A DECISION SUPPORT SYSTEM FOR MACHINE TOOL SELECTION

by

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Abstract

Business globalization, increased worldwide competition, decreased product life cycles and continuous introduction of new technologies force companies to use new machine tools. Appropriate selection of a machine tool for a production system results in increased precision, productivity, flexibility, and manufacturing responsiveness. Meanwhile, machine tool selection is a multi-faceted manufacturing planning problem, typically involving a variety of conflicting goals. Thus, selecting the most suitable machine from the increasing number of available machines is a difficult and demanding task..

In this thesis, a decision support system (DSS) is developed to aid in selection of machine tools for a production system. The DSS uses multi-criteria weighted average method (MCWA) as the decision-making approach. MCWA method considers a set of conflicting objectives such as productivity, flexibility, and adaptability that typically can not be achieved simultaneously. Each machine tool is assigned a score according to its properties in relation to the machines in the database. These scores are then used to rank the machines according to various criteria. A stepwise approach is used in the selection process. The entire tool selection process is demonstrated with examples. Sensitivity analysis is used to determine the most critical criterion and the most critical measure of performance. Cost / benefit analysis is carried out involving the purchasing decision of a selected machine tool and its additional options.

Özet

Küresel ticaret ve rekabet, kısalan ürün ömürleri, hızlı teknolojik gelişmeler, günümüzün sanayi kuruluşlarını sürekli olarak pazara çıkan yeni makinalar arasından seçim yapmaya zorlamaktadır. Bir üretim hattında yer alacak makinaların uygun bir şekilde seçilmesi hassasiyeti, üretkenliği, esnekliği ve üretimin tepkiselliğini arttırmaktadır. Makina takımı seçimi, çoğunlukla birbiriyle çelişen amaçlara aynı anda ulaşmayı hedefleyen karmaşık bir planlama problemidir. Sonuç olarak, sayıları devamlı artan makinalar arasından en uygun makina ve makina takımlarının seçimi yoğun çalışma gerektiren zor bir süreçtir.

Bu tezde, üretim sistemleri için makina takımı seçimini yönlendirecek bir karar destek sistemi (KDS) geliştirildi. Geliştirilen KDS, birbiriyle çelişen ve aynı anda ulaşılması güç olan üretkenlik, esneklik ve adaptasyon gibi kriterleri gözönünde bulundurmaktadır. Her makina tezgahının özellikleri veritabanındaki diğer makinaların özellikleriyle karşılaştırılarak skorlar belirlenmektedir. Bu skorlar makinaları değişik kriterlere göre sıralamak için kullanılmaktadır. Seçim sürecinde farklı aşamalardan oluşan bir yaklaşım kullanılmaktadır. Karar destek sisteminde makina seçimi için geçilen aşamalar tez kapsamında örneklerle sunulmaktadır. Makinanın ve özelliklerinin alım kararı için maliyet/yarar analizi yapılmaktadır. Seçim fonksiyonlarına ek olarak, duyarlılık analizi ile en kritik kriter ve performans değerleri bulunmaktadır.

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1. INTRODUCTION

Machine tool selection is an important decision-making process for many manufacturing companies. Improperly selected machines degrade the overall performance of a production system. The speed, quality, cost, and capacity 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 engineers, managers, and for machine manufacturers. For example, if the customer does not know which machines are suitable for the environment, machine manufacturer should send his staff even if it is costly. If a machine tool with excess capacity were selected, it would increase initial cost and would cause unnecessarily high inventory levels, and low utilization. On the other hand, if a machine tool with insufficient capacity is selected, the production system would not be able to meet the demand . If not properly selected, changing the product type or adding new product to the current production system may cause several problems, even if the selected machine is neither overcapacity nor under capacity. The lack of a standard format in machine catalogues, the large number of factors to be considered, and continuous introduction of new machine tools together with the advancements in the technology complicate 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, the survey "Selection Procedures Adopted by Industry for Introducing New Machine Tools" [1] reveals that the role of engineering staff authorized for final selection is only %6, the rest belongs to upper and middle management (94%). In addition, survey results indicated that most of the companies surveyed were not aware of the academic work in selecting the new technology. Although more recent results are not available, this may still be considered as an indicator of the need for a simplified and practical approach for the machine selection process.

Decision Support Systems (DSS) are interactive computer-based systems intended to help decision-makers utilize data and models to identify and solve problems and make decisions. It should guide the selection process and help in effectively solving the problem by user interaction. DSS help decision-makers use and manipulate data; apply checklists and heuristic; and build and use mathematical model [2].

Multi-criteria decision-making methods, such as weighted sum, weighted product, Analytic Hierarchy Process (AHP), and revised AHP are reviewed for the machine selection problem.

One can complicate the selection procedure by using different decision-making approaches. However, considering that to capture the developments in industry engineering problems should not be complicated unless it is necessarily leading to a better solution, multi-criteria weighted average (MCWA) method using hierarchy tree is used in decision-making. MCWA method simplifies the selection problem

The selection process consists of seven steps. In the first step, decision-maker should decide on machine specifications. For a given process, required machine tool specifications can be determined using force and stability models. These models are useful in determining the requirements such as force, power, speed, feed rate, axial depth of cut, etc. In the second step, criteria weights are determined. The criteria weights are very critical since they determine the machine rankings. Pre-defined weights may be selected for different types of companies and for a variety of production types. These pre-defined weights may still be modified. In the third step, a search algorithm is executed for the machines satisfying the requirements. This algorithm also searches the optional features of the machines, and select the most appropriate combination of features. After obtaining the machines that satisfy the user requirements, in the fourth step, MCWA method is applied. MCWA ranks the machines from best to worst using machine specifications and criteria weights. In the fifth step, sensitivity analysis is done. The sensitivity analysis determines what is the smallest change in current weights of the criteria, which can alter the existing ranking of the alternatives. Sensitivity analysis is also applied for the determination of the most critical measure of performance. In the sixth step, alternatives are re-evaluated considering cost. Machine scores are compared with machine costs. The decision-maker can select a machine based on performance and cost rankings. In the seventh step, cost analysis for machine options can be applied, if additional options are planned to be added to the selected machine.

2. BACKGROUND

This chapter presents a background information that is necessary to understand the machine selection problem. First, the literature in machine selection, robot selection, and decision-making areas is examined. Second, multi-criteria decision-making methods are addressed. Third, sensitivity analysis is presented with examples. Last, tools and knowledge that are necessary for the application environment are presented.

2.1. Machine Selection Literature

The machine selection problem has been studied mostly for a specific type of environment, such as flexible manufacturing systems (FMS). However, new machine selection approach should be applicable to many environments. Subramaniam et al. [3] investigated selection of machines in a job shop. They stated that job shops, being equipped with multi-purpose machining centers, require versatile scheduling strategies to account for multiple job routes. It is demonstrated that significant improvements to the scheduling performance of dispatching rules can be achieved easily using simple machine selection rules.

Tabucanon et al. [4] developed a decision support system for multi-criteria machine selection problem for FMS. The Analytic Hierarchy Process (AHP) technique is used for the selection. In their work, they used AHP software package (Expert Choice), Dbase III + DBMS, Expert System shell (EXSYS) and Turbo Pascal compiler. They stated that the right selection of the number and type of machines in FMS can reduce investment, maintenance, and operation cost, increase machine utilization, improve layout of machines, and increase efficiency of the production facility.

Wang et al. [5] proposed a fuzzy multiple-attribute decision-making model to assist the decision-maker to deal with the machine selection problem for a FMS. Four evaluation criteria are considered: total purchasing cost, total machine floor space, total machine number, and productivity of the constructed FMS. Machine speed is used to estimate the machine productivity. Slowest machine speed among machine tools is referred to as lower limit of productivity. Membership function is used as the base to qualify the importance of attributes, such as cost, floor space. The degree of fuzzy preference relation of pairs of alternatives is used in ranking.

Machine selection from fixed number of available machines is considered by Atmani and Lashkari [6]. They developed a linear, 0-1 integer programming model of the machine tool assignment, and operation allocation in FMS. The model assumes that there is a set of machines with known processing capabilities. The model minimizes total costs of processing, material handling and machine set-ups, determines the optimal machine-tool combinations, and assigns the operations of the part types to the machines. Tool magazine capacity, tool life, and machine capacity constraints are considered. Lin and Yang [7] proposed a model using AHP to evaluate the selection of appropriate machine for machining a certain type of part.

Goh et al. [8] proposed a revised weighted sum decision model for robot selection. The model uses objective criteria, subjective criteria, critical values and the weighting of the criteria to evaluate and select a robot. Critical values are a set of quantitative performance requirements. The values of objective and subjective criteria for robots that satisfy the critical values are normalized to one. Expert opinions are used to overcome the difficulty of quantifying the merit of each robot with respect to the subjective criteria. Expert opinions are also used for the determination of the weights for objective and subjective criteria. Experts assign any real number between 1 (worst) and 9 (best) to indicate performances. In the model, highest and lowest experts' values on the weights and subjective factors are eliminated. The reason for this elimination is the minimization of the impact of [any potential distorted preference]. Finally, weighted average of the criteria gives machine rankings. In this model, criteria are assumed to be independent.

In [9], 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. 7 stages of the methodology are: 1. "Establishing company policy on investment," 2. "Developing the specific requirements of the investment," 3.

“Technological analysis of possible machine investment options,” 4. “Financial analysis of possible machine tool options,” 5. “Selection and justification,” 6. “Introduction of selected new machine tool,” 7. “Post introductory monitoring of new investment.”

Haddock et al. [10] developed a DSS for a specific selection of machine that is required to process specific dimensions of a part. The machines are available in the manufacturing environment. Parts are classified into part families and are identified by part codes. Each part has a unique identification number, along with a part code defining its characteristics. Additional information on part characteristics, such as original size of material, finishing size of part, and the maximum tolerance is added to make appropriate selection. Two types of information are required to develop a database for part codes. The first is the listing of machining processes required for each individual part code. Along with this information, machines capable of completing the specific machining process can be considered. The second type of information is used to compare part characteristics with machine qualifications. Typical part characteristics that are compared with machine specifications are: original part size vs. machine table size, part tolerance versus machine accuracy in positioning and surface finish, concentricity with repeatability of the machine. The choice of the optimal machine(s), vs. possible alternatives is made by a planner by a comparison using a criterion measure(s). Possible criteria are: relative location of machines, machining cost, processing time, and the availability of the machines. A routing sheet is produced with the optimal machine specified and to perform the machining process required. Alternative machines are listed, along with their specifications, after the primary machine selection.

2.2. Multi-Criteria Decision-Making

In this section Triantaphyllou [11] is mainly used as a reference to explain multi-criteria decision-making and its methods.

To make the optimal decision in a given situation is probably the most permanent challenge in science. Thus, it is not surprising that the decision-making literature is very large and continuously increasing. The development of scientific disciplines such as operation research, management science, computer science, and statistics, in combination with the use of modern computers, assists people in making the best decision for a given situation. Theories such as linear programming, dynamic programming, inventory control, optimization of queuing system, and multi-criteria decision-making (MCDM) have as a common element the search for an optimal solution.

Among the methods, MCDM has captured the attention of most of the people for most of the time. That is, given a set of alternatives and a set of decision criteria, what is the best alternative? According to Zimmermann [12], MCDM is divided into multi-objective decision-making (MODM) and multi-attribute decision-making (MADM). However, the terms MADM and MCDM are used to mean the same class of models (i.e., MCDM).

In MODM decision space is continuous, for example; mathematical programming problems with multiple objective functions. On the other hand, in MCDM/MADM decision space is discrete. In these methods, a set of decision alternatives has been predetermined.

There are plethora of alternative methods for solving the same MCDM problem. Thus, a decision-maker has different methods, which all claim that they can correctly solve a given MCDM problem. It is hard to compare MCDM methods because of subjectivity and conceptual complexity. The final goal of determining the best method seems to be unattainable and utopian. Actually, according to [11], there is no single method that outperforms all the other methods in all aspects. However, a method should be selected in which complexity and cost (time spend) are reasonable so that it gives satisfactory results.

In choosing a method for machine selection, the problem should not be complicated. The complexity and cost (time) trade-off is considered similarly by Zadeh, founder of fuzzy sets, as precision and cost trade-off. He stated his observation about a fundamental trade-off between precision and cost, which is referred as “the principle of incompatibility”. He explained his observation as follows: “Stated informally, the essence of this principle is that as the complexity of a system increases, the ability to make precise yet significant descriptions about its behavior diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics.” In other words, one has to pay a cost for high precision. Therefore, the cost for precise modeling and analysis of a complex system can be too high to be practical. An example often used by Zadeh to illustrate this trade-off is the problem of parking a car. Usually, it takes a driver less than half a minute to parallel park. However, if somebody is asked to park a car in a parking place such that the outside wheels are precisely within 0.01 mm from the side lines of a parking space, and the wheels are within 0.01 degree from a specified angle, how long do you think it would take you to park the car? It would take a long time and you will probably give up after trying ten minutes or so. The point is that the cost (i.e., the time required) to park a car increases as the precision of the car parking task increases. This trade-off between precision and cost exists not only in car parking but also in control, modeling, decision-making, and almost any kind of problem [13].

As the precision of the system increases, the cost of developing the system also increases, typically in an exponential manner. On the other hand, the utility (i.e., usefulness) of the system does not increase proportionally as its precision increases-it usually saturates after a certain point. The fundamental principle should be to develop cost-effective approximate solutions to complex problems by exploiting the tolerance for imprecision [13].

2.2.1. Multi-Criteria Decision-Making Methods

There are three steps in utilizing any decision-making technique involving numerical analysis of alternatives:

1) Determine the relevant criteria and alternatives.

2) Attach numerical measures to the relative importance of the criteria and to the impacts of the alternatives on these criteria.

3) Process the numerical values to determine a ranking of each alternative.

Given a set of *m* alternatives denoted as $A_1, A_2, A_3, \dots, A_m$ and a set of *n* decision criteria denoted as $C_1, C_2, C_3, \dots, C_n$. It is assumed that the decision-maker has determined (the absolute or relative) performance value a_{ij} ($i=1..m$, $j=1..n$) of each alternative in terms of each criterion. Matrix *A* is determined with the a_{ij} values, along with the criteria weights w_j.

2.2.1.1. The Weighted Sum Model Method

The weighted sum model (WSM) is one of the most used MCDM methods. It is especially used in single dimensional problems. If there are *m* alternatives and *n* criteria the best alternative is the one that satisfies the following expression:

$$A^{*}_{WSM-score} = \max_{i} \sum_{j=1}^{n} a_{ij} w_j \quad for \ \ i = 1, \ 2, \ 3, \ ..., \ m \tag{2.1}$$

$A^{*}_{WSM-score}$ is the WSM score of the best alternative. Additive utility assumption rules this model, i.e., the total value of each alternative is equal to the sum of the products. When this method is applied to multi-dimensional MCDM problems, the additive utility assumption is violated in combining different dimensions.

2.2.1.2. **The Weighted Product Model Method**

It is similar to the WSM model. Each alternative is compared with the others by multiplying a number of ratios. Each ratio is raised to the power equivalent to the relative weight of the corresponding criterion. In order to compare two alternatives A_K and A_L, $R\ (A_K / A_L)$ should be calculated as follows:

$$R(A_K / A_L) = \prod_{j=1}^{n} (a_{Kj} / a_{Lj})^{w_j} \tag{2.2}$$

If $R\ (A_K / A_L)$ is greater than or equal to one, then it indicates that alternative A_K is more desirable than alternative A_L (in maximization case).

WPM is sometimes called dimensionless analysis because its structure eliminates any units of measure. Thus, it can be used in single- and multi- dimensional MCDM.

An alternative approach with the WPM method is to use only products without ratios. That is:

$$P(A_K) = \prod_{j=1}^{n} (a_{Kj})^{w_j} \tag{2.3}$$

$P(A_K)$ denotes the performance value (not a relative value) of alternative A_K when all the criteria are considered under the WPM model.

2.2.1.3. Analytic Hierarchy Process

AHP was developed by Saaty [14] more than 20 years ago. It can be defined as a mathematic based scientific approach to decision-making or as a tool in assisting the mind to organize its thoughts and experiences or as a decision-making method based upon division of problem spaces into hierarchies.

Can we compare apples and oranges or can we compare cost and productivity? If one of the apples or oranges is fresh and juicy, we can select that one over another, since a decision is made according to ones preferences and needs. The one that will yield more gain to us will be preferred. Accordingly, weights of importance could be given when selecting in considering cost and productivity.

The typical problem in AHP consists of a number of alternatives and a number of criteria. AHP is designed to select the best alternative.

The decision-maker carries out pair-wise comparisons then these comparisons are used to develop overall priorities for ranking the alternatives. The AHP both allows for inconsistency in the judgments and provides a means to improve consistency.

Hierarchy is the ordering of parts or elements of a whole from the highest to the lowest. "The simplest form used to structure a decision problem is a hierarchy consisting of three levels: the goal of the decision at the top, followed by a second level consisting of the criteria by which the alternatives, located in the third level, will be evaluated. The purpose of the structure is to make it possible to judge the importance of elements in a given level with respect to some or all of the elements in the adjacent level above. Once the structuring is completed, the AHP is simple to apply." [15]. Figure 2.1 shows simple AHP structure and Table 2.1 shows scale of relative importance:

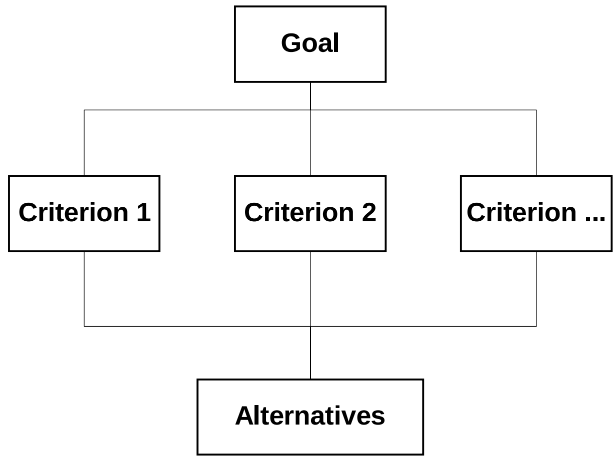

Figure 2.1 Simple AHP Structure

Table 2.1 Scale of Relative Importance

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally
3	Weak Importance of one over another	Experience & Judgment slightly favor one over another
5	Essential or Strong Importance	…Strongly favor one over another
7	Very Strong and Demonstrated	…Strongly favored and its dominance demonstrated in practice
9	Absolute Importance	Evidence favoring one over another is of the highest possible order
2,4,6,8	Intermediate values between adjacent scale values	

AHP has found its widest applications in multi-criteria decision-making, in planning and resource allocation, and in conflict resolution. Typically, the AHP steps are as follows:

(1) Break the problem down into decision elements (Levels)
(2) Make pair-wise comparisons at each level
(3) Check for consistency
(4) Multiply matrixes to obtain the best machine

The purpose of the establishment of a pair-wise comparison matrix is to derive the degree of relative importance amongst the elements. From the pair-wise matrixes ranking of priorities can be retrieved. Saaty [14] demonstrated mathematically that the eigen-vector solution is the best approach. Computed eigenvector gives us the relative ranking of each criterion. The most important criterion has the highest weight. Since MCDM methods alternatives are compared, how a_{ij} 's are calculated is not of primary concern. According to the AHP the best alternative is calculated from [11]:

$$A^{*}_{AHP-score} = \max_{i} \sum_{j=1}^{n} a_{ij} w_j \quad for \;\; i = 1,\ 2,\ 3,\ \ldots,\ m. \tag{2.4}$$

WSM and AHP are similar methods. However, AHP uses relative values instead of actual ones.

2.2.1.4. Revised AHP

Belton and Gear [16] proposed a revised version of the original AHP method. They showed that inconsistent ranking could occur in the original version of AHP. In an example, they demonstrated that best alternative changes when an identical alternative to the one of the non-optimal alternatives is introduced. According to them, the inconsistency occurs since the relative values of the alternatives sum up to one. They proposed to divide each relative value by the maximum value of the relative values, instead of having relative values of alternatives sum up to one.

