A decision support system for machine tool selection

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Introduction

A machine tool selection is an important decision-making process for many manufacturing companies. Improperly selected machines can negatively affect the overall performance of a production system. The speed, quality and cost of manufacturing strongly depend on the type of the machine tool used. Since the selection of new machines is a time-consuming and difficult process requiring advanced knowledge and experience, it may cause several problems for the engineers, managers and also for the machine manufacturer. For example, if the customer does not know which machines are suitable for the application, the machine manufacturer should send his staff, even if it is costly. The lack of standard format in machine catalogues, the large number of factors to be considered, and introduction of new machine tools together with the advancements in the technology complicates the problem further. For a proper and effective evaluation, the decision maker may need a large amount of data to be analyzed and many factors to be considered. The decision maker should be an expert, or at least be very familiar with the machine properties, to select the most suitable machine among the alternatives. However, a survey conducted by Gerrard (1988a) reveals that the role of engineering staff in authorization for final selection is 6 per cent, the rest belongs to upper and middle management (94 per cent). This also indicates the need for a simplified and practical approach for the machine selection process.

The machine selection problem has been studied mostly for specific type of environment, such as flexible manufacturing systems (FMS). However, new machine selection approach should be applicable to many environments. Tabucanon et al. (1994) developed a decision support system for multi-criteria machine selection problem for flexible manufacturing systems. Analytic hierarchy process (AHP) technique is used for selection. Wang et al. (2000) proposed a fuzzy multiple-attribute...
decision-making model to assist the decision maker to deal with the machine selection problem for a FMS. Machine selection from fixed number of available machines is considered by Atmani and Lashkari (1988). They developed a model for machine tool selection and operation allocation in FMS. The model assumes that there is a set of machines with known processing capabilities. AHP is also proposed by Lin and Yang (1994) to evaluate what type of machine is most appropriate for machining a certain type of part. Goh et al. (1995) proposed a revised weighted sum decision model for robot selection by using weights that are assigned by a group of experts. In Gerrard (1988b), a step-by-step methodology for the selection and introduction of new machine tools is proposed. Valuable information is given about how new equipment is selected.

Considering that, to capture the developments in industry, we should not attempt to complicate the engineering problems unless it is necessarily leading to a better solution, multi-criteria weighted average using hierarchy tree is used in decision making. It is designed to select the best from possible alternatives evaluated with respect to several criteria. The selection process consists of three steps. In the first step, the machine specifications will be compared with the database, and then modified database, will be created accordingly. For a better selection, force, power and stability calculations are also done so that a match that satisfies operation requirements can be achieved. The multi-criteria weighted average will be used to find machine rankings in the second step, in which several criteria, such as productivity, flexibility, etc., will be used. In the third step, the number of machines that are feasible will be relatively small. The missing additional information is obtained for these machines and multi-criteria weighted average is applied to rank the machines again. After the selection of best machine, optional machine features will be analyzed considering the cost/benefits calculations, which requires an expert decision again. For example, a decision maker may need to decide purchasing of higher spindle speed option, higher total number of tools option, etc. Application of the developed methodology will be demonstrated with an example.

Selection methodology

Classification of machines
The first step is the creation of a large database, which ideally includes all of the machines available in the market, and there should be a standard way to classify the machines. Both of which are difficult to achieve since each manufacturer produces different types of machines with distinct features. Therefore, as a first step, a sample machining center database is created. The specifications of machining center are shown in Table I.

Decision criteria
The best machine should be selected from available database based on user requirements. In total, nine criteria are considered, with sub-criteria, as shown in Table II. The decision criteria are evaluated as a function of machine properties. Therefore, most criteria depend on a number of machine properties mentioned in classification of machines. For example, productivity depends on spindle speed and power, max. cutting feed, rapid traverse speed, etc. On the other hand, flexibility depends on speed range, number of axes, number of pallets etc. Adaptation is the degree of machine tool’s ability to fit existing system. For example, CNC type can be a critical factor, if operators can use only a certain type of control. Reliability is the ability to operate for a substantial length of time. Material removal rate (MRR), cutting forces, and axial depth of cut are critical factors in productivity and precision calculations. Force and stability models are reviewed for this purpose.

Multi-criteria weighted average method for machine selection
Machine selection problem consists of number of alternatives and number of criteria. Multi-criteria weighted average method is used to rank the alternatives from best to worst. We use weighted average together with hierarchy tree for the selection process. Hierarchy tree is constructed consisting of three levels:
(1) Level 1 contains the goal (selection of the best machine).
(2) Level 2 consists of nine main criteria (refer to Table II).
(3) Level 3 consists of sub-criteria (based on the machine specs given in Table I).

