A DECISION SUPPORT SYSTEM FOR MACHINE TOOL SELECTION

by M. ÇAĞDAŞ ARSLAN

Submitted to the Graduate School of Engineering and Natural Sciences in partial fulfillment of the requirements for the degree of Master of Science

> SABANCI UNIVERSITY Spring 2002

A DECISION SUPPORT SYSTEM FOR MACHINE TOOL SELECTION

APPROVED BY:

Assistant Prof. Dr. Erhan Budak (Dissertation Supervisor)	
Assistant Prof. Dr. Bülent Çatay (Dissertation Supervisor)	
Prof. Dr. Gündüz Ulusoy	
Assistant Prof. Dr. Gürdal Ertek	
Assistant Prof. Dr. Hüsnü Yenigün	

DATE OF APPROVAL:

ACKNOWLEDGMENTS

I would like to express my deepest appreciation to my advisors, Assistant Prof. Dr. Erhan Budak and Assistant Prof. Dr. Bülent Çatay, for the guidance, encouragement, and feedback they provided me during the thesis process.

I would especially like to thank Assistant Prof. Dr. Gürdal Ertek for his valuable encouragement and guidance.

I also would like to thank my parents and my brother for their never-ending support and encouragement. I also would like to thank my friends, Evren Burcu Kıvanç, Özkan Öztürk and Bülent Delibaş for their help and encouragement.

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.

TABLE OF CONTENTS

1.	INTF	RODUCTION	1
2.	BAC	KGROUND	4
2	2.1.	Machine Selection Literature	4
2	2.2.	Multi-Criteria Decision-Making	6
	2.2.1. 2.2. 2.2. 2.2.	Multi-Criteria Decision-Making Methods 1.1. The Weighted Sum Model Method 1.2. The Weighted Product Model Method 1.3. Analytic Hierarchy Process	8 9 9 10
2	2.2. 2.3.	1.4. Revised AHP Sensitivity Analysis	12 12
2	2.3.1. 2.3.2. 2.3.3. 2.4.	Definitions Most Critical Criterion Most Critical Measure of Performance Application Environment	13 14 21 27
2	2.4.1. 2.4.2. 2.4.3. 2.5.	Database Selection Database Construction Database Management Using Visual Basic Summary	27 28 29 30
3.	SELI	ECTION METHODOLOGY	31
3	.1.	Determination of Decision Criteria and Machine Specifications	31
	3.1.1.	Decision Criteria	31
3	3.1.2. 5.2.	Classification of Machines Process Models	33 37
3	3.2.1. 3.2.2. 3.2.3. 3.3.	Productivity Milling Forces, Torque and Power Stability Model Multi-Criteria Weighted Average Method for Machine Selection	38 38 41 42
3	3.3.1. 3.3.2. 5.4.	Approximation of Weights of Criteria and Sub-criteria Calculation of Scores Cost, Benefit, and Option Analysis	43 45 48
3	3.4.1. 5.5.	Detailed Cost and Option Analysis Step-by-Step Selection Methodology	48 49
3	6.6.	Summary	51

4. IMP	LEMENTATION	
4.1.	Software	
4.2.	Application Example	
4.3.	Summary	71
5. CON	ICLUSION	72
5.1.	Conclusion	72
5.2.	Limitations and Further Research	73
REFERI	ENCE LIST	74
APPENI	DIX	77

LIST OF TABLES

Table 2.1	Scale of Relative Importance	11
Table 2.2	Weights	
Table 2.3	Decision Matrix	19
Table 2.4	AHP Results	19
Table 2.5	Percent change in criteria weights	20
Table 2.6	Criticality degrees and sensitivity coefficients	21
Table 2.7	Threshold values in relative terms	
Table 2.8	Criticality degrees for each <i>a_{ij}</i> measure	
Table 2.9	Sensitivity coefficients for each a_{ij} measure	
Table 3.1	Simple Criteria	
Table 3.2	Detailed Criteria	
Table 3.3	Simple machining center specifications	
Table 3.4	Detailed Machining Center Specifications	
Table 3.5	Notation and Definitions	43
Table 3.6	Weights for the example	46
Table 3.7	Machine properties	46
Table 3.8	Normalization	46
Table 3.9	Scores	47
Table 3.10	Normalized Scores	47
Table 3.11	Total Scores	47
Table 3.12	Notation for the analysis	49
Table 3.13	Specifications of machine k	50
Table 4.1	Procurement Costs	68
Table 4.2	Notation and data for the analysis	71

LIST OF FIGURES

Figure 2.1	Simple AHP Structure	11
Figure 2.2	Hierarchy tree for sensitivity example	
Figure 2.3	Database user interaction	
Figure 3.1	Machining Center	
Figure 3.2	Axes of a machining center	
Figure 3.3	Tool Changer	
Figure 3.4	Rotary Table	
Figure 3.5	Cross sectional view of an end mill	
Figure 3.6	Chatter Stability Diagram	42
Figure 3.7	Manufacturing Types	44
Figure 3.8	Types of production lines	44
Figure 3.9	Hierarchy tree	45
Figure 4.1	Connection to the database	
Figure 4.2	Machine Specifications in list form	53
Figure 4.3	Machine Specifications in box form	53
Figure 4.4	Database management tools	54
Figure 4.5	Force modeling	54
Figure 4.6	Searching the database	55
Figure 4.7	Pre-defined weights	56
Figure 4.8	Pre-defined weights can be modified	
Figure 4.9	Ranking the machines	57
Figure 4.10	Sensitivity analysis for top most critical machine	

Figure 4.11	Sensitivity Analysis for the determination of the most critical measure	e of
perform	ance	58
Figure 4.12	Process requirement calculations	60
Figure 4.13	Weights for Company X	61
Figure 4.14	Weights for Company Y	61
Figure 4.15	Weights for Company Z	62
Figure 4.16	Weights for Company T	62
Figure 4.17	Search result	63
Figure 4.18	Ranking of machines for Company X	64
Figure 4.19	Ranking of machines for Company Y	64
Figure 4.20	Ranking of machines for Company Z	65
Figure 4.21	Ranking of machines for Company T	65
Figure 4.22	Percent top sensitivity analyses for Company T	66
Figure 4.23	Percent top sensitivity analysis for Company X	67
Figure 4.24	Percent top sensitivity analysis for Company Y	67
Figure 4.25	Percent top sensitivity analysis for Company Z	68

