	1	
B	10	216	15	1.7	15.0	8.6	8	92.8	92.8	1	
B		216	15	1.7	3.0	8.6	2	23.2	23.2	1	
C	30	220	15	0.9	15.0	16.7	17	102.0	102.0	1	
C		220	15	0.9	3.0	16.7	13	78.0	78.0	0.8	
Total value of t_c plus t_{st} multiplied by Z_i [min]											127.2
Passive time (piece load/unload, tool change time, etc...) [min]											4.2
Total number of cutting tool edges N_t to machine all batches											5.8
Total cost to machine all batches [$]											235.9

The last line of Table 1, colored in gray, shows the drastic reduction in the cost to machine all the batches when using the proposed model instead of the traditional cutting process routine. It is observed that the main influencing factor in reducing the cost is the least time spent in presetting the machine.

4 Material and method

The method can be considered exploratory as regards the development of the research, and applied and quantitative from the standpoint of its objective (COUGHLAN; COGHLAN, 2002; VOSS; FROHLICH, 2002).

The proposed model mentioned before to reduce the presetting time was applied in a company that manufactures parts in an environment of flexible machining. Several parts with different geometries and three different types of steel (SAE 4140 (A), 6150 (B) and 4340 (C)) were machined. The materials were not subjected to heat treatment and had a hardness of approximately 180 HB. The parts and the process used to machine them were routine for the company. Their concept of cutting process flexibility reaches extremes, because their batches tend to have only one piece each.

The machining operation was performed on the same CNC lathe used to machine the mentioned parts during regular production. The tool holder and insert were chosen using the first suggestion of a tool marker catalog: tool holder: ISO - C5-DDJNL-35060-15, and insert - DNMG 15 06 12-PM 4225. Only a rough turning was used to assess the model's performance on the shop floor.

In the theoretical model the criterion adopted for exchanging the cutting tool edge was its useful life as published in the tool maker's catalog. This means that the same cutting speed for all the geometries and materials parts was considered because they have the same hardness. The cutting speed of 325 m/min selected from the catalog for a life of 15 minutes was changed to 280 m/min as a result of some machine constraints. This resulted in the need to calculate the new edge life of 29.42 min, as will be shown further ahead.

On the other hand, the criterion adopted to exchange the cutting tool edge in the shop floor during the theoretical model validation was the dimensional variation of the machined part of 0.2 mm, the same criterion and routine used by the machine operator during regular production of the parts. Furthermore, and still in the tradition of the company, one cutting edge was always replaced by a new one when the percentage of its remaining life was not quite sufficient to machine the next part. The others parameter was the cut depth of 3.0 mm and feed rate of 0.35 mm/rot. The cutting time for each part was measured running the CNC program with no part held in the machine using a block-by-block movement of the tool.

5 Results and discussion

Following the Sandvik Metal Cutting Technical Guide (2009), it was not necessary to make cutting speed or tool life corrections because all the steels – SAE 4140 (A), 6150 (B) and 4340 (C) – have the same hardness.

However, the cutting speed of 325 m/min, forced by some machine's constraints, had to be replaced by 280 m/min. So, to calculate the new tool life, the correction factor presented in the Table 3 was used.

Table 3: Correction factors for tool edge life for cutting speeds different from those selected in the catalog

Tool Life [min]	10	15	20	25	30	45	60
Correction Factor	1,10	1,0	0,95	0,90	0,87	0,80	0,75

Source: Sandvik Coromant do Brasil Ind. e Com. (2009).

It is possible to write:

If 325 [m/min] - original cutting speed corresponds to	→	1 (correction factor because tool life is equal to 15 min)
So, 280 [m/min] new cutting speed corresponds to	→	y (new correction factor to be found)

The correction factor can be given by

$$y = \frac{280 \times 1{,}0}{325} = 0{,}86 \approx 0{,}87 \quad (4)$$

Table 3 shows that the tool life for a cutting speed of 280 m/min is approximately 30 min.

The results of the proposed model simulation and experimental application in an industrial shop floor are shown in Table 4, where the parts were coded with a letter followed by a number. The letter states that the material part is identified as SAE 4140 (A), SAE 6150 (B) or SAE 4340 (C). The numbers following the letters means that the parts are geometrically different from each other.

As the tool edge life was not measured for the part size dimensional variation criterion of 0.2 mm, only the tool life criterion of 30 min from the catalog was informed in Table 4.

However, if a systematic monitoring similar to this work is carried out, it will be possible to forecast the use of cutting edges with a greater match between simulation and real data. Furthermore, such continuous monitoring of the process will, at some point, allow batches with sufficient number of parts, enough to determine the cutting edge life specifically for this case. This would be the ideal situation for the application of the proposed model and its monitoring in practice.