2.3. Sensitivity Analysis

Again, Triantaphyllou [11] is used as a reference in explaining sensitivity analysis.

The decision-maker can make better decisions if he/she can determine how critical each factor is. In other words, how sensitive is the actual ranking of the alternatives to the changes in the current weights of the decision criteria?

The weights assigned to the decision criteria represent the importance of the criteria. It is difficult to represent accurately the importance of criteria when it cannot be expressed in quantitative terms. In this situation, the decision-making process could be improved considerably by identifying the critical criteria. Then weights of these criteria can be re-evaluated. The intuitive belief is that the criterion with the highest weight is the most critical criterion. However, this may not be the case in all of the cases. In some instances, the criterion with the lowest weight can be the most critical criterion.

In a MCDM environment the focus is on the issue of the sensitivity analysis of the weights of the decision criteria and the performance measures of the alternatives. One of the most important sensitivity analysis is to determine the how critical each criterion is, by performing a analysis on the weights of the criteria. It determines what is the smallest change in current weights of the criteria, which can alter the existing ranking of the alternatives. Another important sensitivity analysis is the determination of the most critical measure of performance.

2.3.1. Definitions

In the MCDM problem there are *m* alternatives and *n* criteria (*i=1..m, j=1..n*). The weights of criteria (w_j) and performance values (a_{ij}) are used to rank the alternatives. The alternatives will be ranked in the non-decreasing order of their scores. The score of alternative A_i is defined as S_i. Then, it is assumed that:

$$S_1 \geq S_2 \geq S_3 \geq \ldots \geq S_m$$

Most critical criteria may be defined in different ways. Here, it is determined by looking at the smallest change in the weight of criteria in order for the rankings to change. The smallest change may be defined in two different ways: absolute change and relative change. The absolute change is the difference between the initial and final weights. Relative change is the difference between the initial and the final weights divided by the initial weight. Another important point is the change in rankings. One might be interested with the minimum change in weights that causes any two alternatives to reverse their existing rankings. It is also interesting to know the minimum change in weights that will cause only the top alternative to reverse its ranking with other alternatives. This is also interesting to know in cases where one is interested in best candidate from a number of competing candidates. In sum, one may be interested in absolute change in top alternative (AT), absolute change in any two alternatives (AA), relative change in top alternative (RT), relative change in any alternative (RA).

On the other hand, the absolute changes may be deceptive. For example, a change of 0.09 may be very high when the original value is 0.05 and the same change may not mean much when the original value is 0.50. Thus, it may be more appropriate to use relative changes.

2.3.2. Most Critical Criterion

Determination of the most critical criterion is very important. It is determined by the smallest change in the current weight of criterion that will change the ranking of alternatives.

Theorem: When AHP is used, $\delta'_{k,i,j}$ is defined as the minimum change in the current weight (w_k) of criterion C_k such that the ranking of alternatives A_i and A_j will be reversed for $1 \leq i \leq j \leq m$ and $1 \leq k \leq n$. The new weight of criterion k is defined as [11]:

$$w_k^* = w_k - w_k \times \frac{\delta'_{k,i,j}}{100} \tag{2.5}$$

The following condition defines $\delta'_{k,i,j}$:

$$\begin{aligned} \delta'_{k,i,j} &< \frac{(S_j - S_i)}{(a_{jk} - a_{ik})} \times \frac{100}{w_k}, \quad \text{if } (a_{jk} > a_{ik}), \text{ or :} \\ \delta'_{k,i,j} &> \frac{(S_j - S_i)}{(a_{jk} - a_{ik})} \times \frac{100}{w_k}, \quad \text{if } (a_{jk} < a_{ik}) \end{aligned} \tag{2.6}$$

In order for the $\delta'_{k,i,j}$ to be feasible the following condition should also be satisfied.

$$\frac{(S_j - S_i)}{(a_{jk} - a_{ik})} \leq w_k \tag{2.7}$$

The proof by Triantaphyllou [11] is expanded below for relative changes:

Proof: Assume that the minimum change in the weight of w_k of criterion C_k is needed which will cause the ranking of alternatives A_i and A_j to reverse. The new weight is known as;

$$w_k^* = w_k - w_k \times \frac{\delta'_{k,i,j}}{100}$$

Thus, the remaining criteria weights are normalized and new weights are obtained.

$$w'_h = \frac{w_h}{w_1 + ... + w_{k-1} + w_k^* + w_{k+1} + ... + w_n} = \frac{w_h}{w_k^* + \sum_{\substack{l=1 \\ l \neq k}}^{n} w_l}$$

$$h = 1,..,n \;\; and \;\; \text{if} \;\; h \neq k$$

$$w'_k = \frac{w_k^*}{w_1 + ... + w_{k-1} + w_k^* + w_{k+1} + ... + w_n} = \frac{w_k^*}{w_k^* + \sum_{\substack{l=1 \\ l \neq k}}^{n} w_l}$$

$$\text{if} \quad h = k$$

According to the previous assumption, it is known that $S_i > S_j$. Now, the ranking of alternatives should reverse. It means $S'_i < S'_j$. It can be also written as;

$$S'_i = \sum_{m=1}^{n} w'_m \cdot a_{im} < S'_j = \sum_{m=1}^{n} w'_m \cdot a_{jm}$$

If w_j and w_k^* equivalents are used;

$$S_i^{'} = \sum_{\substack{m=1 \\ m\neq k}}^{n} \frac{w_m}{w_k^* + \sum_{\substack{l=1 \\ l\neq k}}^{n} w_l} \cdot a_{im} + \frac{w_k^*}{w_k^* + \sum_{\substack{l=1 \\ l\neq k}}^{n} w_l} \cdot a_{ik}$$

$$S_i^{'} = \frac{1}{w_k^* + \sum_{\substack{l=1 \\ l\neq k}}^{n} w_l} \cdot (\sum_{\substack{m=1 \\ m\neq k}}^{n} w_m \cdot a_{im} + (w_k - w_k \times \frac{\delta_{k,i,j}^{'}}{100}) \cdot a_{ik})$$

$$S_i^{'} = \frac{1}{w_k^* + \sum_{\substack{l=1 \\ l\neq k}}^{n} w_l} \cdot (\sum_{m=1}^{n} w_m \cdot a_{im} - w_k \times \frac{\delta_{k,i,j}^{'}}{100} \cdot a_{ik})$$

$$S_i^{'} = \frac{1}{w_k^* + \sum_{\substack{l=1 \\ l\neq k}}^{n} w_l} \cdot (S_i - w_k \times \frac{\delta_{k,i,j}^{'}}{100} \cdot a_{ik})$$

$S_j^{'}$ can be found similarly:

$$S_j^{'} = \frac{1}{w_k^* + \sum_{\substack{l=1 \\ l\neq k}}^{n} w_l} \cdot (S_j - w_k \times \frac{\delta_{k,i,j}^{'}}{100} \cdot a_{jk})$$

Using $S_i^{'} < S_j^{'}$:

$$\frac{1}{w_k^* + \sum_{\substack{l=1 \\ l\neq k}}^{n} w_l} \cdot (S_i - w_k \times \frac{\delta_{k,i,j}^{'}}{100} \cdot a_{ik}) < \frac{1}{w_k^* + \sum_{\substack{l=1 \\ l\neq k}}^{n} w_l} \cdot (S_j - w_k \times \frac{\delta_{k,i,j}^{'}}{100} \cdot a_{jk})$$

$$(S_i - w_k \times \frac{\delta^{'}_{k,i,j}}{100} \cdot a_{ik}) < (S_j - w_k \times \frac{\delta^{'}_{k,i,j}}{100} \cdot a_{jk})$$

$$(S_i - S_j) < w_k \times \frac{\delta^{'}_{k,i,j}}{100} \cdot (a_{ik} - a_{jk})$$

Then (2.8) and (2.9) can be obtained as shown below:

$$\begin{aligned} \delta^{'}_{k,i,j} &< \frac{(S_j - S_i)}{(a_{jk} - a_{ik})} \times \frac{100}{w_k}, \quad \text{if } (a_{jk} > a_{ik}), \text{ or :} \\ \delta^{'}_{k,i,j} &> \frac{(S_j - S_i)}{(a_{jk} - a_{ik})} \times \frac{100}{w_k}, \quad \text{if } (a_{jk} < a_{ik}) \end{aligned} \tag{2.8}$$

In order for the $\delta^{'}_{k,i,j}$ to be feasible the following condition should also be satisfied.

$$\frac{(S_j - S_i)}{(a_{jk} - a_{ik})} \le w_k \tag{2.9}$$

The Percent-Top (PT) critical criterion: It is the criterion corresponding to the smallest $\left|\delta^{'}_{k,1,j}\right|$ for $1 \le j \le m$ and $1 \le k \le n$.

The Percent-Any (PA) critical criterion: It is the criterion corresponding to the smallest $\left|\delta^{'}_{k,i,j}\right|$ for $1 \le i < j \le m$ and $1 \le k \le n$.

Criticality degree of criterion C_k ($D^{'}_k$): It is the smallest percent amount by which the current value of w_k must change, such that the existing ranking of alternatives will change. That is:

$$D^{'}_k = \min_{1 \le i < j \le m} \left\{ \left|\delta^{'}_{k,i,j}\right| \right\} \tag{2.10}$$

Sensitivity coefficient of criterion C_k (sens(C_k)): It is the reciprocal of its criticality degree. That is:

$$sens(C_k) = \frac{1}{D_k^{'}}, \text{ for any } n \geq k \geq 1 \tag{2.11}$$

If the criticality degree is infeasible (i.e. impossible to change any alternative rank with any weight change), then the sensitivity coefficient is set to be equal to zero.

Consider the following example, to select the best alternative from a number of available alternatives. There are four criteria and four alternatives as shown in Figure 2.2. The weights of criteria and the decision matrix are given in Table 2.2 and Table 2.3, respectively.

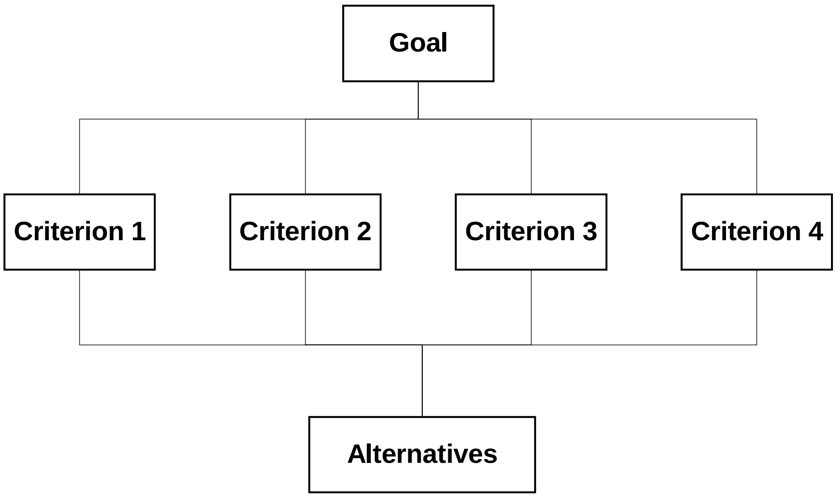

Figure 2.2 Hierarchy tree for sensitivity example

Table 2.2 Weights

Alternatives	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Weights %	38.1	42.9	7.1	11.9

Table 2.3 Decision Matrix

Scores	Criteria			
Alternatives	Criterion 1	Criterion 2	Criterion 3	Criterion 4
A_1	0.374	0.316	0.236	0.130
A_2	0.190	0.219	0.226	0.682
A_3	0.242	0.243	0.172	0.098
A_4	0.194	0.222	0.366	0.090

Table 2.4 shows the results obtained by using AHP.

Table 2.4 AHP Results

Alternatives	Final scores	Ranking	Ranking
A_1	0.310	1	Best
A_2	0.264	2	↓
A_3	0.220	3	
A_4	0.206	4	Worst

The minimum change that is required to change the current weight of the criterion 1 so that the current ranking of the two alternatives A_1 and A_2 will be reversed can be found from the relation:

$$\delta'_{1,1,2} < \frac{(S_2 - S_1)}{(a_{21} - a_{11})} \times \frac{100}{w_1} \quad \Rightarrow \quad \delta'_{1,1,2} < \frac{(0.264 - 0.310)}{(0.190 - 0.374)} \times \frac{100}{0.381}$$

$$\delta'_{1,1,2} < 65.61$$

The following condition should also be satisfied for the new weight to be feasible.

$$\frac{(S_2 - S_1)}{(a_{21} - a_{11})} \leq w_1 \;\Rightarrow\; \frac{(0.264 - 0.310)}{(0.190 - 0.374)} \leq 0.381 \;\Rightarrow 0.25 \leq 0.381$$

Thus, the new weight can be calculated as follows;

$$w_1^* = w_1 - w_1 \times \frac{\delta'_{1,1,2}}{100} \Rightarrow w_1^* = 0.381 - 0.381 \times \frac{65.61}{100}$$

$$w_1^* = 0.131$$

After normalization new weights can be calculated as follows:

$$w_1^* + w_2 + w_3 + w_4 = 0.75$$

$$w_1' = \frac{w_1^*}{w_1^* + w_2 + w_3 + w_4} = \frac{0.131}{0.75} = 0.174$$

$$w_2' = \frac{w_2}{w_1^* + w_2 + w_3 + w_4} = \frac{0.429}{0.75} = 0.572$$

$$w_3' = \frac{w_3}{w_1^* + w_2 + w_3 + w_4} = \frac{0.071}{0.75} = 0.095$$

$$w_4' = \frac{w_4}{w_1^* + w_2 + w_3 + w_4} = \frac{0.119}{0.75} = 0.159$$

Table 2.5 is obtained by doing similar calculations for all of the possible pair of alternatives:

Table 2.5 Percent change in criteria weights

$\delta'_{k,i,j}$	Criteria			
Pair of Alternatives	Criterion 1	Criterion 2	Criterion 3	Criterion 4
A_1 - A_2	**65.61**	NF	NF	-71.5
A_1 - A_3	NF	NF	NF	NF
A_1 - A_4	NF	NF	-1105.94	NF
A_2 - A_3	-218.21	**-411.36**	NF	**62.01**
A_2 - A_4	-3353.36	3166.13	564.13	80.77
A_3 - A_4	76.25	NF	**-99.24**	NF

NF: Not-feasible

This table shows the minimum percent changes in criteria weights that will reverse the ranking of the pair of alternatives. The negative values indicate the increase in criteria weights while the positive values indicate the decrease.

From these equations, Percent-Top (PT) critical criterion and the Percent-Any (PA) critical criterion can be found. PT critical criterion is found by looking at the smallest relative value in absolute terms among pair-wise alternatives that correspond to best alternative, that is A_1. PT can easily found to be 65.61% that correspond to criterion 1. Thus, a decrease of 65.61% in the weight of criterion 1 will cause the alternatives 1 and 2 to reverse their rankings, that is alternative 2 will be a better choice than alternative 1. PA critical criterion can also be found by looking at the smallest percent changes among all possible pair of alternatives. PA critical criterion is criterion 4 since A_2-A_3 percent change is the smallest among all pair-wise alternatives. Thus, a decrease of 62.01% in the weight of criterion 4 will cause the alternatives 2 and 3 to reverse their rankings, that is alternative 3 will be a better choice than alternative 2.

After the calculation of PT and PA, the criticality degrees and sensitivity coefficients can be calculated using the percent change table. Thus, criticality degrees and sensitivity coefficients are obtained as shown in Table 2.6:

Table 2.6 Criticality degrees and sensitivity coefficients

	Criterion 1	Criterion 2	Criterion 3	Criterion 4
D'_k	65.61	411.36	99.24	62.01
$sens(C_k)$	0.015	0.002	0.010	0.016
Sensitivity		Least		Most

Therefore, most sensitive criterion is criterion 4 and least sensitive one is criterion 2.

2.3.3. Most Critical Measure of Performance

Determination of the most critical measure of performance is another important problem that should be investigated.

Theorem: When AHP is used, the threshold value $\tau'_{i,j,k}$ is defined as the minimum change in the current measure of performance of alternative A_i ($a_{i,j}$) of criterion C_k such that the ranking of alternatives A_i and A_k will change [11].

The modified measure of performance ($a_{i,j}$) is given as:

$$a^*_{ij} = a_{ij} - a_{ij} \times \frac{\tau'_{i,j,k}}{100} \tag{2.12}$$

The threshold value $\tau'_{i,j,k}$ is given as:

$$\tau'_{i,j,k} = \frac{(S_i - S_k)}{(S_i - S_k + w_j \cdot (a_{kj} - a_{ij} + 1)} \times \frac{100}{a_{ij}} \tag{2.13}$$

Moreover, threshold value should satisfy another condition to be feasible.

$$\tau'_{i,j,k} \leq 100 \tag{2.14}$$

Again the proof by Triantaphyllou [11] is expanded for relative changes as explained below

Proof: Assume that the rankings of alternatives A_i and A_k should reverse. The threshold value $\tau'_{i,j,k}$ (for $i \neq k$, $k \leq m$ and $1 \leq j \leq n$) is the minimum change in current value of the $a_{i,j}$ measure of performance, such that the ranking between the two alternatives A_i and A_k will be reversed. The new $a_{i,j}$ measure is defined as;

$$a^*_{ij} = a_{ij} - a_{ij} \times \frac{\tau'_{i,j,k}}{100}$$

Suppose the ranking of alternatives 1 and 2 should reverse by changing a_{14} performance measure (it is known that $S_1 > S_2$). Then new performance measure a_{14}^* can be written as:

$$a_{14}^* = a_{14} - a_{14} \times \frac{\tau'_{1,4,2}}{100} \tag{2.15}$$

New performance measure values after normalization can be written as:

$$\begin{aligned}
a'_{1,4} &= \frac{a^*_{1,4}}{a^*_{1,4} + a_{2,4} + \ldots + a_{m,4}} \\
a'_{2,4} &= \frac{a_{2,4}}{a^*_{1,4} + a_{2,4} + \ldots + a_{m,4}} \\
\ldots & \qquad \ldots\ldots\ldots \\
a'_{m,4} &= \frac{a_{m,4}}{a^*_{1,4} + a_{2,4} + \ldots + a_{m,4}}
\end{aligned} \tag{2.16}$$

2.16 can be reformulated using 2.15 as follows:

$$\begin{aligned}
a'_{1,4} &= \frac{a^*_{1,4}}{-a_{1,4} \times \frac{\tau'_{1,4,2}}{100} + a_{1,4} + a_{2,4} + \ldots + a_{m,4}} = \frac{a^*_{1,4}}{1 - a_{1,4} \times \frac{\tau'_{1,4,2}}{100}} = \frac{a_{14} - a_{14} \times \frac{\tau'_{1,4,2}}{100}}{1 - a_{1,4} \times \frac{\tau'_{1,4,2}}{100}} \\
a'_{2,4} &= \frac{a_{2,4}}{-a_{1,4} \times \frac{\tau'_{1,4,2}}{100} + a_{1,4} + a_{2,4} + \ldots + a_{m,4}} = \frac{a_{2,4}}{1 - a_{2,4} \times \frac{\tau'_{2,4,2}}{100}} \\
\ldots & \qquad \ldots\ldots\ldots \qquad \ldots \\
a'_{m,4} &= \frac{a_{m,4}}{-a_{1,4} \times \frac{\tau'_{1,4,2}}{100} + a_{1,4} + a_{2,4} + \ldots + a_{m,4}} = \frac{a_{m,4}}{1 - a_{m,4} \times \frac{\tau'_{m,4,2}}{100}}
\end{aligned} \tag{2.17}$$

Now $S'_1 < S'_2$ is desired. This can be written as:

$$a_{11} \cdot w_1 + a_{12} \cdot w_2 + a_{13} \cdot w_3 + a_{14}^{'} \cdot w_4 + ... + a_{1n} \cdot w_n <$$
$$a_{21} \cdot w_1 + a_{22} \cdot w_2 + a_{23} \cdot w_3 + a_{24}^{'} \cdot w_4 + ... + a_{2n} \cdot w_n \quad \Rightarrow$$

If the terms $(a_{14} - a_{14}) \cdot w_4$ and $(a_{24} - a_{24}) \cdot w_4$ are added the result will not change.

$$a_{11} \cdot w_1 + a_{12} \cdot w_2 + a_{13} \cdot w_3 + a_{14}^{'} \cdot w_4 + (a_{14} - a_{14}) \cdot w_4 + ... + a_{1n} \cdot w_n <$$
$$a_{21} \cdot w_1 + a_{22} \cdot w_2 + a_{23} \cdot w_3 + a_{24}^{'} \cdot w_4 + (a_{24} - a_{24}) \cdot w_4 + ... + a_{2n} \cdot w_n \quad \Rightarrow$$

Using $\sum_{j=1}^{n} a_{ij} \cdot w_j = S_i$:

$$\frac{a_{14} - a_{14} \times \frac{\tau_{1,4,2}^{'}}{100}}{1 - a_{1,4} \times \frac{\tau_{1,4,2}^{'}}{100}} \cdot w_4 - a_{14} \cdot w_4 + S_1 < \frac{a_{2,4}}{1 - a_{1,4} \times \frac{\tau_{1,4,2}^{'}}{100}} \cdot w_4 - a_{24} \cdot w_4 + S_2 \quad \Rightarrow$$

After simplification:

$$\tau_{1,4,2}^{'} < \frac{(S_1 - S_2)}{(S_1 - S_2 + w_4 \cdot (a_{24} - a_{14} + 1)} \times \frac{100}{a_{14}} \tag{2.18}$$

The definition of a_{14}^{*} requires another condition

$$\tau_{i,j,k}^{'} \leq 100 \tag{2.19}$$

The formulations can be generalized to obtain the general formula.