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 multicriteria 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 multiobjective 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 tradeoff 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 , ..., A_m and a set of *n* decision criteria denoted as C_1 , C_2 , C_3 , ..., 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:

$$A_{WSM-score}^{*} = \max_{i} \sum_{j=1}^{n} a_{ij} w_{j} \quad for \ i = 1, \ 2, \ 3, \ ..., \ m$$
(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:

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

$$P(A_K) = \prod_{j=1}^{n} (a_{Kj})^{w_j}$$
(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 and of the highest possible orde		
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]:

$$A_{AHP-score}^{*} = \max_{i} \sum_{j=1}^{n} a_{ij} w_{j} \quad for \quad i = 1, 2, 3, ..., m.$$
(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:

$$S_1 \ge S_2 \ge S_3 \ge \dots \ge S_m$$

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 $1 \le i \le j \le m$ and $1 \le k \le n$. The new weight of criterion k is defined as [11]:

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

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

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

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

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

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

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.

$$w'_{h} = \frac{w_{h}}{w_{1} + \dots + w_{k-1} + w_{k}^{*} + w_{k+1} + \dots + w_{n}} = \frac{w_{h}}{w_{k}^{*} + \sum_{l=1}^{n} w_{l}}$$

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

$$w'_{k} = \frac{w_{k}^{*}}{w_{1} + \dots + w_{k-1} + w_{k}^{*} + w_{k+1} + \dots + w_{n}} = \frac{w_{k}^{*}}{w_{k}^{*} + \sum_{l=1 \atop l \neq k}^{n} w_{l}}$$

$$if \quad h = k$$

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;

$$S'_{i} = \sum_{\substack{m=1\\m\neq k}}^{n} \frac{w_{m}}{w_{k}^{*} + \sum_{\substack{l=1\\l\neq k}}^{n} w_{l}} \cdot a_{im} + \frac{w_{k}^{*}}{w_{k}^{*} + \sum_{\substack{l=1\\l\neq k}}^{n} w_{l}} \cdot a_{ik}$$
$$S'_{i} = \frac{1}{w_{k}^{*} + \sum_{\substack{l=1\\l\neq k}}^{n} w_{l}} \cdot (\sum_{\substack{m=1\\m\neq k}}^{n} w_{m} \cdot a_{im} + (w_{k} - w_{k} \times \frac{\delta'_{k,i,j}}{100}) \cdot a_{ik})$$

$$S'_{i} = \frac{1}{w_{k}^{*} + \sum_{l=1}^{n} w_{l}} \cdot (\sum_{m=1}^{n} w_{m} \cdot a_{im} - w_{k} \times \frac{\delta'_{k,i,j}}{100} \cdot a_{ik})$$

$$S'_{i} = \frac{1}{w_{k}^{*} + \sum_{l=1}^{n} w_{l}} \cdot (S_{i} - w_{k} \times \frac{\delta'_{k,i,j}}{100} \cdot a_{ik})$$

 S'_{j} can be found similarly:

$$S'_{j} = \frac{1}{w_{k}^{*} + \sum_{l=1}^{n} w_{l}} \cdot (S_{j} - w_{k} \times \frac{\delta'_{k,i,j}}{100} \cdot a_{jk})$$

Using $S_i' < S_j'$:

$$\frac{1}{w_{k}^{*} + \sum_{l=1 \atop l \neq k}^{n} w_{l}} \cdot (S_{i} - w_{k} \times \frac{\delta_{k,i,j}^{'}}{100} \cdot a_{ik}) < \frac{1}{w_{k}^{*} + \sum_{l=1 \atop l \neq k}^{n} w_{l}} \cdot (S_{j} - w_{k} \times \frac{\delta_{k,i,j}^{'}}{100} \cdot a_{jk})$$

$$(S_{i} - w_{k} \times \frac{\delta_{k,i,j}^{'}}{100} \cdot a_{ik}) < (S_{j} - w_{k} \times \frac{\delta_{k,i,j}^{'}}{100} \cdot a_{jk})$$
$$(S_{i} - S_{j}) < w_{k} \times \frac{\delta_{k,i,j}^{'}}{100} \cdot (a_{ik} - a_{jk})$$

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

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

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

$$D_{k}^{'} = \min_{1 \le i < j \le m} \left\{ \left| \delta_{k,i,j}^{'} \right| \right\}$$
(2.10)

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

$$sens(C_k) = \frac{1}{D'_k}, \text{ for any } n \ge k \ge 1$$
 (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

Scores	Criteria			
Alternatives	Criterion 1	Criterion 2	Criterion 3	Criterion 4
A_{I}	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 2.3Decision Matrix

Table 2.4 shows the results obtained by using AHP.

Table 2.4 AHP Results

Alternatives	Final scores	Ranking	Ranking
A_{I}	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:

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

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

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

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

Thus, the new weight can be calculated as follows;

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

 $w_1^* = 0.131$

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:

$\delta_{k,i,j}^{'}$	Criteria				
Pair of Alternatives	Criterion 1 Criterion 2 Criterion 3 Criterion				
$A_1 - A_2$	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	

Table 2.5 Percent change in criteria weights

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 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:

	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

Table 2.6 Criticality degrees and sensitivity coefficients

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:

$$a_{ij}^* = a_{ij} - a_{ij} \times \frac{\tau_{i,j,k}^{'}}{100}$$
(2.12)

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

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

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

$$\tau_{i,j,k} \le 100 \tag{2.14}$$

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 $l \leq j \leq n$) 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:

$$a_{14}^{*} = a_{14} - a_{14} \times \frac{\tau_{1,4,2}}{100}$$
(2.15)