Then, it will also be possible to use the proposed method to make predictions about the number of cutting edges that will be used for whatever mix of parts to be machined.

This kind of knowledge will be very useful to manage the process efficiently. First because it will be possible to carry out the planning process with more precision; and second, because it will be easier to follow up on how the process is running in the shop floor.

Another aspect to be discussed concerns the discrepancies between the theoretical model and the practical experiments carried out in this work. This fact can be explained by:

- tool makers probably provide an approximate value for the cutting edge life (15 min) taking into account larger cutting edge wear than a part's dimensional variation, equal to 0.2 mm;
- the criterion used to exchange the cutting edge even with a high percentage of edge life to be used up just to not have to change the cutting edge during the machining of the next part was also a very important factor in the discrepancies that were found. Unfortunately, this criterion is adopted by the company and at least in this research, it was not possible to change. To illustrate this fact, consider the pieces from C3 to C9. The sum of the percentages of life of the cutting edges is 295.7%. This value corresponds to the use of approximately three cutting edges (100% per cutting edge) in total instead of seven, which would mean a reduction in the final four edges. Obviously, in fact this criterion means that money is being thrown out, just what was meant to be prevented with the use of the proposed model.

Table 4: Simulation of the model and experimental test in a regular production shop floor of a typical flexible machining industry

<table>
<tr><th colspan="12">Experimental data</th><th colspan="3">Theoretical data</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th></th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th></tr>
<tr><th>Part</th><th>Material</th><th>Z_{lot}</th><th>s_{cat}</th><th>T_i</th><th>t_{ci}</th><th>t_{st}</th><th>Z_{ti}</th><th>Z_i</th><th>PT_{ai}</th><th>PT_a</th><th>N_t</th><th>PT'_{ai}</th><th>PT'_a</th><th>N'_t</th></tr>
<tr><th></th><th></th><th></th><th>[m/min]</th><th>[min]</th><th>(min)</th><th>[min]</th><th></th><th></th><th>[%]</th><th>[%]</th><th></th><th>[%]</th><th>[%]</th><th></th></tr>
<tr><td>A1</td><td>4140</td><td>2</td><td>280</td><td>30</td><td>0.2</td><td>0.0</td><td>137.1</td><td>2</td><td>1.5</td><td>1.5</td><td rowspan="6">1.0</td><td>1.5</td><td>1.5</td><td rowspan="11">1.0</td></tr>
<tr><td>B1</td><td>6150</td><td>1</td><td>280</td><td>30</td><td>0.7</td><td>0.0</td><td>43.5</td><td>1</td><td>2.3</td><td>3.8</td><td>2.3</td><td>3.8</td></tr>
<tr><td>A2</td><td>4140</td><td>1</td><td>280</td><td>30</td><td>1.1</td><td>0.0</td><td>26.6</td><td>1</td><td>3.8</td><td>7.5</td><td>3.8</td><td>7.5</td></tr>
<tr><td>A3</td><td>4140</td><td>2</td><td>280</td><td>30</td><td>1.3</td><td>0.0</td><td>23.1</td><td>2</td><td>8.6</td><td>16.2</td><td>8.6</td><td>16.2</td></tr>
<tr><td>B2</td><td>6150</td><td>2</td><td>280</td><td>30</td><td>2.9</td><td>0.0</td><td>10.3</td><td>2</td><td>19.4</td><td>35.6</td><td>19.4</td><td>35.6</td></tr>
<tr><td>B3</td><td>6150</td><td>3</td><td>280</td><td>30</td><td>1.3</td><td>0.0</td><td>22.3</td><td>3</td><td>13.5</td><td>49.0</td><td>13.5</td><td>49.0</td></tr>
<tr><td>C1</td><td>4340</td><td>2</td><td>280</td><td>30</td><td>2.8</td><td>0.0</td><td>10.5</td><td>2</td><td>19.1</td><td>19.1</td><td rowspan="2">1.0</td><td>19.1</td><td>68.1</td></tr>
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<tr><td>B5</td><td>6150</td><td>7</td><td>280</td><td>30</td><td>0.3</td><td>0.0</td><td>99.0</td><td>7</td><td>7.1</td><td>14.9</td><td>7.1</td><td>91.1</td></tr>
<tr><td>B6</td><td>6150</td><td>1</td><td>280</td><td>30</td><td>3.0</td><td>0.0</td><td>9.8</td><td>1</td><td>10.2</td><td>25.1</td><td>10.2</td><td>101.3</td></tr>
<tr><td>A4</td><td>4140</td><td>1</td><td>280</td><td>30</td><td>1.4</td><td>0.0</td><td>21.0</td><td>1</td><td>4.8</td><td>29.9</td><td>4.8</td><td>4.8</td><td rowspan="4">1.0</td></tr>
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<tr><td rowspan="2">C4</td><td rowspan="2">4340</td><td rowspan="2">1</td><td rowspan="2">280</td><td rowspan="2">30</td><td rowspan="2">11.1</td><td rowspan="2">0.0</td><td rowspan="2">2.7</td><td rowspan="2">1</td><td rowspan="2">37.3</td><td rowspan="2">37.3</td><td rowspan="2">1.0</td><td>23.8</td><td>100.0</td></tr>
<tr><td>13.5</td><td>13.5</td><td rowspan="4">1.0</td></tr>
<tr><td>C5</td><td>4340</td><td>1</td><td>280</td><td>30</td><td>11.1</td><td>0.0</td><td>2.7</td><td>1</td><td>37.3</td><td>37.3</td><td>1.0</td><td>37.3</td><td>50.8</td></tr>
<tr><td>C6</td><td>4340</td><td>1</td><td>280</td><td>30</td><td>11.1</td><td>0.0</td><td>2.7</td><td>1</td><td>37.3</td><td>37.3</td><td>1.0</td><td>37.3</td><td>88.1</td></tr>
<tr><td rowspan="2">C7</td><td rowspan="2">4340</td><td rowspan="2">1</td><td rowspan="2">280</td><td rowspan="2">30</td><td rowspan="2">14.0</td><td rowspan="2">0.0</td><td rowspan="2">2.1</td><td rowspan="2">1</td><td rowspan="2">47.1</td><td rowspan="2">47.1</td><td rowspan="2">1.0</td><td>11.9</td><td>100.0</td></tr>
<tr><td>35.2</td><td>35.2</td><td rowspan="3">1.0</td></tr>
<tr><td>C8</td><td>4340</td><td>1</td><td>280</td><td>30</td><td>16.8</td><td>0.0</td><td>1.8</td><td>1</td><td>56.7</td><td>56.7</td><td>1.0</td><td>56.7</td><td>91.9</td></tr>
<tr><td rowspan="2">C9</td><td rowspan="2">4340</td><td rowspan="2">1</td><td rowspan="2">280</td><td rowspan="2">30</td><td rowspan="2">12.7</td><td rowspan="2">0.0</td><td rowspan="2">2.3</td><td rowspan="2">1</td><td rowspan="2">42.6</td><td rowspan="2">42.6</td><td rowspan="2">1.0</td><td>7.4</td><td>99.3</td></tr>
<tr><td>35.2</td><td>35.2</td><td>0.4</td></tr>
<tr><td colspan="6"></td><td colspan="5">Total number of cutting tool edges</td><td>10.0</td><td colspan="2"></td><td>4.4</td></tr>
</table>