Criticality degree of alternative A_i in terms of criterion **C_j (Δ'_{ij})** is defined as the smallest amount by which the current value of a_{ij} must change such that the existing ranking of A_i will change.

$$\Delta'_{i,j} = \min_{k \neq i} \left\{ \left| \tau'_{i,j,k} \right| \right\}, \quad \text{for all } m \geq i \geq 1, \text{ and } n \geq j \geq 1 \qquad (2.20)$$

Alternative A_L is **the most critical alternative** if it is the one with the smallest criticality degree.

$$\Delta'_{L,j} = \min_{m \geq i \geq 1} \left\{ \min_{k \neq i} \left\{ \left| \tau'_{i,j,k} \right| \right\} \right\}, \quad \text{for some } n \geq k \geq 1 \qquad (2.21)$$

"sens(a_{ij})" is the sensitivity coefficient of alternative A_i in terms of criterion C_j It is the reciprocal of its criticality degree. That is:

$$sens(a_{ij}) = \frac{1}{\Delta'_{i,j}}, \text{ for any } n \geq k \geq 1 \qquad (2.22)$$

If the criticality degree is infeasible, then the sensitivity coefficient is set to be equal to zero.

Consider the example used in the previous sensitivity analysis. Suppose that the rankings of A_1 and A_2 are required to reverse by changing a_{11} value (0.374). The threshold value can be calculated as;

$$\tau'_{1,1,2} = \frac{(S_1 - S_2)}{(S_1 - S_2 + w_1 \cdot (a_{21} - a_{11} + 1)} \times \frac{100}{a_{11}} \Rightarrow$$

$$\frac{(0.310 - 0.264)}{(0.310 - 0.264 + 0.381 \cdot (0.190 - 0.374 + 1)} \times \frac{100}{0.374} = 34.46$$

Table 2.7 Threshold values in relative terms

$\tau'_{i,j,k}$	Criteria			
Pair of Alternatives	Criterion 1	Criterion 2	Criterion 3	Criterion 4
$\boldsymbol{A_1}$ - A_2	**34.46**	**34.29**	NF	NF
$\boldsymbol{A_1} - A_3$	57.29	58.56	NF	NF
$\boldsymbol{A_1} - A_4$	66.74	66.82	NF	NF
$\boldsymbol{A_2} - A_1$	-61.27	-50.82	**-829.46**	-1096.97
$\boldsymbol{A_2} - A_3$	**51.28**	**41.01**	NF	**68.36**
$\boldsymbol{A_2} - A_4$	68.32	53.54	NF	79.16
$\boldsymbol{A_3} - A_1$	-109.35	-100.43	NF	-2828.16
$\boldsymbol{A_3} - A_2$	-56.21	-47.44	-782.92	**-304.81**
$\boldsymbol{A_3} - A_4$	**15.16**	**13.1**	**80.81**	NF
$\boldsymbol{A_4} - A_1$	-154.96	-128.13	NF	-5833.1
$\boldsymbol{A_4} - A_2$	-91.07	-69.24	-3591.98	-478.42
$\boldsymbol{A_4} - A_3$	**-18.44**	**-14.64**	**-86.01**	**-144.71**

NF: Not-feasible

We should also check the feasibility of threshold value.

$$\tau'_{1,1,2} \leq 100 \quad \Rightarrow \quad 34.46 \leq 100$$

Thus, the score of alternative 1 under criteria 1 is decreased by 34.46%. A_1 and A_2 will reverse their rankings, i.e. A_2 will be more preferable than A_1.

Table 2.8 Criticality degrees for each a_{ij} measure

$\Delta'_{i,j}$	Criteria			
Alternatives	Criterion 1	Criterion 2	Criterion 3	Criterion 4
A_1	34.46 (A_2)	34.29 (A_2)	---	---
A_2	51.28 (A_3)	41.01 (A_3)	-829.46 (A_1)	68.36 (A_3)
A_3	15.16 (A_4)	13.1 (A_4)	80.81 (A_4)	-304.81 (A_2)
A_4	-18.44 (A_3)	-14.64 (A_3)	-86.01 (A_3)	-144.71 (A_3)

Table 2.7 is obtained by calculating all of the threshold values. This table shows threshold values in relative terms. The negative value in the table mean increase, while the positive value mean decrease in the score value of alternative, which is shown with bold typing in the pair of alternatives column.

The criticality degrees for each a_{ij} measure is summarized as shown in Table 2.8. The sensitivity coefficients for each a_{ij} measure are shown in Table 2.9.

Table 2.9 Sensitivity coefficients for each a_{ij} measure

$\Delta'_{i,j}$	Criteria			
Alternatives	Criterion 1	Criterion 2	Criterion 3	Criterion 4
A_1	0.029 (A_2)	0.029 (A_2)	0	0
A_2	0.020 (A_3)	0.024 (A_3)	0.001 (A_1)	0.015 (A_3)
A_3	0.066 (A_4)	13.1 (A_4)	0.012 (A_4)	0.003 (A_2)
A_4	0.054 (A_3)	0.076 (A_3)	0.012 (A_3)	0.007 (A_3)

2.4. Application Environment

A machine tool selection software, which includes machine properties in a database, is developed to implement the methodology. This software applies MCWA method, calculates force and power, and runs a cost / benefit analysis.

2.4.1. Database Selection

Database is a collection of information organized as to make it easy to view it, search it, retrieve the right detail, and collect the necessary facts in an easier, timely, and effortless manner as possible. It should facilitate the storage and retrieval of structural information on a computer’s hard drive. Microsoft Access is selected for this purpose. Access is an enormously complex, industrial strength software development environment. One of its advantages is being a rapid application development environment. It is a relational database system that supports industry standard query language Structured Query Language (SQL). The primary advantage of using MS Access is that it allows the user to learn about an enormous range of information systems concepts without having to interact with a large number of tools.

2.4.2. Database Construction

Databases consist of tables, where data in a database is stored; consequently, tables form the core of any database application. In addition to basic data, most DBMS permits a large amount of domain knowledge (such as captions, default values, constraints, etc.) to be stored at the table level.

When creating tables an extra time should be spent in table design, since it can result in enormous time savings during later stages of the project. Non-trivial changes to tables and relationships become increasingly difficult as the application grows in size and complexity.

A key is a one or more field that uniquely determines the identity of the real-world object that the record is meant to represent. A primary key in this application is the ID that uniquely determines each machine. If this field is known, it can be directly used to find the desired machine.

Relationships in tables are very useful for finding specific records and for data storage concerns. However, in order to construct a useful relationship, there are certain requirements for effectiveness and usefulness. The following should be considered first:

Wasted space: Is the information repeated for each record? Although amount of disk space wasted can be small in certain cases, it becomes an important issue for larger databases.

Difficulty in making changes: If one information is changed, does it require different kind of changes in other places?

Deletion problems: If a certain field in a certain record is deleted, does this affect different records?

Addition problems: If a new section is added, does much information have to be typed in again? This also increases the probability of introducing errors into the system.

In the case of machine selection problem the machine database should consist of many machine specifications. These machine specifications are grouped into six categories as shown in Table 3.3. Although it is grouped into six categories, this is not a relationship in database.

The database contains almost no field that is repeated for each section. Change, deletion, and addition in one field does not affect other fields. Thus, the database consists of only one primary key, which is ID.

2.4.3. Database Management Using Visual Basic

Visual Basic is used as a database management system (DBMS). It can be used in implementing a new application that requires management of a database, connecting to an existing database, or interacting with a database via the internet. Database may be available locally on user's computer, available on a LAN (local area network) shared by multiple users, or only available on a web server via the Internet. Visual Basic application acts as a front-end to the database. That is, the Visual Basic application provides the interface between the user and the database. This interface allows the user to tell the database what he or she needs and allows the database to respond to the request displaying the requested information in some manner. A Visual Basic application cannot directly interact with a database. There are two intermediate components between the application and the database: the data control and the database engine as shown in Figure 2.3.

The data control is a Visual Basic object that connects the application to the database via the database engine. It is the conduit between the application and the engine, passing information back and forth between the two. The database engine is the heart of a Visual Basic database management system. It is the actual software that does the management. Having this engine saves programmers a lot of work. The database engine native to Visual Basic is known as the Jet engine. It is the same engine used by Microsoft Access for database management. Hence, it is primarily used to work with Access databases, but it can work with other databases as well.

The advantage of using Visual Basic as a front-end for database management systems is that, it requires less code to connect to an existing database, to view all the information within that database, and to modify the information within that database.

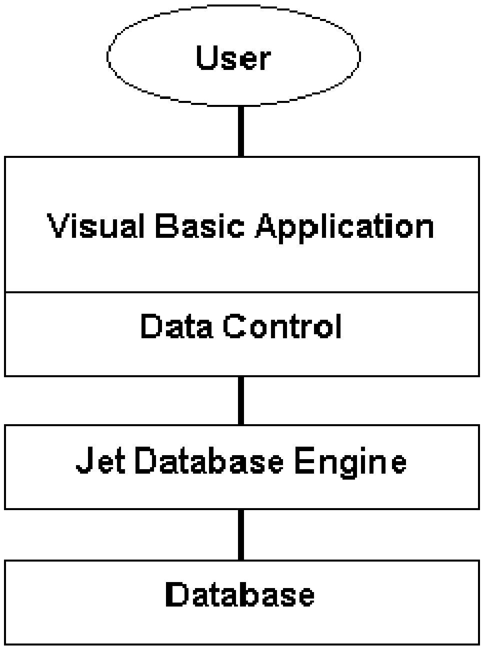

Figure 2.3 Database user interaction

2.5. Summary

In this chapter, the information to better understand problem was summarized. First, the literature in the area of machine selection was investigated. However, nobody has attempted to solve the machine selection problem for different kind of manufacturers and for different kind of production lines at the same time. Second, multi-criteria decision-making methods were summarized. These include the weighted sum model method, the weighted product model method, AHP, and revised AHP. Although methods may differ, there exists no method that overcomes others in all aspects. Third, sensitivity analysis was reviewed in order to determine the effects of changes in weights and changes in machine scores on the ranking of machines. Sensitivity analysis is important in the sense that a slight change in criterion weight may cause the rankings of alternatives to change considerably. Finally, in order to implement DSS, an application environment is required. This should include the database consisting of machines and their properties and database management tools. Moreover, good management of database and database management tools is required in order to apply all the selection methodology. Thus, the necessary background information about the application environment is also presented.

3. SELECTION METHODOLOGY

This chapter mainly presents the methodology used in machine selection problem. First, determination of decision criteria and machine specifications are demonstrated. Second, force and stability models are summarized to determine requirements, such as force, power, speed, feed rate, axial depth of cut, etc. Third, the application of multi-criteria weighted average method is explained. Fourth, cost/benefit analysis and additional machine option analysis are performed. Last, the tool selection methodology is explained in steps.

3.1. Determination of Decision Criteria and Machine Specifications

This section defines decision criteria and machine specifications, so that a selection methodology can be build on it.

3.1.1. Decision Criteria

In a machine selection process, the obvious purpose is to select the best machine from available database based on user requirements. There are so many different requirements, which are grouped under eight different categories in our approach. These criteria with sub-criteria are as shown in Table 3.1 and Table 3.2. The decision criteria are evaluated as a function of machine properties. Therefore, most of them depend on a number of machine properties. 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, pallet changer 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 will be reviewed in Section 3.2 for this purpose. If certain precision is required, it can be a critical factor. Reliability of the machine is very critical since it will determine the failure rate of the machine. Safety and Environment are also important criteria especially when company tries to obtain a standard. Maintenance and Service are other important criteria. Companies often face with machine failures. If service support of the company of selected machine is not good, company will be in trouble. For example, machine manufacturer may not have service personnel in a country where machining center is purchased. This will increase the cost of machine failure to the company. Cost, which is the most important criterion most of the time, is considered separately.

Table 3.1 Simple Criteria

1. Productivity	speed, power, cutting feed, etc.
2. Flexibility	# of tools, rotary table, etc.
3. Space	machine dimensions
4. Adaptability	CNC type, taper #, etc.
5. Precision	repeatability, thermal deformation, etc.
6. Reliability	bearing failure rate, reliability of drive system, etc.
7. Safety and Environment	mist collector, safety door, fire extinguisher, etc.
8. Maintenance and Service	training, repair service, regular maintenance, etc.

Table 3.2 Detailed Criteria

1. Productivity	2. Flexibility	3. Space
P1. Max. Speed	F1. U Axis	S1. Machine dimensions
P2. Main Spindle Power	F2. Articulated Axis	S2. Weight
P3. Tool to tool time	F3. No of Pallets	
P4. # of Spindles	F4. Rotary Table	
P5. Rapid Traverse Speed	F5. Total # of tools	
P6. Cutting Feed	F6. Head Changer	
P7. Auto Pallet Changer	F7. Main Spindle Power	
P8. Taper #	F8. Index Table	
	F9. Dual Axis Rotary Table	
	F10. Max. Speed	
	F11. CNC or not?	
	F12. CNC Control Type	

4. Adaptability	5. Precision	6. Reliability
A1. Taper #	PN1. Axis Precision	R1. Bearing failure rate
A2. Space requirement of the machine	PN2. Repeatability	R2. Reliability of drive system
A3. CNC Control Type	PN3. Thermal Stability	
A4. Coolant Type	PN4. Static and Dynamic Rigidity	
A5. # of tools		

7. Safety and Environment	8. Maintenance and Service
SE1. Safety Door	MS1. Repair Service
SE2. Fire extinguisher	MS2. Training
SE3. Mist Collector	MS3. Spare Parts
	MS4. Regular Maintenance

3.1.2. 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 them. These are both difficult to achieve since each manufacturer produces variety of machines with different features. Therefore, as a first step, a standard classification is prepared as shown in Table 3.3 and Table 3.4.

A machining center, shown in Figure 3.1, is a typical united product, which combines modern information science with mechanical technology. It consists of many mechanical, electronic and computer parts. Axes of a machining center are shown in

Figure 3.2. Tool changer is shown in Figure 3.3. Rotary table is shown in Figure 3.4. The interested reader is referred to [17] for other machining center specifications.

Table 3.3 Simple machining center specifications

1. General	company name, machine name, machine type, CNC type, column style type, etc.
2. Spindle	spindle type, spindle direction type, taper number, max. Speed, power, etc.
3. Tooling	number of tools, tool diameter, etc.
4. Work Support	table size, rotary table, etc.
5. Axis	number of axis, cutting feed, rapid traverse speed, etc.
6. Dimensions and Weight	machine dimensions, machine weight, etc.

Table 3.4 Detailed Machining Center Specifications

1. General	**2. Spindle**	**3. Tooling**
G1. Company Name	S1. Type	T1. Primary Tool Carrier
G2. Machine Type	S2. Direction	T2. Number of Tools
G3. CNC Control	S3. Taper	T3. Max Tool Length
G4. Column Style	S4. Max Speed RPM	T4. Max Tool Diameter
G5. Column Construction	S5. Num of Ranges	T5. Tool Diameter Option
G6. Work Support	S6. Horse Power	T6. Max Tool Weight
G7. Machine Name	S7. Num of Spindle	T7. Tool Change Time
	S8. Articulated Axis	T8. Chip to Chip Time
	S9. U Axis	T9. Head Changer

4. Work Support	5. Axis	6. Dimensions
W1. Table Size Length	A1. Number of Axis	P1. Machine Dim. L
W2. Table Size Width	A2. X1	P2. Machine Dim. W
W3. Max Workpiece Weight	A3. Y1	P3. Machine Dim. H
W4. Auto Pallet Changer	A4. Z1	P4. Machine Weight
W5. Number of Pallets	A5. A1 (Degrees)	P5. Spindle Nose to Table (Min)
W6. Index Table	A6. B1 (Degrees)	P6. Spindle Nose to Table (Max)
W7. Index Table degrees	A7. C1 (Degrees)	P7. Spindle Center to Column
W8. Rotary Table	A8. X1 Cutting Feed	P8. Spindle to Table Center
W9. Dual Axis Rotary Table	A9. Y1 Cutting Feed	P9. Spindle to Table Edge
	A10. Z1 Cutting Feed	
	A11. A1 Cutting Feed	
	A12. B1 Cutting Feed	
	A13. C1 Cutting Feed	
	A14. X1 Rapid Traverse	
	A15. Y1Rapid Traverse	
	A16. Z1 Rapid Traverse	
	A17. A1 Rapid Traverse	
	A18. B1 Rapid Traverse	
	A19. C1 Rapid Traverse	

A machining center is a machine for both milling and hole making on a variety of non-round or prismatic shapes. The unique feature of the machining center is the tool changer. The tool changer system moves tools from storage to spindle and back again in rapid sequence. While most machining centers will store and handle 20 to 40 individual tools, some will have inventories of over 200. Machining centers may either be vertical or horizontal. There is also a universal type capable of both orientations. The vertical type is often preferred when work is done on a single face. With the use of rotary tables, more than one side of a workpiece, or several workpieces, can be machined without operator intervention. Vertical machining centers using a rotary table have four axes of motion. Three are linear motions of the table while the fourth is the table's rotary axis. Horizontal centers with their horizontal spindles are better suited to larger, boxy workpieces. With a horizontal spindle, a wider variety of workpiece shapes are easier to mount and chips fall out of the way better. Like vertical machining centers, horizontal centers have multiple-axis table movements. Typically, the horizontal center's table rotates to present all four sides of a workpiece to the tooling. The principle of the universal machining center is that the workpieces on the table may be addressed by a vertically-oriented or a horizontally-oriented spindle. Further, the combination of tilts and swivels available in the spindles and tables allow the workpieces to be addressed at a variety of compound angles.