New performance measure values after normalization can be written as:

$$a'_{1,4} = \frac{a'_{1,4}}{a'_{1,4} + a_{2,4} + \dots + a_{m,4}}$$

$$a'_{2,4} = \frac{a_{2,4}}{a'_{1,4} + a_{2,4} + \dots + a_{m,4}}$$

$$\dots$$

$$a'_{m,4} = \frac{a_{m,4}}{a''_{1,4} + a_{2,4} + \dots + a_{m,4}}$$
(2.16)

2.16 can be reformulated using 2.15 as follows:

$$a_{1,4}^{'} = \frac{a_{1,4}^{*}}{-a_{1,4} \times \frac{\tau_{1,4,2}^{'}}{100} + a_{1,4} + a_{2,4} + \dots + a_{m,4}} = \frac{a_{1,4}^{*}}{1 - a_{1,4} \times \frac{\tau_{1,4,2}^{'}}{100}} = \frac{a_{14} - a_{14} \times \frac{\tau_{1,4,2}^{'}}{100}}{1 - a_{1,4} \times \frac{\tau_{1,4,2}^{'}}{100}}$$

$$a_{2,4}^{'} = \frac{a_{2,4}}{-a_{1,4} \times \frac{\tau_{1,4,2}^{'}}{100} + a_{1,4} + a_{2,4} + \dots + a_{m,4}} = \frac{a_{2,4}}{1 - a_{2,4} \times \frac{\tau_{2,4,2}^{'}}{100}}$$

$$\dots$$

$$a_{m,4}^{'} = \frac{a_{m,4}}{-a_{1,4} \times \frac{\tau_{1,4,2}^{'}}{100} + a_{1,4} + a_{2,4} + \dots + a_{m,4}}} = \frac{a_{m,4}}{1 - a_{m,4} \times \frac{\tau_{m,4,2}^{'}}{100}}$$

$$(2.17)$$

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

$$a_{11} \cdot w_1 + a_{12} \cdot w_2 + a_{13} \cdot w_3 + a_{14} \cdot w_4 + \dots + a_{1n} \cdot w_n < a_{21} \cdot w_1 + a_{22} \cdot w_2 + a_{23} \cdot w_3 + a_{24} \cdot w_4 + \dots + a_{2n} \cdot w_n \implies$$

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.

$$a_{11} \cdot w_1 + a_{12} \cdot w_2 + a_{13} \cdot w_3 + a_{14} \cdot w_4 + (a_{14} - a_{14}) \cdot w_4 + \dots + a_{1n} \cdot w_n < a_{21} \cdot w_1 + a_{22} \cdot w_2 + a_{23} \cdot w_3 + a_{24} \cdot w_4 + (a_{24} - a_{24}) \cdot w_4 + \dots + a_{2n} \cdot w_n \implies$$

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

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

After simplification:

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

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

$$\tau'_{i,j,k} \le 100$$
 (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.

$$\Delta'_{i,j} = \min_{k \neq i} \left\{ \left| \tau'_{i,j,k} \right| \right\},$$
for all $m \ge i \ge 1$, and $n \ge j \ge 1$

$$(2.20)$$

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

$$\Delta'_{L,j} = \min_{m \ge i \ge 1} \left\{ \min_{k \ne i} \left\{ \left| \tau'_{i,j,k} \right| \right\} \right\},$$
for some $n \ge k \ge 1$

$$(2.21)$$

"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:

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

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

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

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

Table 2.7 Threshold values in relative terms

NF: Not-feasible

We should also check the feasibility of threshold value.

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

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 d	legrees for	each a_{ii}	measure

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

$\Delta'_{i,j}$	Criteria			
Alternatives	Criterion 1	Criterion 3	Criterion 4	
A_{I}	0.029 (A ₂)	$0.029 \ (A_2)$	0	0
A_2	0.020	0.024	0.001	0.015
	(A ₃)	(A ₃)	(A ₁)	(A ₃)
A ₃	0.066	13.1	0.012	0.003
	(A ₄)	(A ₄)	(<i>A</i> ₄)	(A ₂)
A4	0.054	0.076	0.012	0.007
	(A ₃)	(A ₃)	(A ₃)	(A ₃)

Table 2.9 Sensitivity coefficients for each a_{ij} measure

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 realworld 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 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

speed, power, cutting feed, etc.		
# of tools, rotary table, etc.		
machine dimensions		
CNC type, taper #, etc.		
repeatability, thermal deformation, etc.		
bearing failure rate, reliability of drive system,		
etc.		
mist collector sofety door fire extinguisher etc.		
inist confector, safety door, file extinguisher, etc.		
training ranginganing regular maintananag ata		
training, repair service, regular maintenance, etc.		

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	
	F7. Main Spindle	
P7. Auto Pallet Changer	Power	
P8. Taper #	F8. Index Table	
	F9. Dual Axis Rotary	
	Table	
	F10. Max. Speed	
	F11. CNC or not?	
	F12. CNC Control Type	

Table 3.2 Detailed Criteria

4. Adaptability	5. Precision	6. Reliability	
A1. Taper #	PN1. Axis Precision	R1. Bearing failure rate	
A2. Space requirement of	PN2. Repeatability	R2. Reliability of drive	
the machine		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.