The procedure for multi-criteria weighted average method is as follows (refer to Table III for notations and definitions):

• **Step 1.** The importance of each criterion and sub-criterion \((W_i \text{ and } W_{ij})\) determined with its weight.

• **Step 2.** \(S_{ijm}\) is calculated using the database. For quantitative criteria, normalization using the highest or lowest machine properties determines the scores. Giving predetermined scores to criteria also normalizes subjective criteria.

• **Step 3.** Weights are multiplied with their scores to find machine rankings, as shown in the following equations:

\[
S_m = \sum_{j=1}^{J} S_{ijm} W_j, \quad m = 1, \ldots, M, \quad i = 1, \ldots, I. \tag{1}
\]

\[
S_i = \sum_{j=1}^{J} S_{ijm} W_i, \quad m = 1, \ldots, M. \tag{2}
\]

Actually, in this approach we are defining each criterion as a function of machine properties. For example, space requirements as a function of machine dimensions, and productivity as a function of power, speed, tool change time, etc. However, the constants in the function are actually the weights.

### Table I: Machining center specifications

<table>
<thead>
<tr>
<th>1. General</th>
<th>Manufacturer, machine name, machine type, CNC type, configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Spindle</td>
<td>Spindle type, spindle direction, taper number, maximum speed, power, etc.</td>
</tr>
<tr>
<td>3. Tooling</td>
<td>number of tools, maximum tool diameter</td>
</tr>
<tr>
<td>4. Work support</td>
<td>Table size, rotary table, pallet</td>
</tr>
<tr>
<td>5. Axis</td>
<td>Number of axis, cutting feed, rapid traverse speed, etc.</td>
</tr>
<tr>
<td>6. Physical</td>
<td>Machine dimensions, machine weight, installation requirements</td>
</tr>
</tbody>
</table>

### Table II: Criteria

<table>
<thead>
<tr>
<th>1. Productivity</th>
<th>Speed, power, cutting feed, tool change time, rapid speed, pallet changer</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Flexibility</td>
<td>Number of tools, rotary table, number of pallets, index table, CNC type, U or V axis, head changer, spindle power</td>
</tr>
<tr>
<td>3. Space</td>
<td>Machine dimensions, auxiliary equipment (loading/unloading, material handling, quality)</td>
</tr>
<tr>
<td>4. Adaptability</td>
<td>CNC type, number of tools, taper number</td>
</tr>
<tr>
<td>5. Precision</td>
<td>Axis precision, repeatability, thermal stability, static and dynamic rigidity</td>
</tr>
<tr>
<td>6. Cost</td>
<td>Machine procurement cost</td>
</tr>
<tr>
<td>7. Reliability</td>
<td>Bearing failure rate, reliability of drive system, etc.</td>
</tr>
<tr>
<td>8. Safety and environment</td>
<td>Mist collector, safety door, fire extinguisher</td>
</tr>
<tr>
<td>9. Maintenance and service</td>
<td>Training, repair service, spare parts, regular maintenance</td>
</tr>
</tbody>
</table>

### Table III: Notation and definitions

- **i** Criterion index where \(i = 1, \ldots, I\)
- **j** Sub-criterion index where \(j = 1, \ldots, J\)
- **m** Machine index where \(m = 1, \ldots, M\)
- \(S_{ijm}\) Score of machine \(m\) of sub-criteria \(j\) under criteria \(i\)
- \(S_{im}\) Score of machine \(m\) under criteria \(i\)
- \(S_m\) Score of machine \(m\) considering all criteria
- \(W_{ij}\) Weight of sub-criteria \(j\) under criteria \(i\)
- \(W_i\) Weight of criteria \(i\)

### Process models

Part quality and productivity deteriorate during machining owing to excessive cutting forces and chatter vibrations. Process model can be effectively used to improve productivity and quality. Also, they can be very useful in determining machine tool specs. Thus, for a given process, force and stability models can be used to determine requirements, such as force, power, speed, feed rate, axial depth of cut, etc.