Figure 3.1 Machining Center

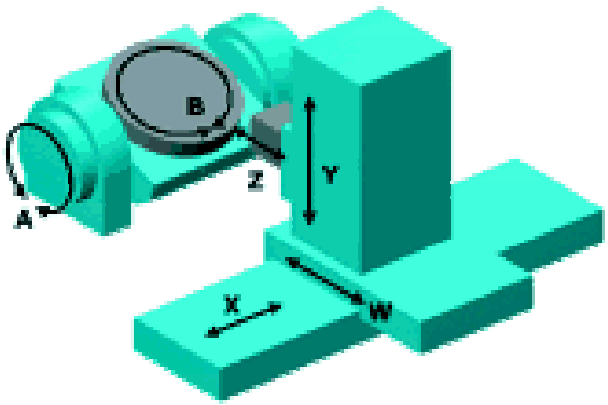

Figure 3.2 Axes of a machining center

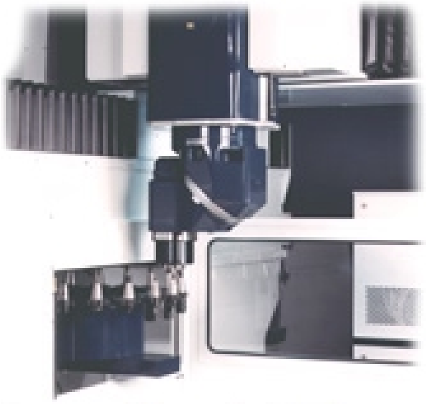

Figure 3.3 Tool Changer

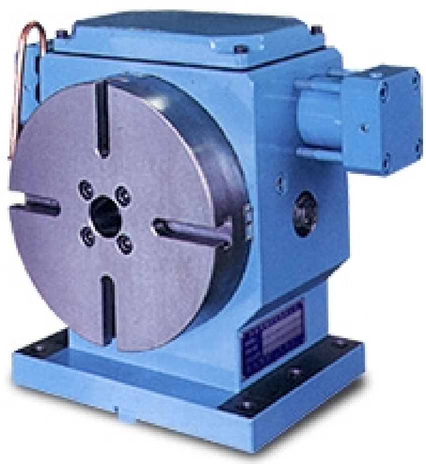

Figure 3.4 Rotary Table

3.2. Process Models

Part quality and productivity deteriorate during machining due to excessive cutting forces and chatter vibrations. Process model can be effectively used to improve productivity and quality. In addition, they can be very useful in determining machine tool specifications. 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.

3.2.1. 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 $MRR = a.b.f$ where a is the axial depth of cut, b is the width of cut, f is feed rate which is defined as $f = f_t.n.N_t$ 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 force, torque, power, deflection, and chatter vibrations are expected 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.

Thus, by process model force, torque, power, deflection, and chatter vibrations can be investigated so that high material removal rate limits can be determined.

3.2.2. 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.

Milling is the most versatile of machining processes. Metal removal is accomplished through the relative motions of a rotating, multi-edge cutter and multi-axis movement of the workpiece. Milling is a form of interrupted cutting where repeated cycles of entry and exit motions of the cutting tool accomplish the actual metal removal and discontinuous chip generation. Milling has more variations in machine types, tooling, and workpiece movement than any other machining method.

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 ([18] and [19]).

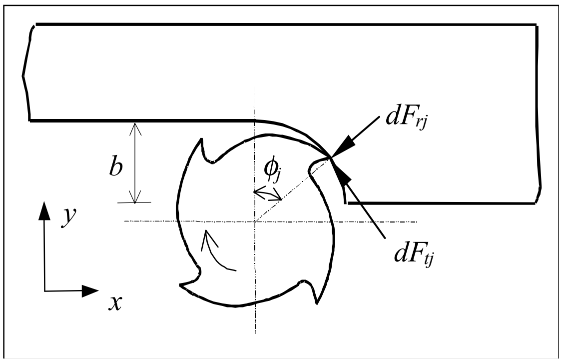

Figure 3.5 Cross sectional view of an end mill

The forces contributed by one tooth of the cutter are determined as follows ([20] and [21]):

$$F_{x_j}(\phi)=\frac{K_t f_t R}{4\tan\beta}\left[-\cos 2\phi_j(z)+K_r\left(2\phi_j(z)-\sin 2\phi_j(z)\right)\right]_{z_{jl}(\phi)}^{z_{ju}(\phi)} \tag{3.1}$$

$$F_{y_j}(\phi)=-\frac{K_t f_t R}{4\tan\beta}\left[\left(2\phi_j(z)-\sin 2\phi_j(z)\right)+K_r\cos 2\phi_j(z)\right]_{z_{jl}(\phi)}^{z_{ju}(\phi)} \tag{3.2}$$

$$F_{z_j}(\phi)=-\frac{K_t K_a f_t R}{\tan\beta}\left[\cos\phi_j(z)\right]_{z_{jl}(\phi)}^{z_{ju}(\phi)} \tag{3.3}$$

where R is the cutter radius, K_t, K_r and K_a are milling force coefficients, $z_{jl}(\phi)$ and $z_{ju}(\phi)$ are the lower and higher limits of the contact for the tooth j, β is the helix angle, f_t is the feed per tooth and $\phi_j(z)$ is the immersion angle for the flute j at axial position z measured from the positive y axis as shown in Figure 3.5. Then, the total milling forces can be determined as follows (Refer to [20] and [21] for details):

$$F_x(\phi)=\sum_{j=1}^{N}F_{x_j}(\phi);\; F_y(\phi)=\sum_{j=1}^{N}F_{y_j}(\phi);\; F_z(\phi)=\sum_{j=1}^{N}F_{z_j}(\phi) \tag{3.4}$$

Tangential force can be calculated similarly:

$$F_{t_j}(\phi)=\frac{K_t f_t R}{\tan\beta}\left[\cos\phi_j(z)\right]_{z_{jl}(\phi)}^{z_{ju}(\phi)} \tag{3.5}$$

$$F_t(\phi)=\sum_{j=1}^{N}F_{t_j}(\phi) \tag{3.6}$$

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

$$T(\phi)=F_t(\phi).R \tag{3.7}$$

$$P(\phi)=F_t(\phi).R\Omega \tag{3.8}$$

where Ω is defined as $\frac{n \cdot 2\pi}{60}$ and n is the spindle speed. Forces, torque and power variations are estimated for one full revolution of the cutter (ϕ: $0 \rightarrow 2\pi$) using (3.8) and the peak values are determined. These values are the force, torque and power requirements for the process.

The cutting parameters K_t and K_r can be determined either by looking them in some machinery handbooks or by experimental analysis. In experimental analysis, K_t and K_r are expressed as exponential functions of the average chip thickness as follows ([20]);

$$K_t = K_T h_a^{-p} \quad ; \quad K_r = K_R h_a^{-q} \tag{3.9}$$

Constants K_T, K_R, p and q are usually determined using mechanistic models where linear regression on measured milling forces is performed for different feedrates. Therefore, they depend on the workpiece material and cutting tool geometry. The average chip thickness is defined as the ratio of the chip volume produced in one revolution of the cutter to the exposed chip area:

$$h_a = f_t \frac{\cos\phi_{st} - \cos\phi_{ex}}{\phi_{ex} - \phi_{st}} \tag{3.10}$$

where ϕ_{st} and ϕ_{ex} are the start and exit angles of the tooth to and from the cut, respectively. (Refer [20] for details).

3.2.3. 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 (3.11). (Refer to [21] and [22] for details)

$$a_{\lim} = -\frac{2\pi\Lambda_R}{NK_t}\left(1+\kappa^2\right) \tag{3.11}$$

$$\kappa = \frac{\Lambda_I}{\Lambda_R} \;\; ; \;\; \Lambda = -\frac{1}{2a_0}\left(a_1 \pm \sqrt{a_1^2 - 4a_0}\right) \tag{3.12}$$

$$\begin{aligned} a_0 &= G_{xx}(i\omega_c)\cdot G_{yy}(i\omega_c)\cdot\left(\alpha_{xx}\alpha_{yy} - \alpha_{xy}\alpha_{yx}\right) \\ a_1 &= \alpha_{xx}\cdot G_{xx}(i\omega_c) + \alpha_{yy}\cdot G_{yy}(i\omega_c) \end{aligned} \tag{3.13}$$

where G_{xx} and G_{yy} are transfer functions in the specified directions, α is directional coefficient, ω_c is the chatter frequency, Λ_R and Λ_I are the real and imaginary parts of the eigenvalue, respectively.

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 3.6 gives us chatter stability diagram of a certain process. It is clear from the diagram that with speed of 15000 rpm, 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, the required maximum spindle speed and dynamic rigidity of the spindle can be predicted depending on productivity or geometry considerations. The spindle speed information is available in 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.

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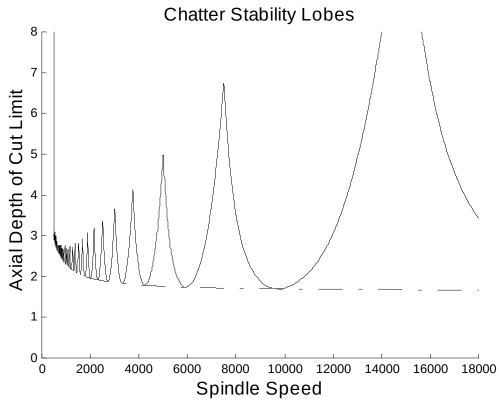


Figure 3.6 Chatter Stability Diagram

3.3. Multi-Criteria Weighted Average Method for Machine Selection

Machine selection problem consists of number of alternatives and number of criteria. MCWA is used to rank the alternatives from best to worst. We use weighted average together with hierarchy tree for the selection process. This method is much like AHP, but comparison matrices are not used to determine the weights. Since criteria weights are directly used in this methodology, they may implicitly include inconsistencies. Therefore, the determination of the criteria weights is critically important.

The hierarchy tree consists of three levels: level 1 contains the goal (selection of the best machine); level 2 consists of eight main criteria; and level 3 consists of sub-criteria (based on the machine specs in; speed, power, etc.).

The procedure for MCWA method is as follows (refer to Table 3.5 for notations and definitions):

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

Step 2: S_{ijm} score is calculated using the database. For quantitative criteria, normalization using the highest or lowest machine properties determines the scores. Supplying predetermined scores to criteria also normalizes subjective criteria.

Step 3: Weights are multiplied with their scores to find machine rankings as shown in equations below.

$$S_{im} = \sum_{j=1}^{Ji} S_{ijm} \text{ x } W_{ij} \quad , m = 1,..,M, \ i = 1,..,I \tag{3.14}$$

$$S_m = \sum_{i=1}^{I} S_{im} \text{ x } W_i \quad , m = 1,..,M \tag{3.15}$$

In this approach each criterion is defined 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 3.5 Notation and Definitions

i	Criterion index	i=1..I	I	Total # of criteria
j	Sub-criterion index	j=1..J_i	J_i	Total # of sub-criteria
m	Machine index	m=1..M	M	Total # of machines
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			

3.3.1. Approximation of Weights of Criteria and Sub-criteria

It is hard to determine the weights of criteria, which will determine machine rankings. However, for the variety of the needs of the companies, weights of criteria can differ significantly. Thus, a survey is prepared in order to determine the importance of selection criteria for companies having different needs and different production types. Although complete survey results are not available yet, some limited information is obtained about the preferences. It is noticed that productivity, cost, and adaptability are usually the most important criteria in many cases. Classification of manufacturing types and shop types are shown below. The survey is included in the Appendix.

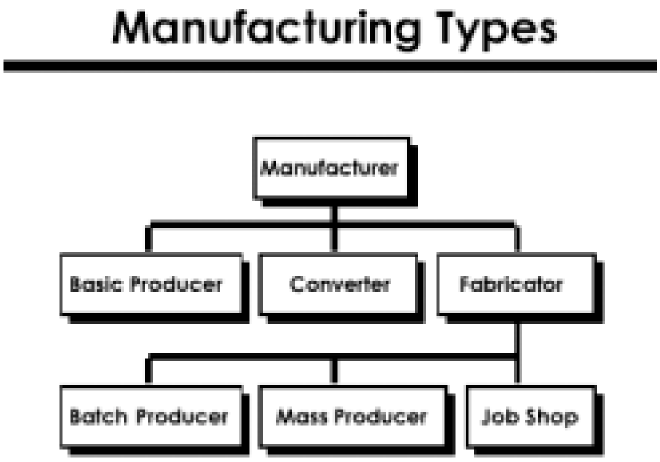


Figure 3.7 Manufacturing Types

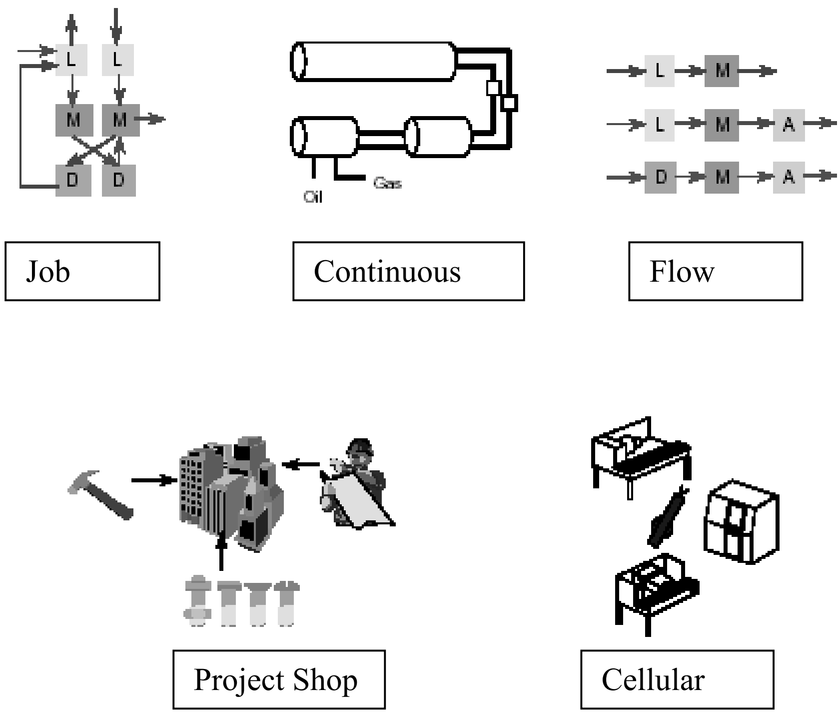


Figure 3.8 Types of production lines

Figure 3.7 shows manufacturing types. Basic Producer takes a natural resource such as iron ore and converts it to a steel ingot. Converter takes basic products such as iron ore and converts into workable items such as sheet steel. Fabricator takes converted product and produces discrete products such as TVs.

Figure 3.8 shows types of production lines. Job shops typically produce numerous individual products. Batch production involves producing medium sized batches of parts or components. Mass production involves high production rates of typically only one or two individual products. Quantity production involves producing extremely large quantities of simple parts or products. Flow production involves assemblies of high quantities of complex products.

3.3.2. Calculation of Scores

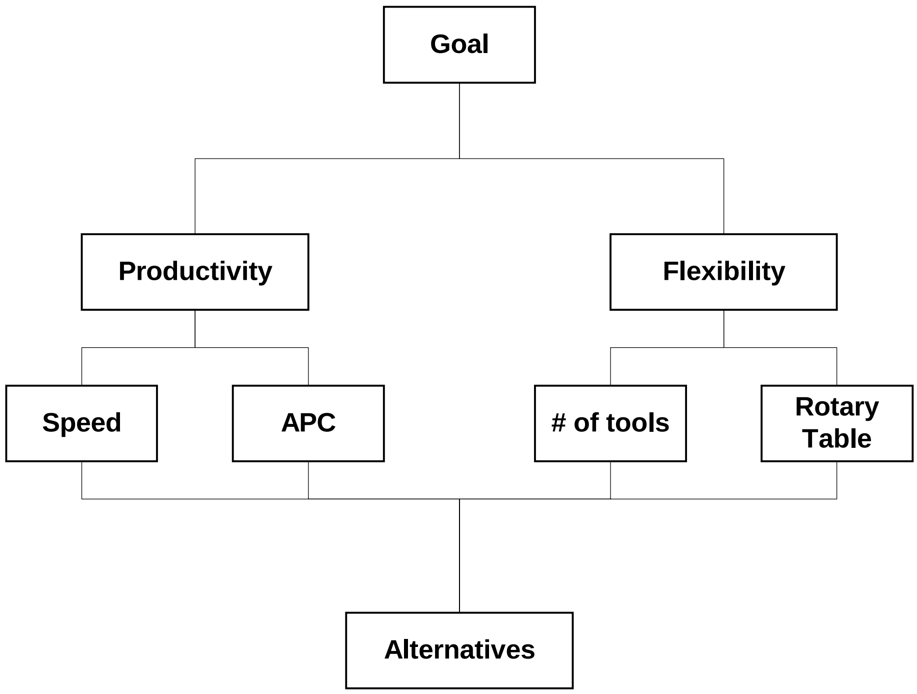


Figure 3.9 Hierarchy tree

The hierarchy tree means that there are two criteria, Productivity and Flexibility, and four sub-criteria, Speed, Auto Pallet Changer, # of tools and Rotary Table, and three alternative machines, i.e., M=3. The goal is the selection of the best machine. If the previous notation is used, total # of criteria (I), J_1 and J_2 are two.

Assume that the following data is available as shown in Table 3.6 and Table 3.7.

Table 3.6 Weights for the example

Criteria	Sub-Criteria	Weight	Notation
Productivity	---	0.60	W_1
Productivity	Speed	0.70	W_{11}
Productivity	APC	0.30	W_{12}
Flexibility	---	0.40	W_2
Flexibility	# of tools	0.65	W_{21}
Flexibility	Rotary Table	0.35	W_{22}

Table 3.7 Machine properties

Alternatives	Criteria			
i	Productivity		Flexibility	
j	Speed	APC	# of tools	Rotary Table
Machine 1	7000	Standard	40	Optional
Machine 2	6000	Optional	30	Optional
Machine 3	4000	Standard	30	None

By normalization using maximum values and using predetermined values Table 3.8 is obtained.

Table 3.8 Normalization

Alternatives	Criteria							
i	Productivity (0.6)				Flexibility (0.4)			
j	Speed (0.7)	Not.	APC (0.3)	Not.	# of tools (0.65)	Not.	Rotary Table (0.35)	Not.
Machine 1	1.000	S_{111}	1.000	S_{121}	1.000	S_{211}	0.500	S_{221}
Machine 2	0.857	S_{112}	0.100	S_{122}	0.750	S_{212}	0.500	S_{222}
Machine 3	0.571	S_{113}	1.000	S_{123}	0.750	S_{213}	0.000	S_{223}

Then scores of machines under criteria can be calculated as shown in Table 3.9 using

$$S_{im} = \sum_{j=1}^{Ji} S_{ijm} \text{ x } W_{ij} \quad , m = 1..M, \; i = 1..I$$

Table 3.9 Scores

Alternatives	Criteria			
i	Productivity		Flexibility	
		Notation		Notation.
Machine 1	1.0000	S_{11}	0.8250	S_{21}
Machine 2	0.6299	S_{12}	0.6625	S_{22}
Machine 3	0.6997	S_{13}	0.4875	S_{23}

Then these scores are normalized as shown in Table 3.10.

Table 3.10 Normalized Scores

Alternatives	Criteria			
i	Productivity		Flexibility	
		Notation		Notation.
Machine 1	0.4293	S_{11}	0.4177	S_{21}
Machine 2	0.2704	S_{12}	0.3354	S_{22}
Machine 3	0.3004	S_{13}	0.2468	S_{23}

Now overall score of machines can be calculated using the following formula:

$$S_m = \sum_{i=1}^{I} S_{im} \text{ x } W_i \quad , m = 1..M$$

Then scores are obtained as shown in Table 3.11.

Table 3.11 Total Scores

Alternatives	Scores
Machine 1	0.4246
Machine 2	0.2964
Machine 3	0.2789

3.4. Cost, Benefit, and Option Analysis

For a better machine selection, the effects of cost should be investigated in detail. Sometimes the cost of machine can be very critical in selecting the machine tool. Thus, a proper analysis of cost is necessary. Performance, cost rankings, sensitivity analysis, and decision-maker judgment are used to justify the machines. The decision-maker may use these to conclude a solution.

3.4.1. Detailed Cost and Option Analysis

After the selection of the best machine, more detailed cost analysis is applied. Annual production requirement can be calculated when annual revenue equals annual cost. Similar cost calculations may also be done to find desired unknowns, for example, the payback period.

Table 3.12 shows the notation for the analysis. The formulations for the taxable income (*TI*) and net profit after tax (*NPAT*) are as follows:

$$\begin{aligned} TI = P \times X + S \times (A/F, i, T) - C_{OH} - C_D \\ - C_O \times T_O \times X - C_S \times (T_S + T_{CH}) \times X \end{aligned} \tag{3.16}$$

$$\begin{aligned} NPAT = -C_M \times (A/P, i, T) + P \times X + S \times (A/F, i, T) \\ - C_{OH} - C_O \times T_O \times X - C_S \times (T_{SE} + T_{CH}) \times X - rxTI \end{aligned} \tag{3.17}$$

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 annual worth of a future fund of *F* using *MARR* of *i* in *T* periods. Here, straight-line depreciation is used. Standard operating time assumption is used in calculations (refer to [23] for details). Then break-even production quantity can be computed.