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

 Table 3.3
 Simple machining center specifications

Table 3.4	Detailed Machining Center Specifications
14010 2.1	Betailed Maching Center Speemeanons

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	A3. Y1	P3. Machine Dim. H	
Weight			
W4. Auto Pallet	A4. Z1	P4. Machine Weight	
Changer			
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	A7. C1 (Degrees)	P7. Spindle Center to	
degrees		Column	
W8. Rotary Table	A8. X1 Cutting Feed	P8. Spindle to Table	
		Center	
W9. Dual Axis Rotary	A9. Y1 Cutting Feed		
Table		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 multiaxis 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]):

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

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

$$F_{Z_j}(\phi) = -\frac{K_t K_a f_t R}{\tan \beta} \left[\cos \phi_j(z) \right]_{Z_{il}(\phi)}^{Z_{ju}(\phi)}$$
(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):

$$F_{x}(\phi) = \sum_{j=1}^{N} F_{x_{j}}(\phi); \ F_{y}(\phi) = \sum_{j=1}^{N} F_{y_{j}}(\phi); \ F_{z}(\phi) = \sum_{j=1}^{N} F_{z_{j}}(\phi)$$
(3.4)

Tangential force can be calculated similarly:

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

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

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

Constants K_{τ} , K_{s} , 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:

$$h_a = f_t \frac{\cos\phi_{st} - \cos\phi_{ex}}{\phi_{ex} - \phi_{st}}$$
(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)

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

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

$$a_{0} = G_{xx}(i\omega_{c}) \cdot G_{yy}(i\omega_{c}) \cdot \left(\alpha_{xx}\alpha_{yy} - \alpha_{xy}\alpha_{yx}\right)$$

$$a_{1} = \alpha_{xx} \cdot G_{xx}(i\omega_{c}) + \alpha_{yy} \cdot G_{yy}(i\omega_{c})$$

(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.



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 subcriteria (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.

$$S_{im} = \sum_{j=1}^{J_i} S_{ijm} \ge W_{ij} \quad , m = 1, ..., M, \ i = 1, ..., I$$
(3.14)

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

i	Criterion index	i=1I	Ι	Total # of criteria
j	Sub-criterion index	$j = 1J_i$	J_i	Total # of sub-criteria
т	Machine index	m=1M	М	Total # of machines
S_{ijm}	Score of machine <i>m</i> of sub-criteria <i>j</i> under criteria <i>i</i>			
S_{im}	Score of machine <i>m</i> under criteria <i>i</i>			
S_m	Score of machine <i>m</i> considering all criteria			
W_{ij}	Weight of sub-criteria j under criteria i			
W_i	Weight of criteria <i>i</i>			

 Table 3.5
 Notation and Definitions

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.

Manufacturing Types



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.

Criteria	Sub-Criteria	Weight	Notation
Productivity		0.60	W_1
Productivity	Speed	0.70	<i>W</i> ₁₁
Productivity	APC	0.30	<i>W</i> ₁₂
Flexibility		0.40	W_2
Flexibility	# of tools	0.65	W ₂₁
Flexibility	Rotary Table	0.35	W ₂₂

Table 3.6Weights for the example

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.

Alternatives		Criteria						
i	Productivity (0.6)					Flexi	bility (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	<i>S</i> ₁₁₃	1.000	<i>S</i> 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

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

Alternatives	Criteria					
i	Produ	ctivity	Fle	exibility		
		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	\overline{S}_{13}	0.4875	S ₂₃		

Table 3.9 Scores

Then these scores are normalized as shown in Table 3.10.

Table 3.10 Normalized Scores

Alternatives	Criteria						
i	Produc	ctivity	Fle	xibility			
		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_{I3}	0.2468	S_{23}			

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

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

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:

$$TI = P \times X + S \times (A/F, i, T) - COH - CD$$

-Co×To×X - Cs×(Ts + TCH)×X (3.16)

$$NPAT = -CM \times (A/P, i, T) + P \times X + S \times (A/F, i, T)$$

-COH - CO \times TO \times X - CS \times (TSE + TCH) \times X - rxTI (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.

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 and Part Change Cost Setup Time	C_S T_S	€/operating hr hrs/part
Setup and Part Change Cost Setup Time Part Change Time	$\begin{array}{c} C_S \\ T_S \\ T_{CH} \end{array}$	€/operating hr hrs/part hr/part
Setup and Part Change Cost Setup Time Part Change Time Planning Horizon	$\begin{array}{c} C_S \\ T_S \\ T_{CH} \\ T \end{array}$	€/operating hr hrs/part hr/part Years
Setup and Part Change Cost Setup Time Part Change Time Planning Horizon MARR	$\begin{array}{c} C_S \\ T_S \\ T_{CH} \\ T \\ i \end{array}$	€/operating hr hrs/part hr/part Years %
Setup and Part Change Cost Setup Time Part Change Time Planning Horizon MARR Tax Rate	$\begin{array}{c} C_S \\ T_S \\ T_{CH} \\ T \\ i \\ r \end{array}$	€/operating hr hrs/part hr/part Years %

Table 3.12 Notation for the analysis

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.	Max. Max. Speed		Total # of tools	
	Speed	Option	of tools	Option	
Machine <i>k</i>	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 subcriteria. 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, multicriteria 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.

🕂 INT	ELLIGENT I	MACHINE S	ELECTION	7 3.3 - [Intell	igent Macl	ine Sele	ction]					_8×
🕕 nie	Options	Help										_ 8 ×
tart C	on End Co	n Di New	ic) Edit	Delete	- @ Print:	1 Dist	Previous.	Next.	Cont	Search.	× DR	
	stablish Cor	mection to D	atabase	View Result	6 1	Search	Ť.	-	Cost Anal	psis Power C	alculation	Senskivity

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.