### Productivity

Productivity of a company is one of the most important criteria in machine selection. It depends on different factors, for example, cutting time, tool change time, set-up time, load-unload time, etc. In many applications, machining time is one of the most critical factors. Thus, maximization of the material removal rate is crucial.
MRR in milling is defined as 
\[ MRR = a \cdot b \cdot f \]
where \( a \) is the axial depth of cut, \( b \) is the width of cut, \( f \) is feed rate which is defined as 
\[ f = f_t \cdot n \cdot N_t \]
where \( N_t \) is the number of teeth, \( n \) is the spindle speed, \( f_t \) is the feed per tooth. Though high MRR is desired, there are several constraints. For example, if the axial depth of cut \((a)\) is high, we expect force, torque, power, deflection, and chatter vibrations to increase. An increase in feed rate will deteriorate surface finish and tool life. Number of teeth is limited with tool geometry and may increase total cutting forces on the tool.

**Milling forces, torque and power**

High cutting forces can negatively affect productivity and quality of products. By modeling the cutting forces for a given process, one can calculate force and power requirements. In many applications, higher than required power is selected to be on the safe side. However, this approach may not necessarily yield a good choice since heavy spindles cannot accelerate fast enough, take more space and cost more.

A cutting force model for cylindrical milling cutters will be given below. The model can also be extended to ball end mills as presented in Altintas and Lee (1998) and Yang and Park (1991).

The forces contributed by one tooth of the cutter are determined as follows (Budak et al., 1996; Altintas, 2000):

\[
F_x(\phi) = \frac{K_f f_t R}{4 \tan \beta} (-\cos 2d_{\phi}(z) + K_r (2d_{\phi}(z) - \sin 2d_{\phi}(z)))^{z_{\phi}(z)}_{z_{\phi}(\phi)}
\]

\[
F_y(\phi) = -\frac{K_f f_t R}{4 \tan \beta} \left[(2d_{\phi}(z) - \sin 2d_{\phi}(z)) + K_c \cos 2d_{\phi}(z)\right]^{z_{\phi}(z)}_{z_{\phi}(\phi)}
\]

\[
F_z(\phi) = -\frac{K_f f_t R}{\tan \beta} \left[\cos d_{\phi}(z)\right]^{z_{\phi}(z)}_{z_{\phi}(\phi)}
\]

where \( R \) is the cutter radius, \( K_f, K_r, \) and \( K_c \) are milling force coefficients, \( z_{\phi}(\phi) \) and \( z_{\phi}(z) \) are the lower and higher limits of the contact for the tooth \( j \), \( \beta \) is the helix angle, \( f_t \) is the feed per tooth and \( d_{\phi}(z) \) is the immersion angle for the flute \( j \) at axial position \( z \) measured from the positive \( y \) axis as shown in Figure 1.

Equation (3) can be used to determine the milling forces in three directions for one full revolution of the cutting tool. \( K_r, K_c, \) and \( K_a \) are experimentally determined cutting force coefficients in three orthogonal directions which relate the cutting chip area to the cutting forces. In simulations, the angular position of the tool is varied \((0 - 2\pi)\) in order to simulate one revolution of the tool. For each tool orientation \((\phi)\), the angular positions of the cutting teeth \((d_{\phi}(z))\) are determined based on the number of teeth on the cutter \((N)\):

\[ d_{\phi}(z) = \phi + 2\pi(j - 1)/N. \]

The lower and upper limits of the contact between the cutting tooth \( j \) and the material, \( z_{\phi}(\phi) \) and \( z_{\phi}(z) \), are determined based on the tool and cutting geometry. They depend on the tool radius and helix angle as well as the radial and axial depth of cuts. For a very short contact between a tooth and the material (owing to very small axial or radial depth of cut), the lower and higher limits can be very close to each other. The longest contact is achieved for large depths of cuts, in which case the lower limit is zero and the higher limit is equal to the axial depth of cut. (The interested reader is referred to Budak et al. (1996) and Altintas (2000) for further details.) Then, the total milling forces can be determined as follows:

\[
F_x(\phi) = \sum_{j=1}^{N} F_{x,j}(\phi); \quad F_y(\phi) = \sum_{j=1}^{N} F_{y,j}(\phi);
\]

\[
F_z(\phi) = \sum_{j=1}^{N} F_{z,j}(\phi).
\]
Tangential force can be calculated similarly:

\[
F_t(\phi) = \frac{K_f R}{\tan \beta} \cos \phi(z) \frac{\tau^a(\phi)}{\tau^a(\phi)}
\]  

(5)

\[
F_t(\phi) = \sum_{j=1}^{N} F_j(\phi)
\]  

(6)

From these the instantaneous cutting torque and power can be calculated as follows:

\[
T(\phi) = F_t(\phi) \cdot R
\]  

(7)

\[
P(\phi) = F_t(\phi) \cdot R \cdot \Omega
\]  

(8)

where \( \Omega \) is defined as \( n \cdot 2\pi/60 \) and \( n \) is the spindle speed. Forces, torque and power variations are estimated for one full revolution of the cutter \( (\phi : 0 \rightarrow 2\pi) \) using Equations (3-8) and the peak values are determined. These values are the force, torque and power requirements for the process.