Table 3.12 Notation for the analysis

Machine Procurement Cost	C_M	€
Overhead Cost	C_{OH}	€/year
Depreciation Cost	C_D	€/year
Salvage Value	S	€
Part Sale Price	P	€/part
Operating Cost	C_O	€/operating hr
Operating Time	T_O	hrs/part
Setup and Part Change Cost	C_S	€/operating hr
Setup Time	T_S	hrs/part
Part Change Time	T_{CH}	hr/part
Planning Horizon	T	Years
MARR	i	%
Tax Rate	r	%
Annual Production	X	Parts

3.5. Step-by-Step Selection Methodology

In this section, the machine selection procedure will be summarized. The summary of the selection is as follows:

Step 1: Determination of selection factors

In this step, decision-maker should decide on machine specifications. For a given process, required machine tool specifications can be determined using force and stability models. These models are useful in determining the requirements such as force, power, speed, feed rate, axial depth of cut, etc.

Step 2: Determination of selection criteria weights

In the second step, criteria weights are determined. Criteria weights are very critical since they will determine the machine rankings. Pre-defined weights may be chosen for different types of companies and for variety of production types or these pre-defined weights may be modified.

Step 3: Searching the database

After the determination of selection factors, database is searched for the machines satisfying the requirements.

Search algorithm will also search the optional features of the machines and select the most appropriate combination of features. Suppose that a machine is searched such that its spindle speed should be larger than 8000 and its total number of tools should be larger than 25. Also, suppose that a machine is available in the database with the specifications shown in Table 3.13.

Table 3.13 Specifications of machine *k*

	Max. Speed	Max. Speed Option	Total # of tools	Total # of tools Option
Machine *k*	6000	10000	30	60

The search algorithm will select this machine with a max. speed of 10000 and with total number of 30 tools.

Step 4: Application of MCWA (ranking of machines)

After obtaining the machines satisfying the user requirements, in step 4, MCWA is applied. MCWA ranks the machines from best to worst using machine specifications and criteria weights.

Step 5: Sensitivity analysis

The sensitivity analysis determines the smallest change in current weights of the criteria that may alter the existing ranking of the alternatives. Sensitivity analysis is also applied for the determination of the most critical measure of performance.

Step 6: Re-evaluation considering cost

After ranking the machines based on productivity, flexibility, etc., the effect of machine cost is also considered. Machine scores are compared with machine costs. The decision-maker may select a machine based on performance and cost rankings.

Other machine properties data, i.e., precision, reliability, safety and environment, maintenance and service may be obtained for the selected machines and selection procedure may be repeated from step 2.

Step 7: Option analysis

Cost analysis for machine options may be applied, if additional options are planned to be added to the selected machine.

3.6. Summary

In this chapter, the methodology that is necessary to solve the machine selection problem was proposed. First, the decision criteria were determined with their sub-criteria. They are the main determining factors in the selection. Second, machines were classified according to their specifications. Machine database was constructed using these specifications and classifications. Third, process models were summarized. Force and stability models can be used to approximate process requirements, such as force, power, speed, feed rate, axial depth of cut, etc. Thus, machines that are capable of achieving the desired tasks were selected. Fourth, the developed methodology, multi-criteria weighted average method, was proposed. The method used the criteria weights and machine specifications and then ranked the machines from best to worst. The determination of weights was also investigated. Fifth, the effects of cost and machine options were presented. Approaches were proposed in order to justify the effect of cost. Last, machine selection procedure was demonstrated in steps.

4. IMPLEMENTATION

In this chapter, the implementation of the developed methodology will be demonstrated. First, the application environment is demonstrated. The developed software is capable of achieving different tasks. Then, all of the developed methodology will be demonstrated for possible machine selection problems.

4.1. Software

The implementation of the methodology is difficult and time consuming to achieve. Although, it is easy to program with Visual Basic and Microsoft Access, many programming and implementation obstacles were faced. However, as a result, a Decision Support System for machine selection, which is capable of implementing the methodology, is developed.

The machine selection software (MSS) is capable of connecting to an external database as shown in Figure 4.1.

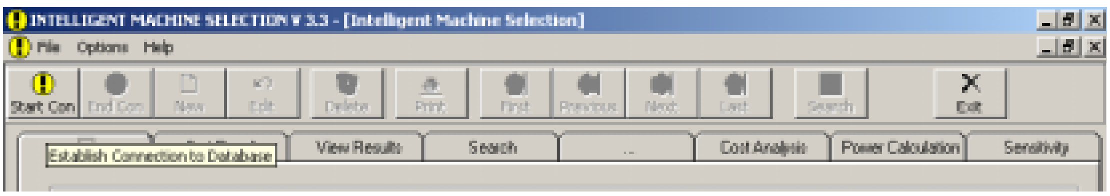


Figure 4.1 Connection to the database

After connecting to database, user can view the machine specifications in database both in list form and in box form as shown in Figure 4.2 and Figure 4.3.

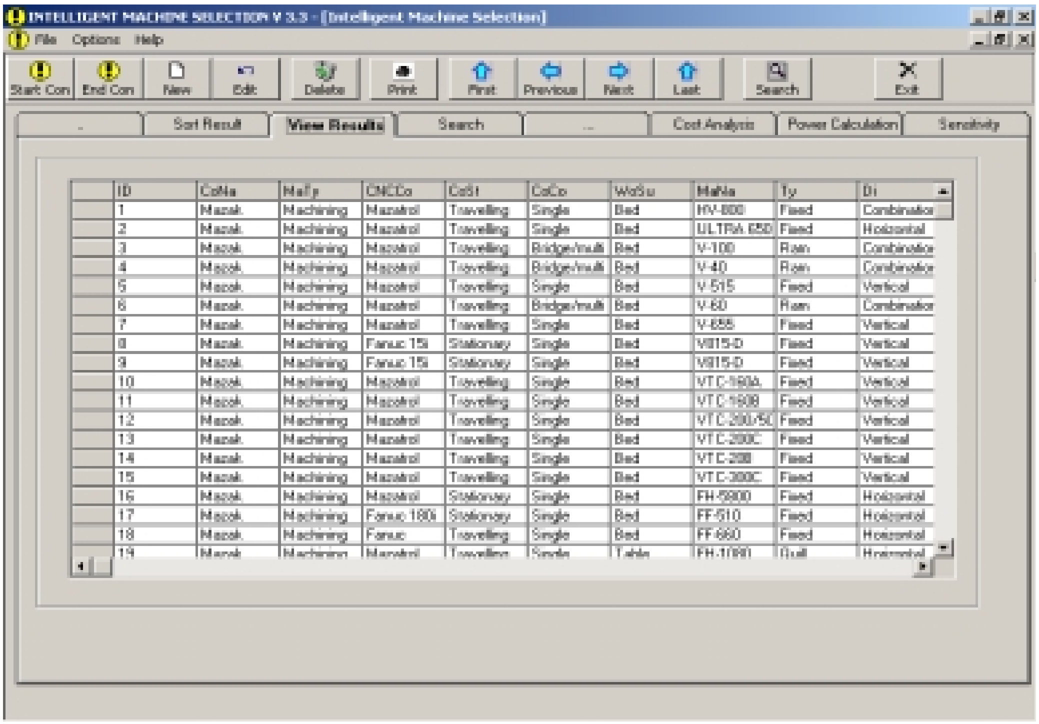


Figure 4.2 Machine Specifications in list form

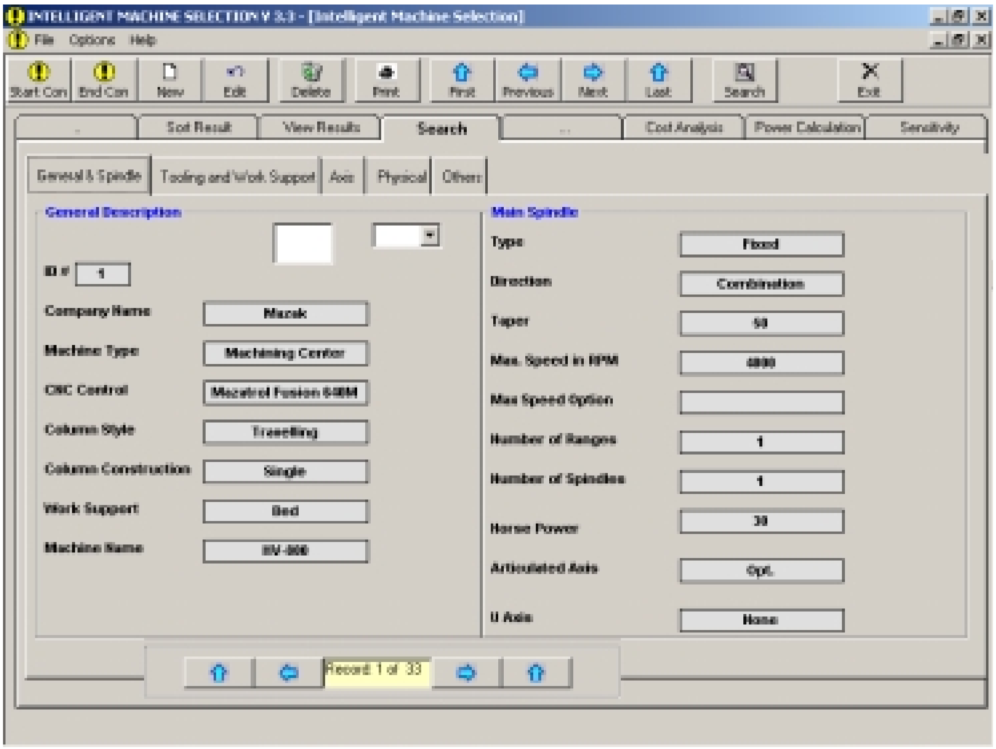


Figure 4.3 Machine Specifications in box form

It is possible to add a new machine to the database, delete a machine from the database, and edit the specifications of machines in database as shown in Figure 4.4. It is also possible to navigate through the records using the arrows. For example, one can go directly to the first record, last record, the previous record, or the next record.

Figure 4.4 Database management tools

With MSS force and power can be calculated as shown in Figure 4.5.

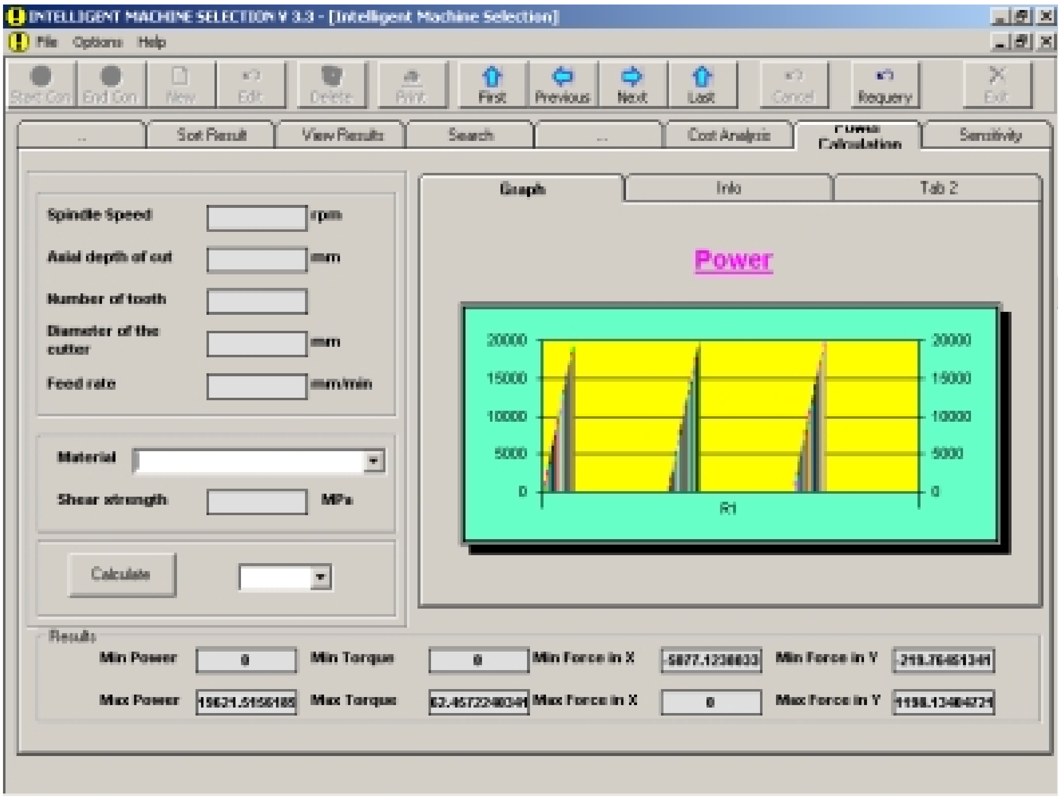


Figure 4.5 Force modeling

MSS is capable of searching the database for specific user requirements. It also allows the user to choose multiple machines using their unique ID numbers as shown in Figure 4.6.

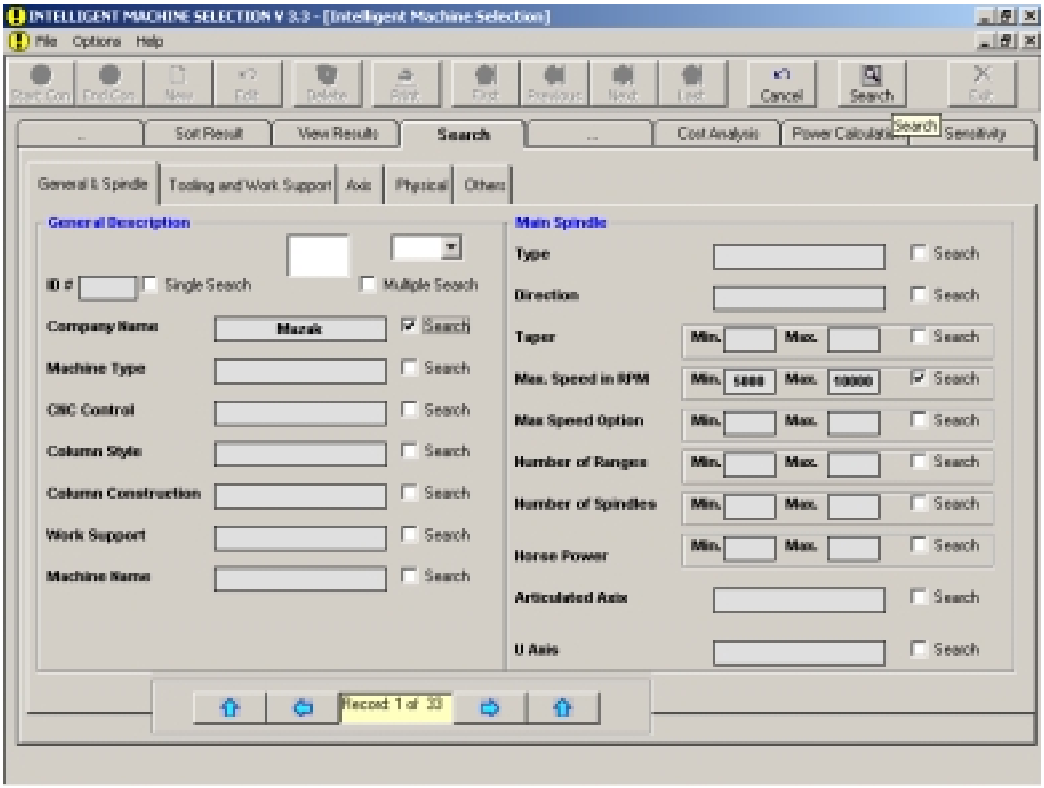


Figure 4.6 Searching the database

MSS can be used to determine the weights of criteria depending on the type of company and type of production as shown in Figure 4.7. If desired, these weights can be modified as shown in Figure 4.8.

MSS will also sort the machines using criteria weights and machine specifications as shown in Figure 4.9.