End C) Can I	Werver Edd	t Delete	Print	1 Prot	Previoue 1	Went	Leet Sec	anch .	× Ext	
-	T	Sort Result	Mew Res	utta 📄	Search		1	Cost Analysis	Power(Calculation	Ser
	ID	CoNe	NaTz	CNCCo	Cast	CaCo	WaSu	MaNa	Ťv	Di	-
	1	Mazak.	Machining	Mazahol	Traveling	Single	Bed	HV-800	Field	Combination	
	2	Mazak.	Machining	Mazahol	Traveling	Single	Bed	ULTRA 650	Field	Hotzontal	_
	3	Mazak.	Machining	Mazahol	Traveling	Bridge/multi	Bed	V-100	Ran	Conbinatio	
	4	Macak.	Machining	Macahol	Traveling	Bridge/multi	Bed	V-40	Ran	Conbination	
	5	Macok.	Machining	Macohol	Traveling	Single	Bed	V-515	Field	Vertical	
	6	Mazok.	Machining	Macehol	Traveling	Bridge/multi	Bed	V-60	Ren	Combination	
	7	Mazak.	Mechining	Manetrol	Traveling	Single	Bed	V-655	Field	Vertical	
	0	Mazak.	Machining	Fanue 15	Stationary	Single	Bed	VII15-D	Field	Vertical	
	9	Mazak.	Machining	Fanue 15i	Stationary	Single	Bed	V915-D	Field	Vertical	
	10	Mazak.	Machining	Mazahol	Travelling	Single	Bed	VTC-160A	Field	Vertical	
	11	Macak.	Machining	Macohol	Traveling	Single	Bed	VTC-1608	Field	Vartical	
	12	Macok.	Machining	Macohol	Traveling	Single	Bed	VTC-200/50	Fired	Vertical	
	13	Mazek.	Machining	Mapetrol	Traveling	Single	Bed	VTC-200C	Field	Vertical	
	14	Mazak.	Machining	Mazatrol	Traveling	Single	Bed	VTC-208	Field	Vertical	
	15	Mazak.	Machining	Mazahol	Traveling	Single	Bed	VTC-300C	Field	Vertical	
	16	Mazak.	Machining	Mazahol	Stationary	Single	Bed	FH-5800	Field	Hoizontal	
	17	Macak.	Machining	Fanuo 180i	Stationary	Single	Bed	FF-510	Field	Horizontal	
	18	Macok.	Machining	Fanue	Traveling	Single	Bed	FF-660	Field	Horizontal	
	19	Marvak	Machining	Manatri	Townline	Sinda	Table	TEH-1080	Guil	Hotmotal	-
										-	_

Figure 4.2 Machine Specifications in list form

INTELLIGENT MACHINE SELECTION V 3.3 - [Intelligent Machine Sele The Options Help	sten)
Rat Con End Con New Edit Deleto Pint Pint	Provious Next Lost Search Ext
Sof Result View Results Search General & Spindle Tooling and Work Support Avia Physical Others Ground Executions	Cost Anayas Power Calculation Sensitivity
	Type Pixed
Company Name Manak	Toper 50
Machine Type Machining Center CRC Central Mezatrol Fusion 648M	Max Speed in RPM 4890 Max Speed Option
Column Style Travelling Column Construction Sincle	Humber of Ranges
Work Support Bed	Harse Power 30
Muchine Same BV-800	Articulated Axis Opt.
	U Asis Hane

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.

INTELLIGENT MACHINE SELECTION V 3.3 - [Intelligent Machine 5	ielection]
😲 File Options Help	_(e) ×
Start Con End Con New Edit Delete Print Fi	rst Previous Next Last Search Exit
	h Cost Analysis Power Calculation Sensitivity

Figure 4.4 Database management tools

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

UNTELLIGENT MACHINE SELECTION V 3.3 - [Intelligen	nt Machine Selection]
🚺 File Options Help	_18
Stert Con End Con New Edt. Deete P	Image: Control Image:
Sot Result View Results	Search Cost Analysis Calculation Sensitivity
	Gaaph Into Tab 2
Spindle Speed rpm	
Axial depth of cut mm	Power
Humber of tooth	
Diameter of the mm	20000 20000
Feed rate mm/min	15000 15000
	10000 - 10000
Material	5000 5000
Shear strength MPa	P Rt 0
Calculate	
Results	
Min Power g Min Torque	0 Min Force in X -5877.1236833 Min Force in Y -213.76451341
Max Power 19621.5156185 Max Torque	62.4572240349 Max Force in X 0 Max Force in Y 1198.13404721

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.

Con Delete State Delete State Delete State Context Cont				AL 10 1 10	
Soft Result Vew Results Swarch Cost Analysis Power Calculation Tooling and Work Support Axis Physical Others Type Search Type Search Type Search Tager Main Spinalle Tager Main Search Main Main Search Main Main Search Main Search Main Main Search Main Search Main Search Main Main Search Main Main Main Se	Con EndCon New Edit Delete	Pitt Dis	Previous Next	Cancel Seaw	th con
General Description Main Spindle 0 d Single Search Multiple Search 10 d Single Search Multiple Search Company Name Mazak Search Machine Type Search Search Colorano Syde Search Main Spindle Machine Name Search Main Spindle Machine Name Search Main Spindle Machine Syde Search Main Spindle Machine Syde Search Main Spindle Machine Name Search Main Spindles Main Spindle Main Spindles Main Spindles Main Spindle Main Spindles Main Spindles Main Spindle Search Main Spindles Main Spindle Main Spindles Main Spindles Machine Name Search Harriber of Spindles Machine Name Search Main Spindles Machine Name Search Main Max. Machine Name Search Machine Name Search		ub Search		Cost Analysis Power Calcula	Search Servitive
General Bescription Main Spinkle ID c Single Search ID c Single Search ID c Single Search Main Spinkle Birection Company Name Mazak Main Spinkle Search Machine Type Search Mas. Speed in RPM Min. Max. Search Mas. Speed in RPM Min. Column Style Search Column Construction Search Mark Support Search Mark Support Search Markine Name Search Articulated Asix Search Articulated Asix Search	Interal & Special Tooling and Work Support A	AL PHILES CONS.	*		
B # Single Seach Multiple Seach Birection Seach Company Name Mazak # Saach Taper Min. Mac. Seach Machine Type Seach Mas. Speed in 89M Min. Seach Mas. Seach Column Style Seach Mas. Speed in 89M Min. Mas. Seach Column Construction Seach Humber of Ranges Min. Mas. Seach Work Support Seach Harse Power Min. Mas. Seach Machine Name Seach Articulated Asis Seach	General Description	-	Main Spindle Type		Gearch
Company Name Mazak P Search Taper Min. Mac. Search Machine Type Search Max. Speed in 80M Min. Max. 90000 Search Column Style Search Max Speed Option Min. Max. Search Column Style Search Hamber of Panges Min. Max. Search Work Support Search Hamber of Spindles Min. Max. Search Machine Name Search Horse Power Min. Max. Search U Asis Search U Asis Search Search	D # Single Search	Multiple Search	Direction] □ Search
Machine Type Search Max. Speed in BPM Min. S888 Max. 10000 Search Column Style Search Max. Speed in BPM Min. Max. 10000 Search Column Construction Search Humber of Ranges Min. Max. 10000 Search Work Support Search Humber of Spindles Min. Max. 10000 Search Machine Name Search Humber of Spindles Min. Max. 10000 Search Machine Name Search Humber of Spindles Min. Max. 10000 Search Machine Name Search Horse Power Min. Max. 10000 Search Machine Name Search Articulated Asix Search	Company Names Mazak	P Search	Taper	Min. Max.	□ Search
Calc Control Column Style Column Construction Column Construction Search Mark Support Mark Support Search Marker of Search Marker of Spindles Min. Max. Search Humber of Spindles Min. Max. Search Articulated Asix U Asis Search	Machine Type	E Search	Max. Speed in RPM	Mir. 5888 Max. 18800	R Search
Column Style Search Column Construction Search Work Support Search Machine Name Search Humber of Spindles Min. Machine Name Search Horse Power Min. Articulated Asix Search U Asis Search	CNC Control	Search	Max Speed Option	Mirs. Max.	C Search
Column Construction Search Aritsculated Asix Search Aritsculated Asix Search U Asis	Column Style	Search	Humber of Ranges	Min. Max.	□ Search
Mork Support Search Machine Name Search Search U Aais Search	Column Construction	E Search	Humber of Spindles	Min. Max.	Search
Machine Name Horse Power Horse Power Articulated Asix U Asis Search Search	Work Support	E Search		Min. Max.	C Seach
Articulated Asis Search	Machine Name	Search	Horse Power		
U Aais Search			Articulated Axis] □ Search
			U Anis		Search