**Stability model**

Chatter vibrations reduce productivity, surface and dimensional quality. Thus, stability model can be very effective in improving product quality and productivity. Chatter free axial depth of cut limit \( a_{\lim} \) can be calculated as given in Equation (9) (refer to Altintas (2000) and Budak and Altintas (1998) for details):

\[
a_{\lim} = -\frac{2\pi \Lambda R}{NK_t}(1 + \kappa^2)
\]  

(9)

\[
\kappa = \frac{\Lambda_I}{\Lambda_R}; \quad \Lambda = -\frac{1}{2a_0}(a_1 \pm \sqrt{a_1^2 - 4a_0})
\]  

(10)

\[
a_0 = G_{xx}(i\omega_c)G_{yy}(i\omega_c)(\alpha_{xx} \alpha_{yy} - \alpha_{xy} \alpha_{yx})
\]

\[
a_1 = \alpha_{xx} G_{xx}(i\omega_c) + \alpha_{yy} G_{yy}(i\omega_c)
\]  

(11)

where \( G_{xx} \) and \( G_{yy} \) are transfer functions in the specified directions, \( \alpha \) is directional coefficient, \( \omega_c \) is the chatter frequency, \( \Lambda_R \) and \( \Lambda_I \) are the real and imaginary parts of the eigenvalue, respectively.

Transfer functions are widely used for the analysis of dynamic systems. A transfer function defines the relationship between the output and input of a dynamic system usually in frequency domain (Altintas, 2000). If the transfer function of a system is known – by experimental or analytical means – its output to a given input can easily be predicted. Transfer functions for structures can be identified using experimental methods such as impact tests. In an impact test, a known force input is applied to the structure while its output is measured, usually using accelerometers. After input and output are expressed in frequency domain (Fourier transform), the ratio of output to input gives the transfer function for the structure. For simple structures such as beams the transfer function can be determined analytically; numerical methods such as the finite element method can be used for more complicated systems.

These calculations can be used to generate stability diagrams from which stable cutting conditions, i.e. axial depth and spindle speed resulting in higher productivity can be determined. For example, Figure 2 gives us chatter stability diagram of a certain process. It is clear from the diagram that with speed of 15,000rpm, much higher chatter free axial depth and thus higher MRR are obtained.

In addition, for a certain application, if a certain axial depth of cut is desired, depending on productivity or geometry considerations, the required maximum spindle speed and dynamic rigidity of the spindle can be predicted. The spindle speed information is available in the machine tool database, however dynamic rigidity or transfer functions of the spindles are almost never available, which is expected to change in the near future based on the increasing understanding of chatter stability in industry.

**Figure 2 Chatter stability diagram**

[Figure showing chatter stability diagram]
Implementation

Machine tool selection software, which includes machine properties in the database, is developed to implement our methodology. This software applies multi-criteria weighted average, calculates force and power, and runs a cost benefit analysis.

Type of manufacturing in the company and machine working conditions are important criteria for machine selection. Before comparing the machines, the machine requirements should be determined. Spindle power and force requirements can be calculated as stated in process models. In addition, spindle speeds resulting in much higher stability can also be approximated using the above equations. Furthermore, other machine specifications should be determined for a better adaptation of the machine to the current and future working conditions of the company.

Example application

An application in a job shop will be considered for demonstration of the method. In this application cylindrical milling cutter with zero helix angle is used in full slottng operation. Work material is free machining steel with approximate tangential milling force coefficient of 2,000 MPa. Desired flute rate per tooth is 0.1 mm/rev-tooth and spindle speed of 10,000 rpm is required to achieve a certain production rate. End mill with three teeth and 25 mm diameter is used with axial depth of cut of 8 mm. Using these values in Equations (5-8) the required power is calculated as 14 HP. Figure 3 illustrates the power calculation on the software. Equations (9-11) can be used to determine the required dynamic rigidity of the spindle.

In order to apply multi-criteria weighted sum method we need to define the weights that are specific to the facility. Figure 4 illustrates the interface for entering the weights and other necessary data. Table IV shows the weights used in this example.