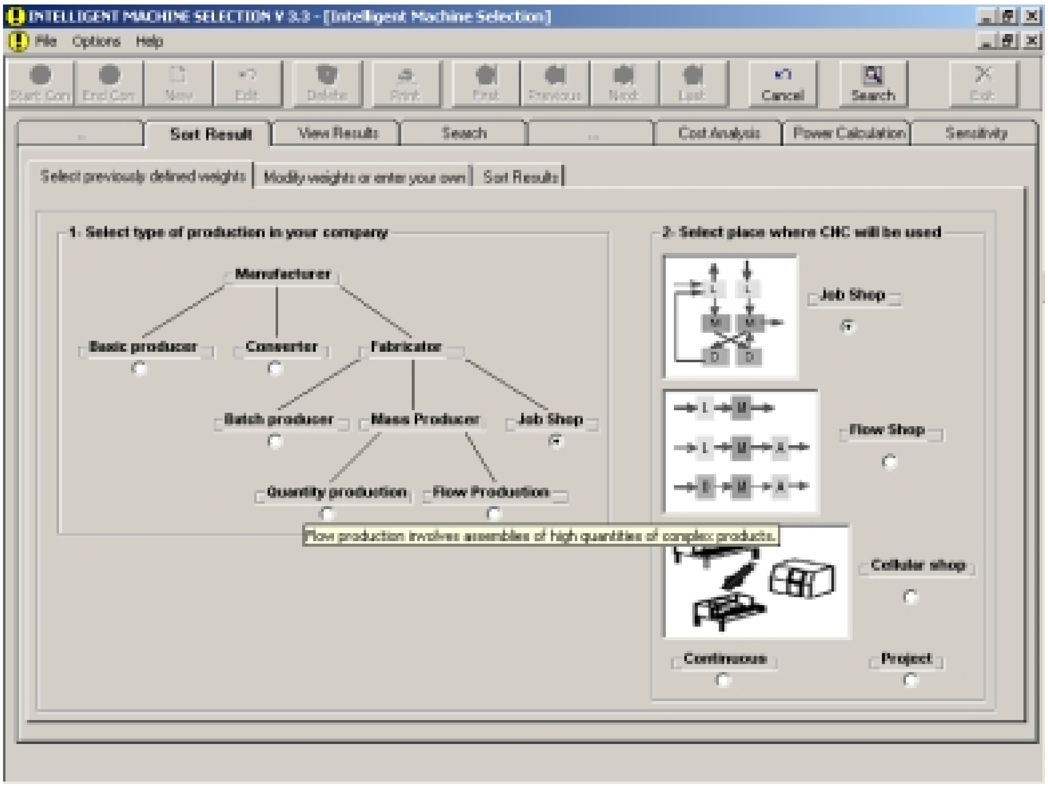


Figure 4.7 Pre-defined weights

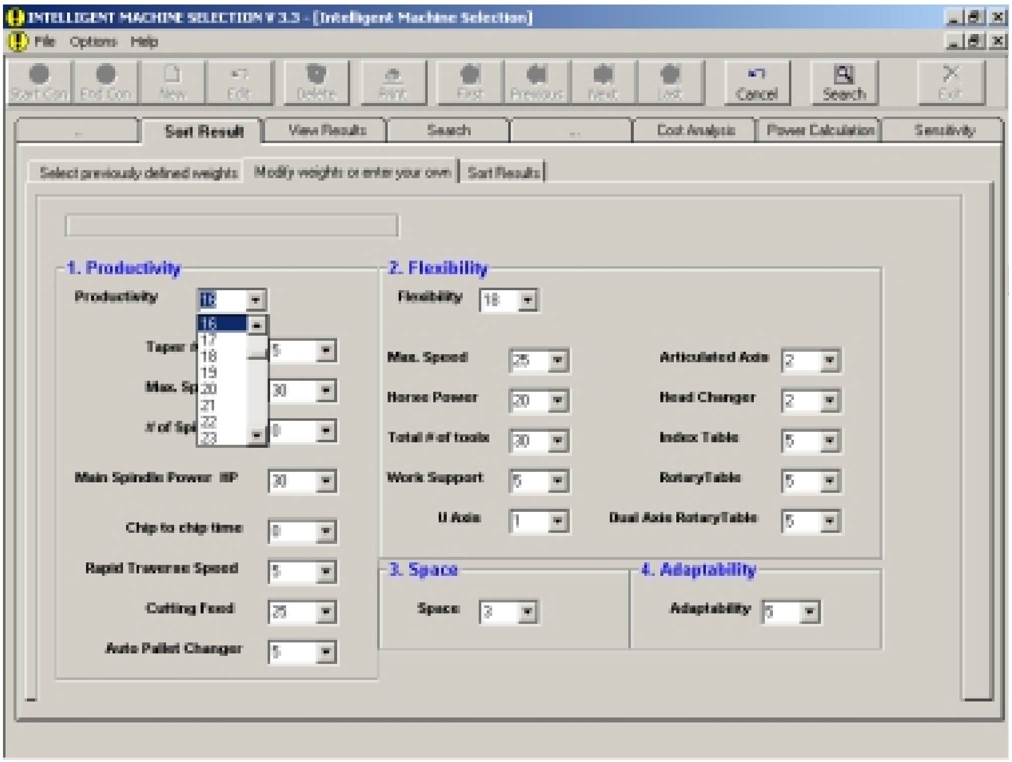


Figure 4.8 Pre-defined weights can be modified

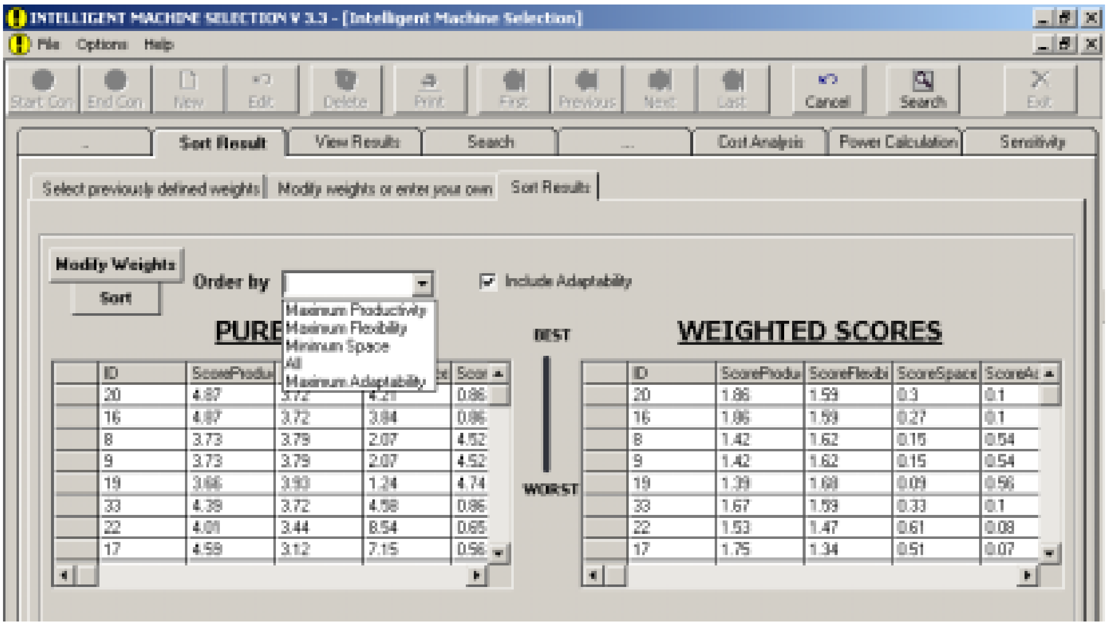


Figure 4.9 Ranking the machines

MSS will determine the smallest change in current weights of the criteria, which can alter the existing ranking of the alternatives as shown in Figure 4.10. Sensitivity analysis is also applied for the determination of the most critical measure of performance as shown in Figure 4.11.

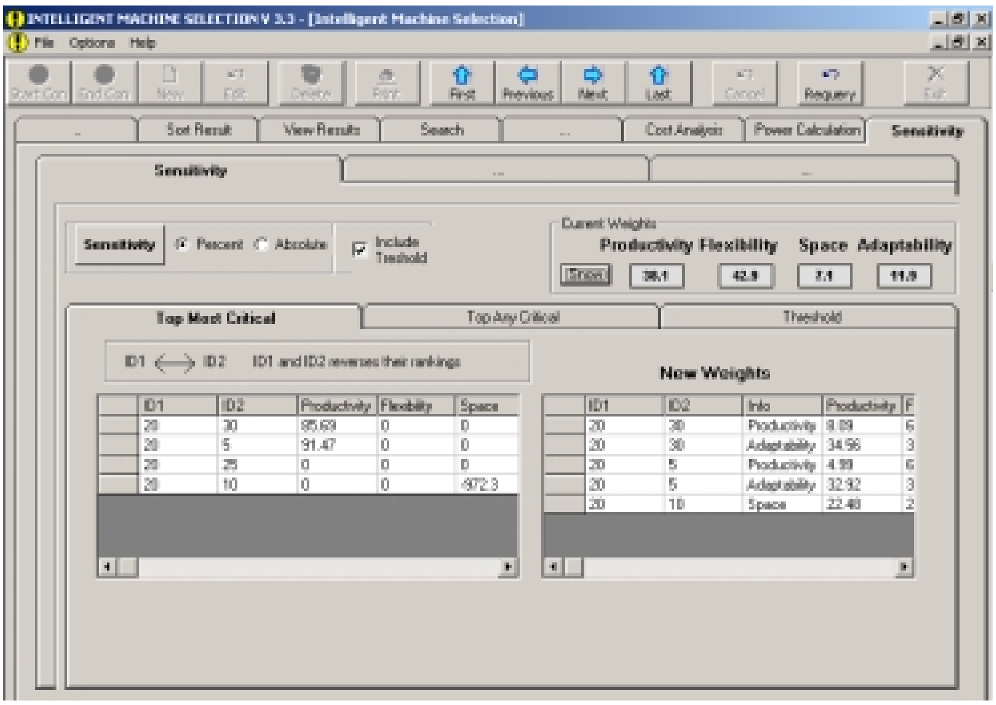


Figure 4.10 Sensitivity analysis for top most critical machine

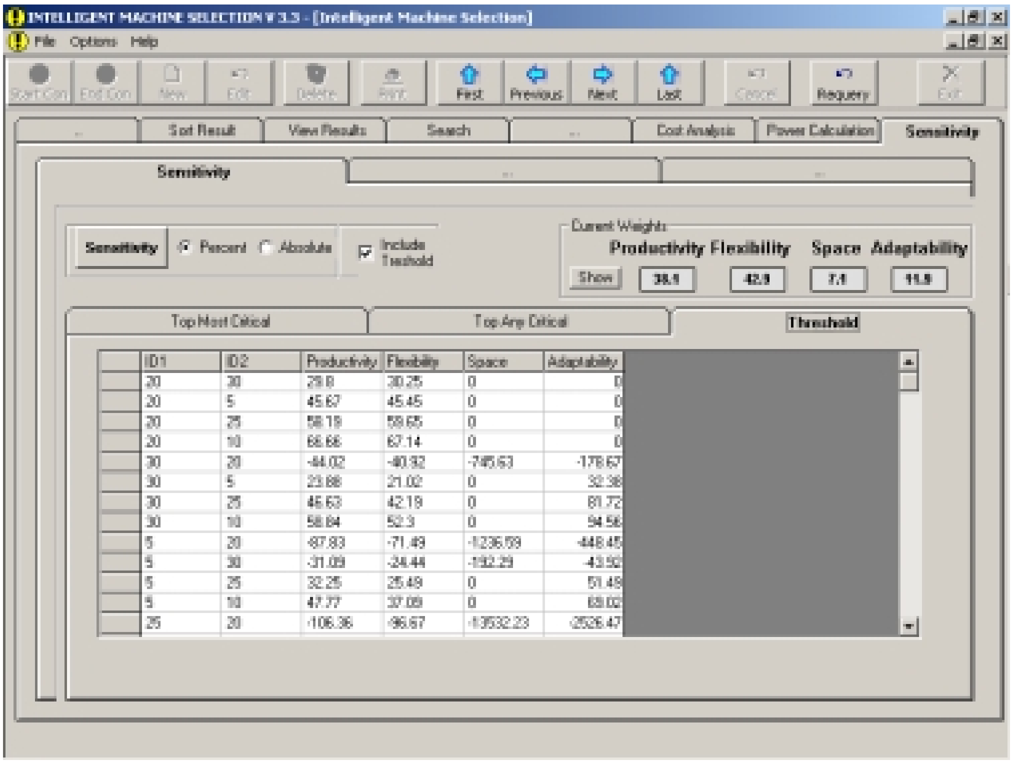


Figure 4.11 Sensitivity Analysis for the determination of the most critical measure of performance.

4.2. Application Example

The 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 modeling. In addition, spindle speeds resulting in much higher stability can also be approximated using the stability models. Furthermore, other machine specifications should be determined for a better adaptation of the machine to the current and future working conditions of the company.

Suppose that four companies will purchase machining centers for their production factories. Suppose also that they will do similar machining processes. However, their budgets and preferences differ. The weights of criteria will be determined considering these preferences. However, they cannot be exactly determined. Sensitivity analysis will be used to justify these weights. If sensitivity analysis indicate that a small change in weights changes machine rankings, weights should be considered again.

Company X: Company X will open a new production line. Company is a mass producer. Company wants the productivity and quality to be very high. Machining Center should also be flexible. Cost of the machine tool is not as important as productivity. Criteria weights are determined based on these preferences. Figure 4.13 shows the weights for Company X. These weights will be justified in sensitivity analysis.

Company Y: Company Y will buy a new machining center to its existing production line. Company Y has high production rates. Company wants the adaptability to be very high, since their workers can best work on Fanuc CNC control. Productivity is also another very important selection criterion for the company. Cost is not the most important criterion. Figure 4.14 shows selected criteria weights for Company Y. These weights will be justified in sensitivity analysis.

Company Z: Type of manufacturing is job shop. Company wants a flexible and adaptable machining center since it produces variety of products. Cost is also an important selection criterion. Figure 4.15 shows selected criteria weights for Company Z. These weights will be justified in sensitivity analysis.

Company T: Company T is a job shop. Company has small space for machining center. Company needs a machining center satisfying minimum production requirements. Space and cost are the most important criteria. Figure 4.16 shows selected criteria weights for Company T. These weights will be justified in sensitivity analysis.

Step 1: Determination of minimum process requirements

First, if desired, spindle power and force requirements can be calculated. For simplification purposes, all of the companies are assumed to produce similar products. In this application cylindrical milling cutter with zero helix angle is used in full slotting operation. Work material is free machining steel with approximate tangential milling force coefficient of 2000 MPa. Desired feet rate is 3000 mm/minute (0.1mm/rev-tooth) and spindle speed is 10000 rpm. It is required to achieve a certain production rate. End mill with 3 teeth and 25mm diameter is used with axial depth of cut of 8mm. After the calculations (refer to [20] and [21] for formulations), the required power is calculated to be 14 HP. Chatter stability model can also be used to determine the required dynamic rigidity of the spindle. However, machine manufacturers do not provide information for the analysis of the dynamic rigidity of the spindle. Figure 4.12 shows an output of the process requirement calculation.

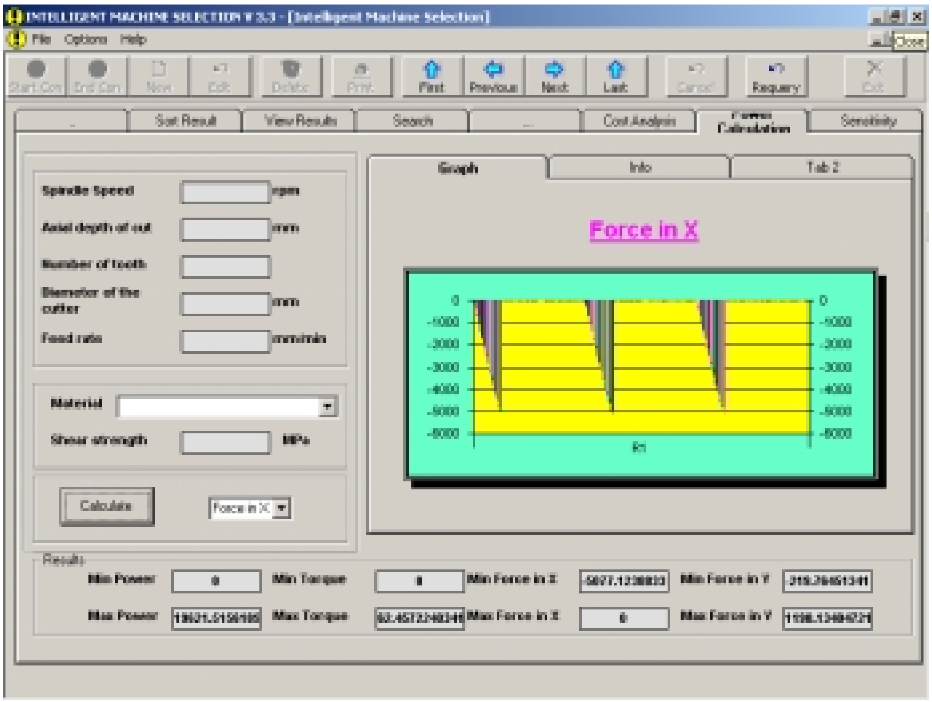


Figure 4.12 Process requirement calculations

Step 2: Determination of selection criteria weights

In order to apply multi-criteria weighted sum method the weights should be defined that are specific to the companies and production requirements. Figure 4.13, Figure 4.14, and Figure 4.16 illustrate the weights used in this example for the companies X, Y, Z, and T, respectively. For this example, four criteria are considered, since in this case the manufacturers do not provide data for other criteria.

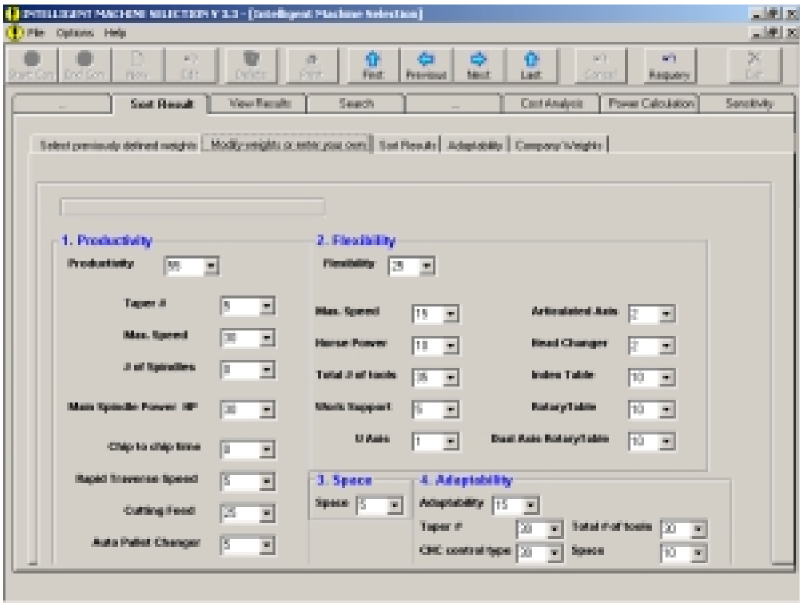


Figure 4.13 Weights for Company X

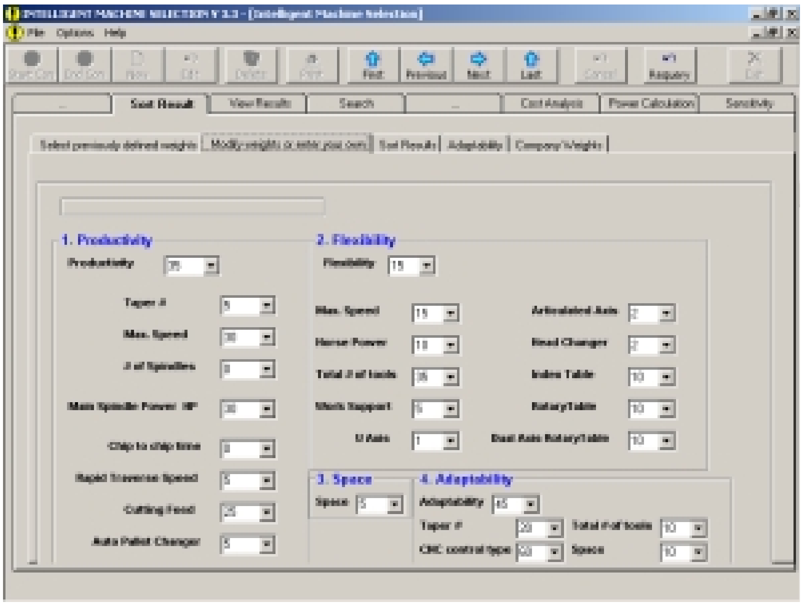


Figure 4.14 Weights for Company Y

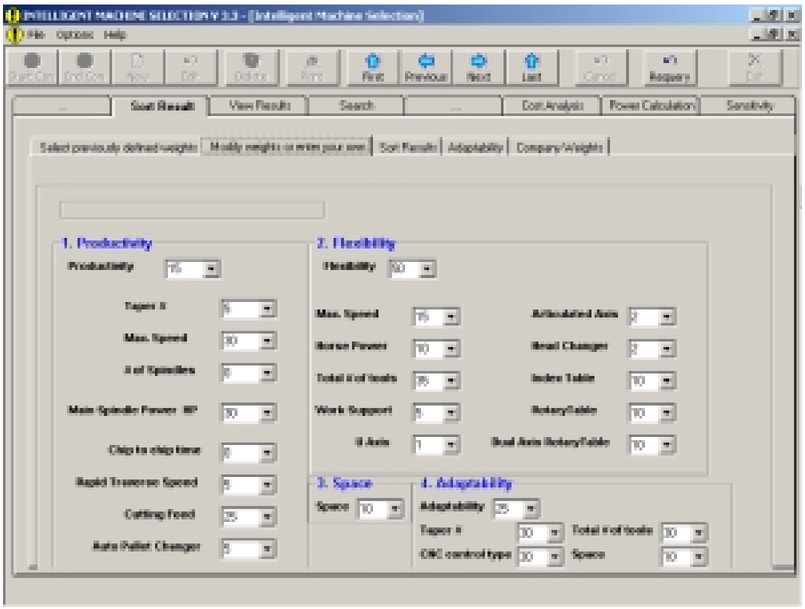


Figure 4.15 Weights for Company Z

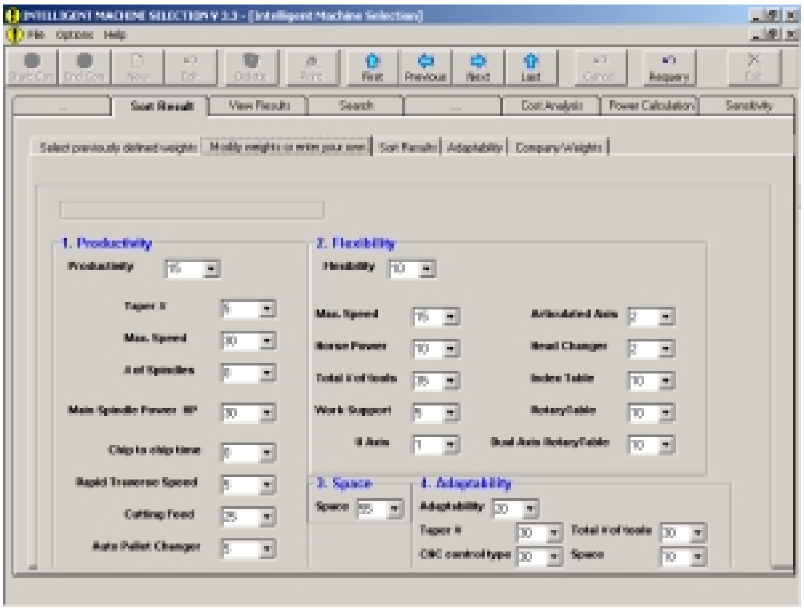


Figure 4.16 Weights for Company T

Step 3: Searching the database

Based on power calculations main spindle power should be larger than 14 HP. upper limit is taken as 30 to be on the safe side in design. Thus, main spindle power requirement is chosen 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.