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

le Options Help			_181
Can End Can New Edit Delete	RVT. First Previous 18	Cancel Search	×. Ext
. Sert Result Vev Results	Search	Cost Analysis Power Calculation	Sensitivity
Select previously defined weights Modify weights or en	nter your own Sort Results		
-			
-1. Productivity	-2. Flexibility		
Productivity	Flexibility 18 -		
Taper 9 12 5 V	Max Second Data	Adjustication form	
19 Max. Sp 20 30 w			
X of Sec 22	Horse Power 20 ¥	Head Changer 2 ¥	
23 10 1	Total # of tools 30 ¥	Index Table 5	
Main Spindle Power HP 30 x	Work Support 5 ¥	RotaryTable 5 x	
Chip to chip time 🔋 💌	U Axis 1 💌	Dual Axis RotaryTable 5 💌	
Rapid Traverse Speed 5	-3. Space	4. Adaptability	
Cutting Food 🖉 💌	Space 3 ¥	Adaptability 5	
Auto Pallet Changer 5 w			

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.

1	e l o		-	- 1		1 1 1			-	_
on En	d Carr New	67 68	Delete		Rest Revi	ous Mexit	1 Last	General Re	equery	5
-	Sot	Renk	View Results) See	ech 🏹	Ť	Cost Analysi	is Power Cal	culation	Sensi
	Sensi	livity					r –	-		
s	ensitivity 6	Peceri C	Abcolute 17	Include Treahold		Current Weig Prod	hts activity Fil 38.1	exibility Sp 42.9	ace Ada	ptabil 11.9
(C	Tap B	Most Critical	<u> </u>		Top Any Cr	lical	γ	Thes	hold	
	$\mathbb{D}^1 \longleftrightarrow$	ID2 ID1	and ID2 reverse	a their rankir	ngs		New W	/eights		
		ID2 ID1	and ID2 reverse Productivity	c their rankir Flexibility	Spece	101	New W	/eights	Productive	F
		1D2 1D1 1D2 30	Productivity 95.69	c their rankir Flexibility 0	Space 0	101	New W	linia Productivity	Productive 9.09	9 F 6
	D1	102 101 102 30 5	Productivity 95.69 91.47	C their ranks Flexibility 0	Space 0 0	101 20 20	New W	Anights Into Productivity Adaptability	Productive 8.09 34.96	9 F 6 3
	D1 20 20 20 20	102 101 30 5 25	Productivity 95.69 91.47 0	C their ranks Flexibility 0 0 0	Space 0 0 0	20 20 20 20	Now W 20 30 5	Aeights Into Productivity Adaptability Productivity	Productive 0.09 34.96 4.93	9 F 6 3 6
	D1 (102 101 30 5 25 10	and ID2 reverse Productivity 65.69 91.47 0 0 0	Flexibility 0 0 0 0	972.3	101 20 20 20 20 20	Now W 102 30 30 5 5 5	Veights Into Productivity Adaptability Productivity Adaptability	Productise 8.09 34.96 4.29 32.92	y F 6 3 6 3
	D1 20 20 20 20	102 101 30 5 25 10	and ID2 reverse Productivity 85,69 91,47 0 0	Flexibility 0 0 0 0	Space 0 0 0 972.3	20 20 20 20 20 20 20	Now W 102 30 30 5 5 10	Productivity Adaptability Adaptability Adaptability Space	Productivil 8.09 34.96 4.93 32.92 22.49	9 F 6 3 6 3 2
	D1 20 20 20 20	102 101 102 70 5 25 10	and ID2 reverse Productivity 85,69 91,47 0 0	Flexibility 0 0 0 0	972.3	20 20 20 20 20 20 20	Now W 102 30 5 5 5 10	Productivity Productivity Adaptability Productivity Adaptability Space	Productive 8.09 34.96 4.29 32.92 22.40	y F 6 3 6 3 2
		102 101 102 30 5 25 10	and ID2 revenue Productivity 95,69 91,47 0 0	Flexibility 0 0 0 0	5pace 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	101 20 20 20 20	Now W 102 30 30 5 5 5 10	Asights Into Productivity Adaptability Productivity Adaptability Space	Productivil 8.09 34.56 4.30 32.92 22.40	7 F 6 3 6 3 2
	D1 (102 101 30 5 25 10	and ID2 revenue Productivity 95,63 91,47 0 0	Flexibility 0 0 0 0	Space 0 0 0 972 3	101 20 20 20 20 20	Now W 102 30 5 5 10	Neights Into Productivity Adaptability Adaptability Adaptability Space	Productivil 8.09 34.96 4.39 32.92 22.40	y F 6 3 6 3 2
	D1 (102 101 30 5 25 10	and ID2 revenue Photlactivity 95.63 91.47 0 0	Flexibility 0 0 0 0	Space 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	101 20 20 20 20 20	Now W 102 30 5 5 10	Neights Productivity Aclastitability Productivity Aclastitability Space	Productivil 8.09 34.96 4.39 32.92 22.40	y F 6 3 6 3 2
	D1	102 101 30 5 25 10	and ID2 revenue Productivity 95.69 91.47 0 0	Flexibility 0 0 0 0	rgi 5pace 0 0 0 972.3	101 20 20 20 20 20	Now W 102 30 5 5 10	Neights Into Productivity Adaptability Productivity Adaptability Space	Productivil 8.09 34.56 4.39 32.92 22.40	9 F 6 3 6 3 2