For demonstration purposes, a sample database of 33 machining centers is created:

• First stage. Main spindle power requirement is chosen to be between 15-30 HP. A horizontal main spindle direction is selected because of the orientation of the workpiece. The number of tools requirement is chosen to be between 20 and 40. These requirements eliminate 20 machines.

• Second stage. The remaining 13 machines are ranked according to maximum productivity, maximum flexibility, minimum space, maximum adaptability and weighted sum of those. For example, in our problem machines are ranked as follows: machine number 23 having a score of 83, machine number 12 having a score of 80, machine number 32 having a score of 79, etc. (scores are out of 100).

• Third stage. Additional information (cost, precision, etc.) can be obtained for all of these machines or some of the top ranking machines and weighted sum can be redone to obtain new rankings. In this stage, machines are ranked as follows: machine number 12 having a score of 85, machine number 23 having a score of 80, machine number 27 having a score of 78, etc.

Based on these rankings a machine satisfying the company needs can be selected. This selection is not necessarily the top ranking machine. In this example we select machine number 12 which has 12,000 rpm spindle speed, 30 HP power, horizontal spindle direction, and 40 tools.

Sample cost calculations

After the selection of the machine, a simple cost calculation is done to find the annual production when annual revenue equals annual cost. Similar cost calculations can be done to find desired unknowns, for example, the payback period. Table V shows the notation and data for the analysis. The formulations for the taxable income (TI) and net profit after tax (NPAT) are as follows:

\[ TI = PX + S(A|F, i, T) - C_{OH} - C_D - C_{OT}X - C_S(T_S + T_{CH})X \]  
where \( MARR \) is minimum attractive rate of return, \( A|P, i, T \) is annual worth of an investment \( P \) using \( MARR \) of \( i \) in \( T \) periods, \( A|F, i, T \) is the sinking fund factor which is the
Figure 3 Force modeling

![Image of force modeling interface]

Figure 4 User interface for data entry

![Image of user interface for data entry]

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annual worth of a future fund of \( F \) using MARR of \( i \) in \( T \) periods. Straight-line depreciation is used. Standard operating time assumption is used in calculations (refer to Edmonds (1994) for details). Then break-even production quantity for this example is computed as 10,960 units/year.

**Deciding on optional features**

After the selection of the machine that is most suitable to the company, a decision on additional features will be made. Machine number 12 has a rotary table option. The cost of rotary table is €12,000. In this process rotary table option eliminates the need of an additional fixture at a cost of €500 and also reduces operation time per part by two minutes. A new break-even production quantity is obtained as 10,340 units/year by adding the cost of rotary table. Thus, buying the rotary table for this company may be a logical option.

If the selected machine is not capable of producing the desired production rate of a company, then additional options should be sought in order to increase the productivity. The decision whether or not to buy options is dependent on some factors that are difficult to be assessed financially, e.g. quick response manufacturing abilities and flexibility of the facility. Other options, such as different spindle speed, different horsepower, additional axis, auto pallet changer, head changer, index table, etc. may be evaluated similarly.

**Conclusion and further research**

One of the major challenges in machine selection process is the lack of a standard format in the machine catalogues. This significantly complicates the classification and comparison of machines. Moreover, not all of the properties of the machine are specified. Transfer functions of the machine tools, detailed precision data, and force and torque limitations can be effectively used in the selection procedure, if the manufacturer provides them.

In this paper, the machine tool selection problem is addressed. Machine properties and decision criteria are listed and critical ones are investigated. Machining process models are reviewed in order to determine process requirements. These models are integrated in to the decision-making process in the selection criteria. This reduces the ranges for the sub-criteria and increases the accuracy in the selection. A multi-criteria weighted average method considering different criteria is proposed. The developed methodology is demonstrated with a potential application example. Cost/benefit analysis is also carried out to justify the purchase of the machine and its optional features.

The approach presented in this paper is not limited to machine selection and may be applied to other types of selection problems with minor adjustments, e.g. construction equipment selection, material-handling system selection, vehicle selection. Other methods such as AHP, fuzzy logic, neural networks may also be used in the selection process. The authors are currently investigating these techniques to extend and improve the methodology.

A survey covering different industries and processes may be conducted to obtain appropriate weights for the criteria. These
default values in the software would facilitate the decision maker’s selection process. In today’s competitive market, the machine industry is continuously developing and new machines with new features are frequently introduced to the market. Thus, criteria for the selection of a suitable machine can be affected by changes in the database created with respect to the machines available in the market. Therefore, the machine database as well as the selection criteria should be regularly updated for the quality of the solution.

References