The search results in seven machines from 82 available machines in database. The search is executed for minimum production requirements. Thus, the result is the same for all companies. Figure 4.17 shows the search results.

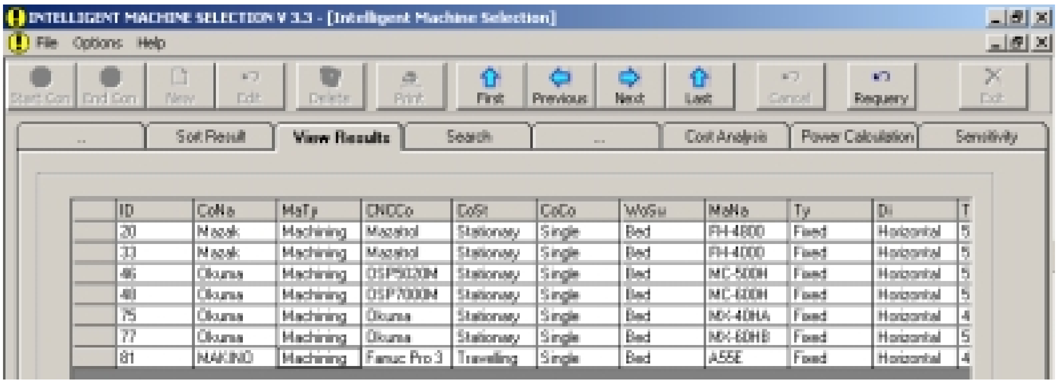


Figure 4.17 Search result

Step 4: Application of MCWA method (ranking of machines)

The remaining seven machines are ranked according to maximum productivity, maximum flexibility, minimum space, maximum adaptability, and weighted sum of those using MCWA method. Results are shown in Figure 4.18, Figure 4.19, Figure 4.20, and Figure 4.21. Weighted scores are calculated using criteria weights. For example, pure productivity score is the score without considering productivity weight.

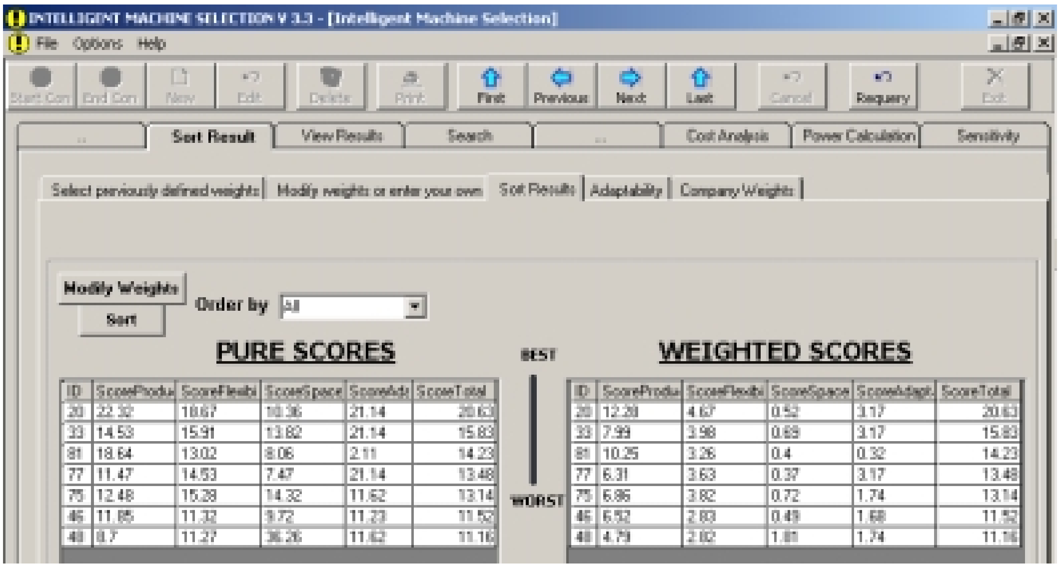


Figure 4.18 Ranking of machines for Company X

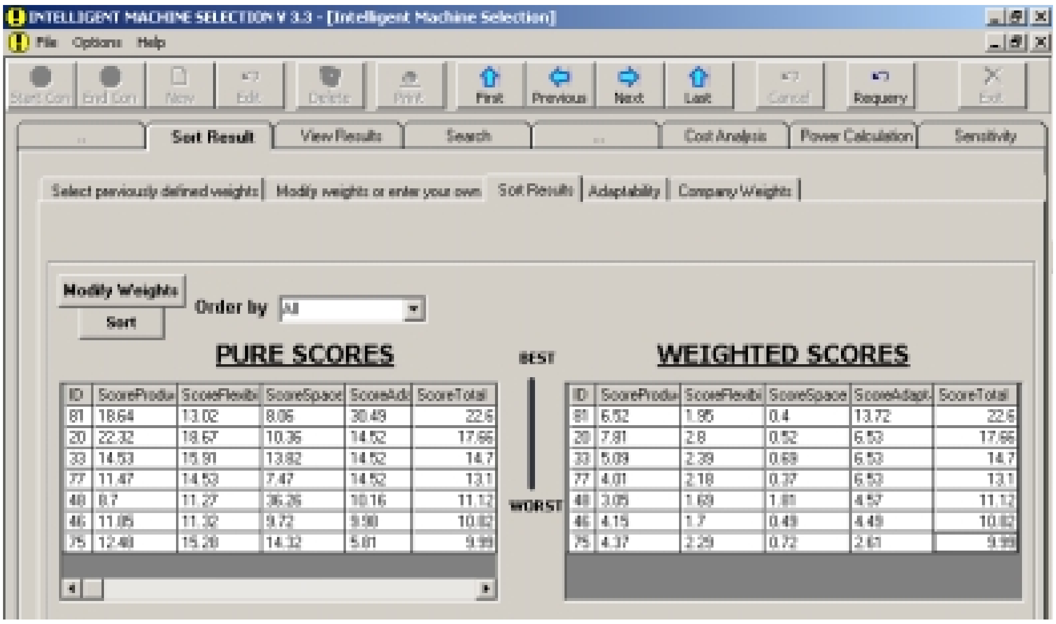


Figure 4.19 Ranking of machines for Company Y

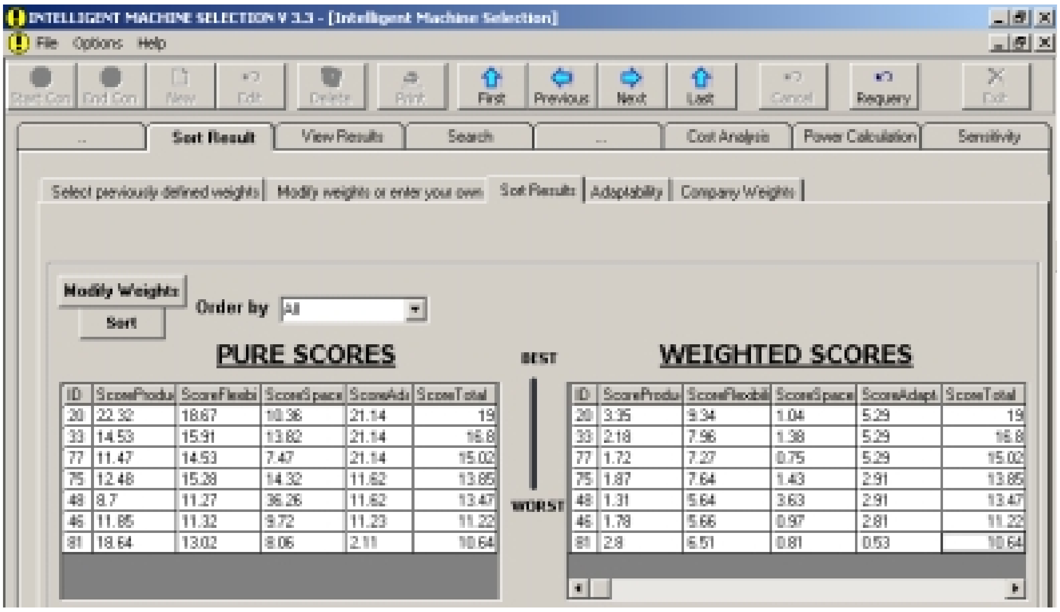


Figure 4.20 Ranking of machines for Company Z

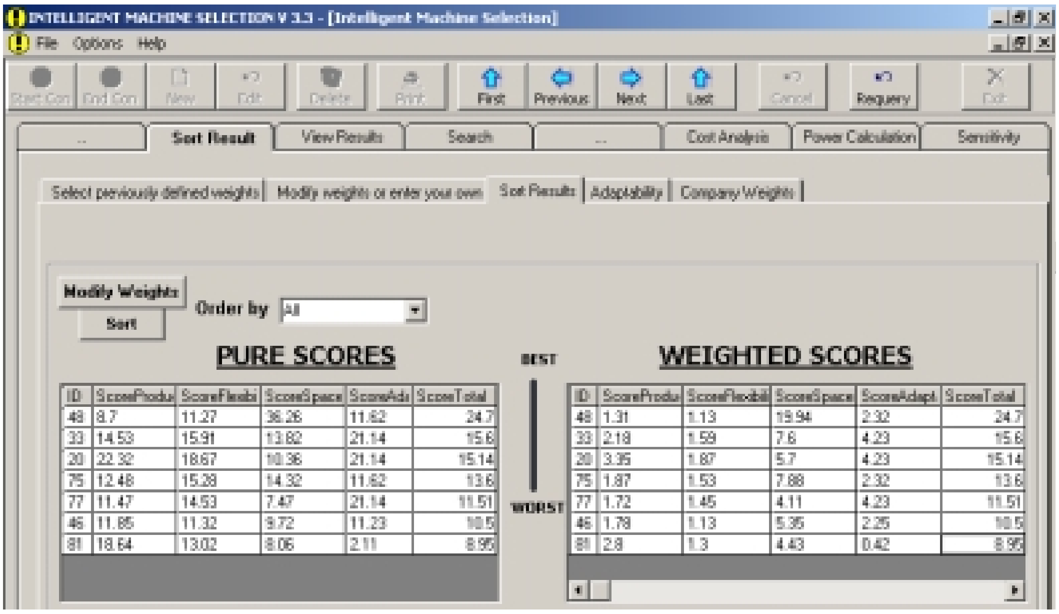


Figure 4.21 Ranking of machines for Company T

Step 5: Sensitivity analysis

Sensitivity analysis is an important part of the selection. With sensitivity analysis, we can be sure whether small changes in weights or performance values will change the rankings. This is very critical to justify the weights. Figure 4.22 shows the sensitivity analysis results for the percent top most critical machine, i.e., machine with ID 48 for Company T. First column shows the minimum changes in criteria weights that will cause machine ID1 and machine ID2 to reverse their rankings. In this example, space weight should be decreased by 73.76% in order for machine ID 48 to reverse its ranking with machine ID 33. In that case, the most preferred alternative would be machine with ID 33. The second column shows new weights after normalization. Sensitivity analysis for Company X, Y, and Z are given in Figure 4.23, Figure 4.24, and Figure 4.25, respectively.

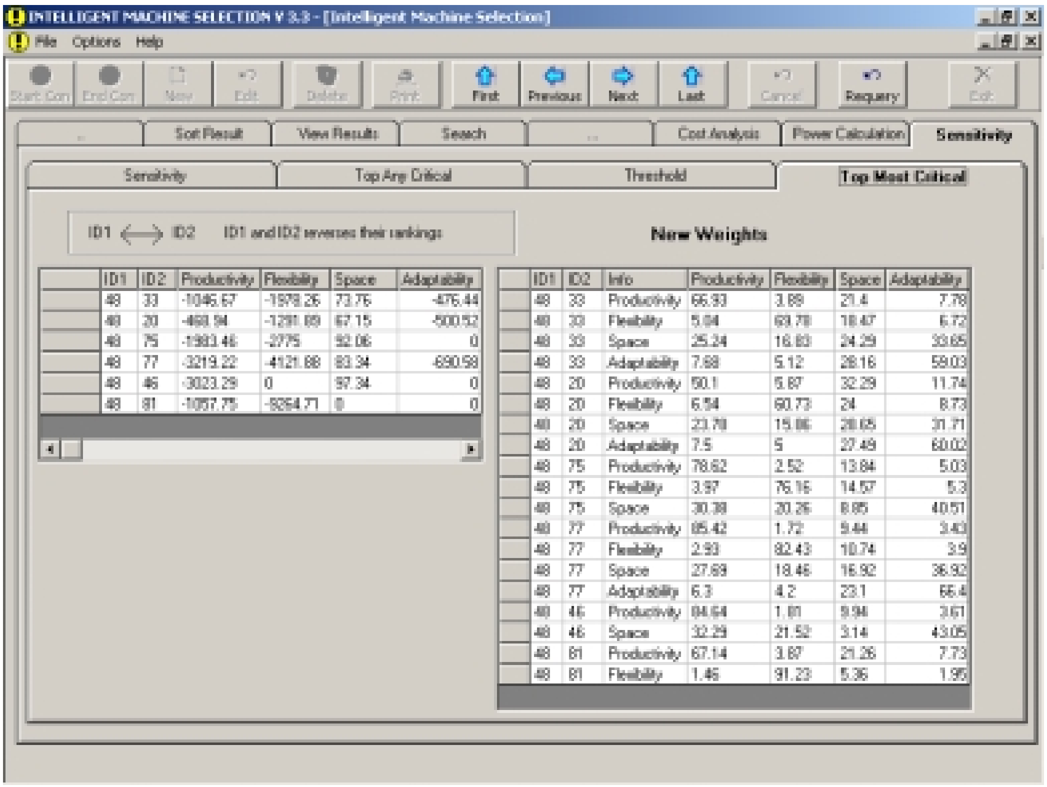


Figure 4.22 Percent top sensitivity analyses for Company T

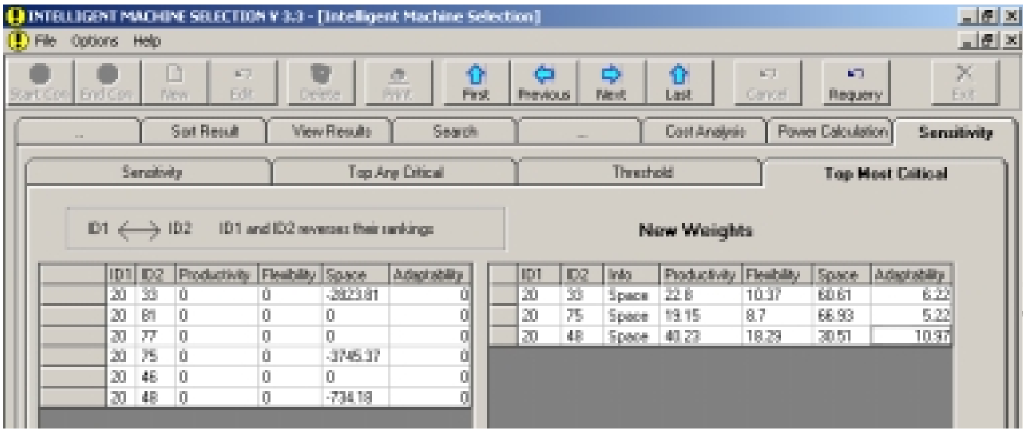


Figure 4.23 Percent top sensitivity analysis for Company X

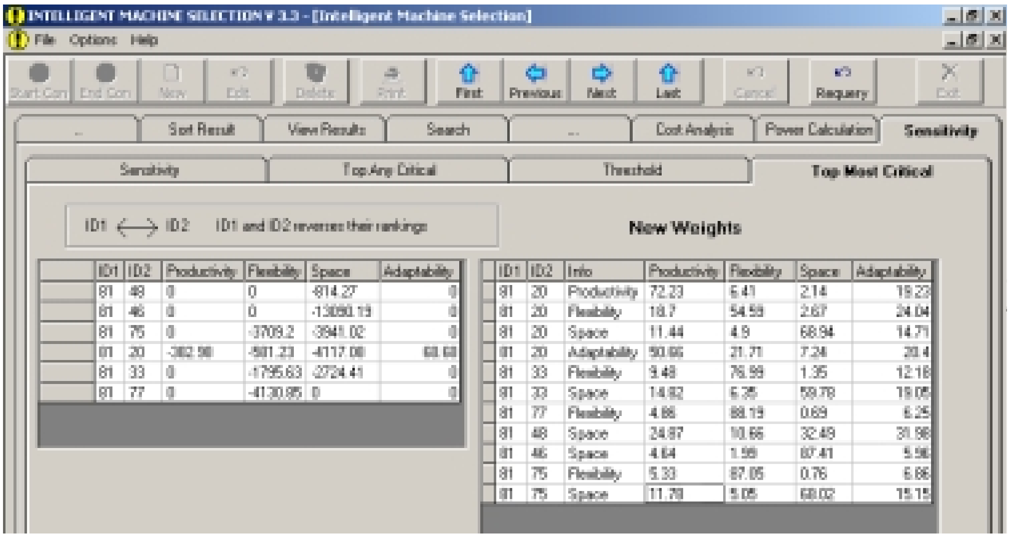


Figure 4.24 Percent top sensitivity analysis for Company Y

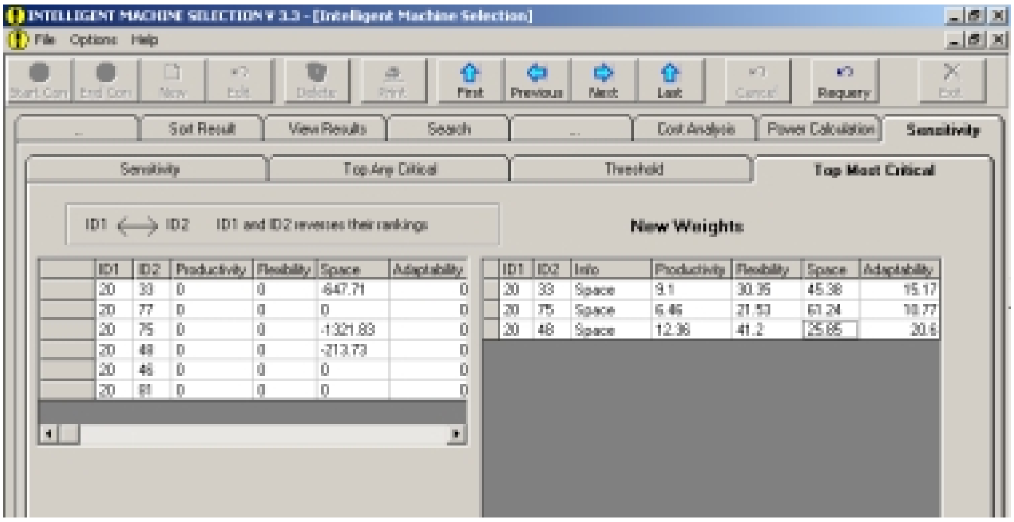


Figure 4.25 Percent top sensitivity analysis for Company Z

Step 6: Re-evaluation considering cost

Now, machines procurement costs for some of the selected machines will be obtained from the manufacturers and the final selection will be made based on machine rankings and procurement costs. The procurement costs of the selected machines are shown in Table 4.1. These values also include the additional option costs.

Table 4.1 Procurement Costs

Machines	Procurement Cost
ID 20	240000 $
ID 81	200000 $
ID 77	190000 $
ID 75	180000 $
ID 46	165000 $
ID 33	120000 $
ID 48	100000 $

Company X: If performance rankings of machines for Company X are investigated from Figure 4.18, machining center with ID 20 (MC 20) can be noticed to be the best machine. This is mainly because productivity is the most important criterion and MC 20 has highest scores in productivity. If cost is not considered, other machines are not good alternative solutions. This is because performance values of the other machines are much lower than MC 20. Sensitivity analysis also indicates this conclusion since performance ranking of the best machine does not change with the small changes in criteria weights. When cost is considered, it is also the most expensive machine. However, based on Company preferences machine performance is more important than the cost of the machine. Thus, MC 20 should be selected for Company X.