Figure 4.10 Sensitivity analysis for top most critical machine

	New	#7 E08	Delete	<u>æ</u> 897.	First Prei	Next	Last	67 (1973)	Requery	e
	Sot	Recuit	View Results	Sea	ich 👔		Cost Ana	psis Pow	er Calculation	Sensi
	Senii	livity					1		-	
Senait	way @	Percent C	Absolute 🖵	Include Treshold	Top Any D	Durrent W/ Pro	aductivity 38.1	Flexibility 42.9	Space Ar	daptabi 11.9
_	Linu	Les	In case		1.	1.0	_	-		
	101	102	Productivity	P lexbelly	Space	Asaptability				
	-20	- 49	28.8	AE AE	0					P
	20	2	40.0/ 80.10	40.40 RD / R	0	0				
	20	50	66.66	67.14	0	1				
	20	20	-44.02	-80.92	-245.63	-178.67				
	30	5	23.88	21.02	0	22.98				
	30	25	45.53	4219	0	81.72				
	30	10	58.64	52.3	ů.	94.56				
	5	20	-87.83	-71.49	-1236.59	-448.45				
	5	30	-31.09	-24.44	-192.29	-43.92				
		25	32.25	25.49	0	51.49				
	5		1.00.000	37.09	0	68.02				
	5	10	47.77	-av -100						

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.

IGENT MACHINE MELICITED	v 1.1 - (httelige	at Plachuse Weberl	ka)			
Options Help						
End Son New Cat	Delete	n fet	Province March	Lat	areal 1	anguery
- Sont Reput	Vev Tarah	Seach	-	Cast Analysis	Power Ca	Aculation 5
lest perimaly defined weights	Modily-verights or e	the past own live	Rev.its Adaptati	Ry Company Weig	He	
1. Productivity		2. Flexibility				
Productivity (55	-	Fiesdally 3	-			
Teper 4	1					_
Max. Speed		man. speed	13 -	Articulation (and B	-
d of Saturday		Horse Poever	11 -	Read Char	au 5	-
	P 24	Total 2 of books	16 <u>-</u>	Index Tabl	10	-
Man Spindle Power IP	× •	Mork Support	5 .	BalacyTak	10	-
Chip to chip time	1 .	U Auto	1 .	Dail Asia Rolary1	10	-
Rapid Traverse Speed	5 .	3. Spece	4. Adaptab	(hy		
Cutting Feed	3 .	Spece 5	Adaptability	15		
A de la des de seres	12 21		Tapar #	20 - 10	al Pol'tosta	20 -
Auto Pater Changer	5 ×		CHC controls	Sector Inc. Sec.	10.00	100

Figure 4.13 Weights for Company X

PRE Options Help	1.3 - [Intelligent Plachme Select	ka)	교환 X 교환 X
Sart Can End Con Nov Lit	Verer Per	Previous text Last	Repay X
Sot Result	Yev Reals Seach		Sensitivity Sensitivity
Select previously delived weights _Mo	diy weights or weter your own 1 tow	Results Adaptability Company Weights	
1. Productivity	2. Flexibility		
Productivity 35 -	Fiexbilly 1	*	
Taper A	Hen. Speed	11 w Articulated Ant	
Max. Speed	Harse Power	11 . Read Changer	
J of Spindles	Total 2 of books	35	10 .
Man Spindle Power IP	their Toppert	5 • RelayIste	10 .
Chip to chip time	UAste	1 . Daal Asia Rotary/Lakia	10
Rapid Traverse Speed	- 1. Seece	A Advertishibly	
Cutting Feed	S w Spece 5 w	Adaptability (5 x	
Auto Pullet Changer		Taper # 20 x Botal #4	f tosis 10 -
	_	cher manimistra (10 k) pinera	

Figure 4.14 Weights for Company Y

INTELECONTEMPORENE SELECTION (1986 - Options: Help	V 3.3 - [Intelligent M	achine Selection)				- 191
PECH Delles Dev 12	Odex Arre	Part Pre-	A DE LE	e Cerce	N) Requery	X
Sort Result	Vew Results	Seath		et.Analysis Po	ver Calculation	Senakvity
Select previously defined weights	Modily resignation writes a	na me Sot Fam	h Adaphtik Con	and Wester		
1. Productivity	2	Heckling	-			
Productedly 16		mentionly [50]	1			
Taper X		as. Speed	-	Articulated Aves		
Max. Speed	10 · .	and Paver	-	Read Changer		
A of Spindles	n	stat Koffeels	-	index Table	10.1	
Main Spindle Pawer IIP		terk Support	-	Rotary Table		
	1. 21					
Chip to chip time		U Anna 1	- Bost Act	s ilotary1able	10 1	
Rapid Transree Speed	P P	Space 4	Adaptability			
Catting Feed	5 1 9	ARCO 10 - A	deptability 🗵 🗴	3		
Auto Pullet Changer		T	aper # 30	* Total Fof	teals 30 -	
			and the second sec			