where
12th – is the real total number of tool cutting edges used up;
13th – is the theoretical percentage of edge life used up for an effective number of machined parts;
14th – is the theoretical percentage of cutting edge life accumulated until 100% of it is used up;
15th – is the theoretical number of tool cutting edges used up.

6 Final considerations

Based on what was accomplished in this study, it is possible to present the following closing remarks:

- the corrections provided for the theoretical model that was proposed during EngOpt 2008 allowed the comparison between the theoretical and practical model, remaining faithful to the concept sought by the proposal. The cutting speeds for different batches of parts were kept constant and only the correction of the cutting edge lives due to possible variations in the hardness was provided;

- still, based on the proposed model, after simulation it is observed that the reduction in cost to machine all the batches, around 30%, was mainly due to the reduction of the presetting time;
- the simulation followed by the validation in shop floor showed discrepancies. The main reason for these is that the cutting edge life criterion is not declared by tool makers. Without this information, it is very difficult to make forecasts for establishing the planning process and impossible to follow up the process in the manufacturing plant;
- the systematic monitoring of the proposed model on the shop floor with the recording of data related to the tool's performance allowed the determination of the tool lives for a given parts mix machined in actual production conditions. In addition, it will be possible to have a more realistic cutting edge exchange criterion;
- based on actual data, the planning process will be more realistic and the process management in the shop floor will be easier to carry out;
- this work is a specific case and the results cannot be considered for all situations. Another case must be run to make the proposed model more reliable.

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Recebido em 8 jun. 2011 / aprovado em 18 nov. 2011

Para referenciar este texto
BAPTISTA, E. A.; OLIVEIRA, A.; COPPINI, N. L. Flexible machining environments – tests on the shop floor in order to minimize setup times. *Exacta*, São Paulo, v. 10, n. 1, p. 27-35, 2012.