Company Y: If performance rankings of machines for Company Y are investigated from Figure 4.19, machining center with ID 81 (MC 81) is the best machine. This is mainly because adaptability is the most important criterion. Mostly CNC type determines the adaptability score.

If cost is not considered, other machines are not good alternative solutions since performance values of the other machines are much lower. Sensitivity analysis also indicates this conclusion since performance ranking of the best machine does not change with the small changes in criteria weights. When cost is considered, selected machine is also acceptable since cost is not the most important criterion. Thus, MC 81 is selected for Company Y.

Company Z: If performance rankings of machines for Company Z are investigated from Figure 4.20, machining center with ID 20 (MC 20) is the best machine. If cost is not considered, other machines are not good alternative solutions since performance values of the other machines are much lower. Sensitivity analysis also indicates this conclusion since performance ranking of the best machine does not change with the small changes in criteria weights. When cost is considered, MC 20 is not acceptable since cost is the most important criterion and this machine is the most expensive machine. Then, next machine with a good performance value is considered for selection by reinvestigating Figure 4.20. Machining center with ID 33 (MC 33) can be noticed with a good performance value. Moreover, it is among the cheapest machines. Other machines with good performance values are also considered, but they are much more expensive than this machine. Sensitivity analysis also indicates that the performance ranking of MC 33 does not change by small changes in criteria weights. Thus, MC 33 is selected for Company Z.

Company T: If performance rankings of machines for Company T are investigated from Figure 4.21, Machining Center with ID 48 (MC48) is the best machine. If cost is not considered, other machines are not good alternative solutions since performance values of the other machines are much lower. Sensitivity analysis also indicates this conclusion since performance ranking of the best machine does not change with the small changes in criteria weights. When cost is considered, selected machine is also acceptable since it is the cheapest machine and cost is one of the most important criteria for the Company T. Thus, MC 48 is selected for Company T.

Some of the machines satisfying the minimum requirements could be selected. If other machine properties data, i.e. precision, reliability, safety and environment, maintenance are available for these machines, selection procedure can be repeated from step 2 to consider the effect of other criteria.

Step 7: Option Analysis

Although the selected machine is capable of producing the desired production rate of the company, additional options can be considered if the company plans to increase productivity in the future. The decision whether or not to buy an option depends 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 higher spindle speed, different horsepower, additional axis, auto pallet changer, head changer, index table, etc. may be evaluated financially. Cost analysis for additional options will be investigated. First, the required production rate for the company to profit will be calculated. Then, the purchasing of machine options will be analyzed considering its cost and benefits.

For example, a simple cost calculation is applied for the selected machine MC 20 of the company X to find the annual production quantity. The calculations are based on break–even analysis, i.e. when annual revenue equals annual cost. Similar cost calculations can be applied to find desired unknowns, e.g. the payback period. Notation and data are given in Table 4.2.

Table 4.2 Notation and data for the analysis

Machine Procurement Cost	C_M	240 000	€
Overhead Cost	C_{OH}	45 000	€/year
Depreciation Cost	C_D	20 000	€/year
Salvage Value	S	40 000	€
Part Sale Price	P	15.5	€/part
Operating Cost	C_O	30	€/operating hr
Operating Time	T_O	9/60	hrs/part
Setup and Part Change Cost	C_S	27	€/operating hr
Setup Time	T_S	2/500	hrs/part
Part Change Time	T_{CH}	3/60	hr/part
Planning Horizon	T	10	years
MARR	i	15	%
Tax Rate	r	33	%
Annual Production	X	?	parts

Break-even production quantity for this example is computed as 10960 units/year.

Then, other machine options can be investigated considering their cost and their benefits. MC 20 has a rotary table option. The cost of rotary table is 12000 €. 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 2 minutes. A new break-even production quantity is obtained as 10340 units/year by adding the cost of rotary table. Thus, buying the rotary table for this company may be a logical option.

4.3. Summary

In this chapter, implementation of the methodology is demonstrated. First, the developed software and its capabilities are shown. Then, the developed methodology is explained with examples. Four different companies with different preferences are considered for the selection.

5. CONCLUSION

5.1. Conclusion

Selecting the most suitable machine from the increasing number of available machines is an important task. Productivity, precision, flexibility, and company's responsive manufacturing capabilities all depend on the machine properties.

In this thesis, the machine tool selection problem is addressed. Machine tool properties and decision criteria are listed and critical ones are investigated. Machining process models are reviewed in order to determine process requirements. A multi-criteria weighted average method considering different criteria is proposed. The developed methodology is demonstrated with a potential application example. Sensitivity analysis is also conducted in the determination of the most critical criterion and the most critical measure of performance. Cost/benefit analysis is also carried out to justify the purchase of the machine tool and its optional features. All of the methodology is demonstrated with the developed software. Application examples show that different machines are selected, though companies have similar production requirements. This shows that preferences of the companies and machine working conditions are also very critical factors in machine selection.

The developed methodology for machine tool selection can be applied for any type of selection, e.g. selection of the best automobile. The uniqueness of the thesis is that decision-making, process modelling, database mangement, expert and knowledge based systems, sensitivity analysis, and cost analysis concepts are combined in order to solve machine selection problem.

5.2. Limitations and Further Research

There are limitations in construction and application of a decision support system for machine tool selection. First limitation is the lack of a standard format in machine catalogues. This complicates the classification of machine types and their properties. As a result, it is difficult to design a unique database for all machine types and specifications. Second limitation is the possible changes in the developed database. It is certain that, because of advances in technology, new machine tools with new specifications will be available soon. Third limitation is the pre-defined weights. They do not include all of the production and company types. A survey is prepared to determine these weights. These limitations can be handled by a periodical update of the decision support system. Further development of the decision support system is still necessary. The development of industry standard for all existing machine tools will further increase the usefulness of proposed method.

Programming can be an enormously complex and difficult activity, or it can be quite straightforward. VBA is an interpreted language. In interpreted languages, each line of the program is interpreted (converted into machine language) and executed when the program is run. Other languages (such as C, Pascal, FORTRAN, etc.) are compiled, meaning that the original (source) program is translated and saved into a file of machine language commands. This executable file is run instead of the source code. Predictably, compiled languages run much faster then interpreted languages (e.g. compiled C++ is generally ten times faster than interpreted Java).

However, the aim is not to develop the fastest software. The aim in this thesis is to test whether a decision support system can be constructed for machine selection problem and to find out possible obstacles in doing so. Interpreted languages may be preferred since they are typically easier to learn and experiment with. Other programming languages may as well be implemented, if the execution time becomes a problem.

REFERENCE LIST

[1] Gerrard, W., "Selection Procedures Adopted by Industry for Introducing New Machine Tools," in: B. Worthington (ed.), *Advances in Manufacturing Technology III,* Proc. Fourth Natl. Conf. on Production Research, Kogan Page, London, pages 525-536, 1988.

[2] Power, D. J., *Decision Support Systems Glossary,* DSS Resources, World Wide Web, http://DSSResources.COM/glossary/, 1999.

[3] Subramaniam, V., Lee, G. K., Ramesh, T., Hong, G. S. and Wong, Y. S., "Machine Selection Rules in a Dynamic Job Shop," *International Journal of Advanced Manufacturing Technology*, Vol. 16, pages 902-908, 2000.

[4] Tabucanon, M. T., Batanov, D. N. and Verma, D. K., "Intelligent Decision Support System (DSS) for the selection process of alternative machines for Flexible Manufacturing Systems (FMS)," *Computers in Industry,* Vol 25, pages 131-143, 1994.

[5] Wang, T.-Y., Shaw, C.-F. and Chen Y.-L., "Machine Selection in flexible manufacturing cell: a fuzzy multiple attribute decision making approach," *International Journal of Production Research,* Volume 38, No.9, pages 2079-2097, 2000.

[6] Atmani, A. and Lashkari, R.S., "A model of machine-tool selection and operation allocation in Flexible Manufacturing System," *International Journal of Production Research,* Volume 36, No.5, pages 1339-1349, 1998.

[7] Lin, Z.-C. and Yang, C.-B., "Evaluation of machine selection by the AHP method," *Journal of Materials Processing Technology,* Volume 57, pages 253-258, 1994.

[8] Goh, C.-H., Tung, Y.-C. A and Cheng, C.-H. "A revised weighted sum decision model for robot selection," *Computers and Industrial Engineering,* Volume 30, No.2, pages 193-199, 1995.

[9] Gerrard, W. "A Strategy for Selecting and Introducing New Technology/Machine Tools," in: B. Worthington (ed.), *Advances in Manufacturing Technology III,* Proc. Fourth Natl. Conf. on Production Research, Kogan Page, Londan, pages 532-536, 1988.

[10] Haddock, J. and Hartshorn, T. A., "A Decision Support System for Specific Machine Selection," *Computers and Industrial Engineering*, Vol. 16, No. 2, pages 277-286, 1989.

[11] Triantaphyllou, E., *Multi-Criteria Decision Making Methods: A Comparative Study,* Kluwer Academic Publishers, 2000.

[12] Zimmermann, H.-J., *Fuzzy Set Theory and Its Applications,* Kluwer Academic Publishers, Third Revised Edition, Boston, MA, USA, 1996.

[13] Yen, J. and Langari R., *Fuzzy Logic, Intelligence, Control and Information,* Prentice Hall, 1999.

[14] Saaty, T.L., *The Analytic Hierarchy Process,* McGraw-Hill, New York, 1980.

[15] Saaty, T. L. and Vargas, L.G. "*Models, Methods, Concepts & Applications of the Analytical Hierarchical Process,*" Kluwer Academic Publishers, University of Pittsburgh, Operation Research Management Science.

[16] Belton, V., and Gear, T., "On a Short-Coming of Saaty's Method of Analytic Hierarchies," *Omega*, pages 228-230, 1983.

[17] Tlusty, G., *Manufacuring Processes and Equipment*, Prentice Hall, 1999.

[18] Altintas, Y. and Lee, P., "Mechanics and Dynamics of Ball End Milling," *Trans. ASME Journal of Manufacturing Science and Engineering*, Volume 120, pages 684-692, 1998.

[19] Yang, M. and Park, H., "The Prediction of Cutting Force in Ball End Milling," *International Journal of Machine Tools and Manufact*uring, Volume 31, No.1, pages 45-54, 1991.

[20] Budak, E., Altintas, Y. and Armarego, E.J.A., “Prediction of Milling Force Coefficients from Orthogonal Cutting Data,” *Trans. ASME Journal of Manufacturing Science and Engineering*, Vol. 118, pages 216-224, 1996.

[21] Altintas, Y., *Manufacturing Automation,* Cambridge University Press, 2000.

[22] Budak, E. and Altintas, Y., "Analytical Prediction of Chatter Stability in Milling-Part I: General Formulation; Part II: Application to Common Milling Systems," *Trans. ASME, Journal of Dynamic Systems, Measurement, and Control*, Vol. 120, pages 22-36, 1998.

[23] Edmonds, Cindy D., “Analyzing Machine Efficiency,” *The National Public Accountant*, Washington, Vol. 39, Iss. 12, pages.28-34, Dec 1994.

APPENDIX

Sabancı Üniversitesi

FACULTY OF ENGINNERING AND NATURAL SCIENCE

"Criteria Affecting CNC (Machining Center) Purchasing"
Survey

Dear Sir/Madam,
The e-mail you just received contains a survey in Word format. The results of this survey will be used in a master thesis at Sabancı University. Your contribution is important for us. You could complete this survey in a short time interval. The responses will be evaluated in professional standards and will be used for academic purposes. You could forward this e-mail to any person in your company or in other companies who has knowledge on machining centers or CNC machines. The results of this survey will be mailed to the participants.
Thanks for your interest and time you have spend

Asst. Professor Erhan Budak
Asst. Professor Bülent Çatay
M. Çağdaş Arslan

How to complete the survey?
This survey consists of 3 parts.
Please answer the questions by selecting the most appropriate option from the list. You could also write your answers without selecting from the list.

Important Note: If you want you could stop at any part of the survey and continue from where you left afterwards by saving the document.

P.S.:
* Please save the attached word file after completing the survey and e-mail us at. cagdasarslan@su.sabanciuniv.edu
* You could go to the next question by pressing Tab button.
* You could select your answer by left clicking the mouse to the list
* You could also write your choice by entering it to the empty boxes.

PLEASE AFTER YOU GET THE FORM RETURN THE WORD FILE AS SOON AS POSSIBLE (PREFERABLY NOT LATER THAN 10 DAYS) TO THE FOLLOWING E-MAIL ADDRESS: cagdasarslan@su.sabanciuniv.edu

Address:
M.Çağdaş Arslan
Sabancı Üniversitesi Mühendislik ve Doğa Bilimleri Fakültesi Orhanlı, Tuzla 81474, İstanbul
Tel: 0216-483-9558 Fax: 0216-4839550
cagdasarslan@su.sabanciuniv.edu

SECTION 1: PLEASE ANSWER THE FOLLOWING QUESTIONS BY GIVING INFORMATION ABOUT YOURSELF AND YOUR COMPANY

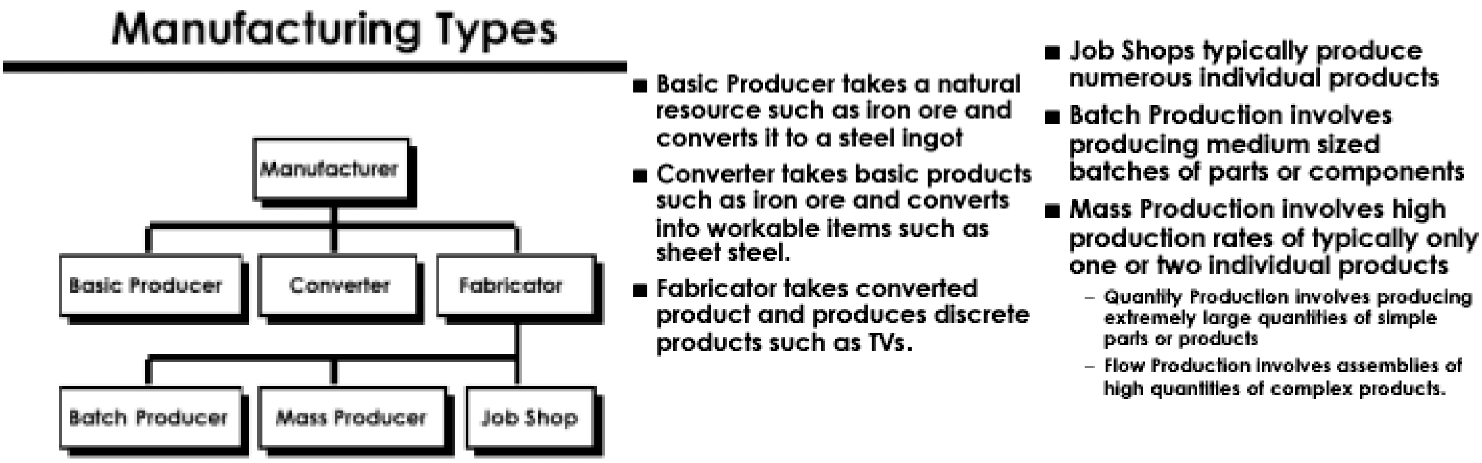
1. Name of the Company: 2. Total number of employees:

3. Your name and Surname :

4. Please specify your position in the company?
   Technician Please specify if different :

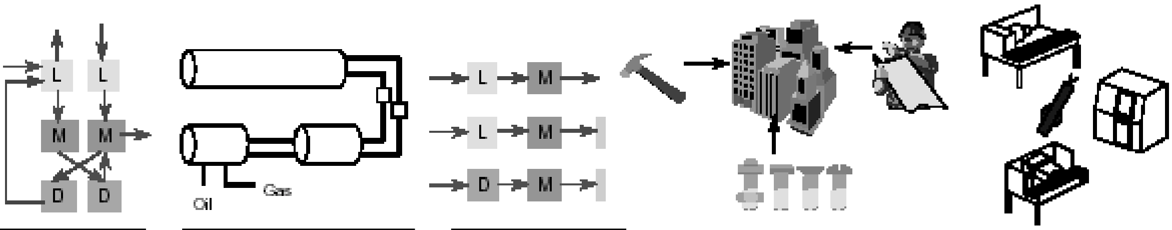
5. Which of the following defines your company's working area?
   Automotive Please specify if different:

6. Which of the following best defines the type of manufacturing in your company?



Please select one .... Please specify if different :

7. Please specify the place where CNC will be used.



Job	Continuous	Flow	Project Shop	Cellular

1st Choice .... 2nd Choice ....
Please specify if different: 1st Choice 2nd Choice
If you specify 2nd Choice for place you should give associated weights in Section 2 and Section 3

8. Telephone :

9. Address :

SECTION 2: PLEASE SPECIFY THE WEIGHTS IN MACHINE PURCHASING ACCORDING TO YOUR EXPERIENCES.

Considering Section 1 of Question 7
If you have selected 2 choice then complete the 2 column

MACHINING CENTER CRITERIA FOR SELECTION	**Weight 1st Choice**	**Weight 2nd Choice**
1. Productivity	%0	%0
2. Flexibility	%0	%0
3. Space Requirement of the machine	%0	%0
4. Adaptability	%0	%0
5. Precision	%0	%0
6. Cost	%0	%0
7. Reliability	%0	%0
8. Safety and Environment	%0	%0
9. Maintenance and Service	%0	%0
10.	%0	%0
Total weight should give %100	**%100**	**%100**

SECTION 3: SUB CRITERIA

1. Productivity	Weight 1st Choice	Weight 2nd Choice
1. Max. Speed	%0	%0
2. Main Spindle Power	%0	%0
3. Tool to tool time	%0	%0
4. # of Spindles	%0	%0
5. Rapid Traverse Speed	%0	%0
6. Cutting Feed	%0	%0
7. Auto Pallet Changer	%0	%0
8. Taper #	%0	%0
9.	%0	%0
10.	%0	%0
11.	%0	%0
12.	%0	%0
Total weight should give %100	**%100**	**%100**

2. Flexibility	Weight 1st Choice	Weight 2nd Choice
1. U Axis	%0	%0
2. Articulated Axis	%0	%0
3. No of Pallets	%0	%0
4. Rotary Table	%0	%0
5. Total # of tools	%0	%0
6. Head Changer	%0	%0
7. Main Spindle Power	%0	%0
8. Index Table	%0	%0
9. Dual Axis Rotary Table	%0	%0
10. Max. Speed	%0	%0
11. CNC or not?	%0	%0
12. CNC Control Type	%0	%0
13.	%0	%0
14.	%0	%0
Total weight should give %100	**%100**	**%100**

4. Adaptability	Weight 1st Choice	Weight 2nd Choice
1. Taper #	%0	%0
2. Space Requirement of the machine	%0	%0
3. CNC Control Type	%0	%0
4. Coolant Type	%0	%0
5. # of tools	%0	%0
6.	%0	%0
7.	%0	%0
8.	%0	%0
9.	%0	%0
10.	%0	%0
11.	%0	%0
Total weight should give %100	**%100**	**%100**

5. Precision	Weight 1st Choice	Weight 2nd Choice
1. Axis Precision	%0	%0
2. Repeatability	%0	%0
3. Thermal Stability	%0	%0
4. Static and Dynamic Rigidity	%0	%0
5.	%0	%0
6.	%0	%0
7.	%0	%0
Total weight should give %100	**%100**	**%100**

8. Safety and Environment	Weight 1st Choice	Weight 2nd Choice
1. Safety Door	%0	%0
2. Fire extinguisher	%0	%0
3. Mist Collector	%0	%0
4.	%0	%0
5.	%0	%0
Total weight should give %100	**%100**	**%100**

9. Maintenance and Service	Weight 1st Choice	Weight 2nd Choice
1. Repair Service	%0	%0
2. Training	%0	%0
3. Spare Parts	%0	%0
4 Regular Maintenance	%0	%0
5.	%0	%0
6	%0	%0
7	%0	%0
Total weight should give %100	**%100**	**%100**