Figure 4.15 Weights for Company Z

JOINT MACHINE SELECTED	V 3.3 - [Intelligent	Machine Select	en)			
Options Help						
Delice Nov Life	Oddar 2	P. D. First	Previoue Re	at Last	an) Caroot Reg) 1079
- Sont Republic	View Repuits	Search		East.Analysis	Fower Calcul	ation Ser
lect previously defined weights (Modily resigns or ex	mpilut anni Sot	Fersiti Adipt	ddilly Company/Wei	phis	
1. Productivity		2. Desibility				
Productivity Total	-	Personal Tr				
	-		-			
Tapes 8	N	Max. Speed	15 -	Arboulate	d Ann D	1
Max. Speed	30 .	Barne Payers		Real Char	-	2
A of Spindles			10 21			
		Total if of teals	10 1	index Tab	· 10 ·	1
Main Spindle Power 8P	30 .	Work Support		RotaryTab	fe 10 -]
Chin in chin line.		U Axis	1 -	Busi Axis Rotary?	able 10 -	1
cap to cap to a	P 20					·
Rapid Traverse Speed		3. Space	4. Adapta	Lity		
Cutting Food	3 .	Space 35 *	Adaptabilit	¥ 20 -		
	_		Faptor #	30 v Te	fail if of tools 3	
Auto Dallet Chancer						

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.

File Op	tions Help										1
t Con D	nd Con N	n n n n n n n n n n n n n n n n n n n	Delete	Pitt.	first	Previous	Next I	ter a	#7 Incel	C Requery	X
		Sot Result	View Re	sult:	Seach	<u> </u>		Cost Analysis	Power	Calculation	Sensitiv
-	L.c.	1		1	1	1	1	L		1	-
	ID	CoNa	MaTe	CNCCo	CoSt	CoCo	WoSu	MaNa	Ту	Di	T
E	1D 20	CoNa Mazak	MaTy Machining	CNCCo Mazabol	EoSt Stationary	CoCo Single	WoSu Bed	MaNa FH-4800	Ty Feed	Di Horizontal	T 5
-	ID 20 33	CoNa Mazak Mazak	MaTy Machining Machining	CNCCo Mazahol Mazahol	EoSt Stationary Stationary	CoCo Single Single	WoSu Bed Bed	MaNa FH-4800 FH-4000	Ty Fixed Fixed	Di Horizontal Horizontal	T 5 5
	1D 20 33 46	CoNa Mazak Mazak Okuma	MaTy Machining Machining	ENDEo Mazabol Mazabol OSP5020M	EoSt Stationary Stationary Stationary	CoCo Single Single	WoSu Bed Bed	MaNa PH-4800 PH-4000 MC-500H	Ty Feed Feed Feed	Di Horizontal Horizontal Horizontal	T 5 5 5 5
	1D 20 33 46 40	CoNa Mazak Mazak Okuma Okuma	MaTy Machining Machining Machining	ENECo Mazabol OSP5020M OSP7000M	EoSt Stationary Stationary Stationary Stationary	CoCo Single Single Single Single	WoSu Bed Bed Bed Bed	MaNa FH-4800 FH-4000 MC-500H MC-600H	Ty Field Field Field	Di Horizontal Horizontal Horizontal Horizontal	T 5 5 5 5
	1D 20 33 46 40 75	CoNa Nazak Nazak Oliuma Oliuma Oliuma	MaTy Machining Machining Machining Machining	ENICCo Mazahol Mazahol OSP5020M OSP7000M Okuma	EoSt Stationary Stationary Stationary Stationary Stationary	CoCo Single Single Single Single Single	WoSu Bed Bed Bed Bed Bed	MaNa FH-4800 FH-4000 MC-500H MC-600H NO:40HA	Ty Fired Fired Fired Fired Fired	Di Horizontal Horizontal Horizontal Horizontal	T 5 5 5 5 4
	1D 20 33 46 40 75 77	CoNa Nazak Nazak Oliuma Oliuma Oliuma Oliuma	MaTy Machining Machining Machining Machining Machining	ENICEo Mazahol OSP5020M OSP7000M Okuma	EoSt Stationary Stationary Stationary Stationary Stationary Stationary	CoCo Single Single Single Single Single Single	WoSu Bed Bed Bed Bed Bed Bed	MaNa FH-4800 FH-4000 MC-500H MC-600H MC-600H MC-600H	Ty Fixed Fixed Fixed Fixed Fixed Fixed	Di Horizontal Horizontal Horizontal Horizontal Horizontal	T 5 5 5 5 4 5

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.

	NULTS Help						-		-			
27 5	and Serr N	li +7 kay Edit	Delet	s	2. 10 16. Pro	t Previ	3.8	o Next	Last	*7 Carol	Requery	X
		Sort Result	View R	leculto 👔	Seach	T		. Y	Cost Analysia	Power(Calculation	Sensië
ielect	t perviously de	fined weights	Modify we	ghits or ené	er your own	Solt Result	•]#	kdoptability	Company We	ightz		
Not	dily Weight	·			_							
Mo	dily Weight Sort	Order b	y jai	1	•							
Mo	dily Weight Sort	Order by	y 🖂 RE SCO	RES	•	BEST		M	/EIGHT	ED SCO	DRES	
Ho	Bert ScoreProdu	Order by PUF	y AI	RES ScoreAdt	▼ ScoreTatal	BEST	D	ScareProdu	/EIGHT	ED SCO	DRES	ScareTata
More and a second	Sort ScoreProduce 22.32	Order by PUF	y Al RE SCO ScoreSpece 10.36	RES Scorelda	ScoreTotal 20.63	BEST	D 20	ScoreProdu 12:20	/EIGHT	ED SCO	Scowldgt	ScoreTota 20
Hor 10 20 33	ScoreProdu 22.32 14.53	Order by PUF	y AI <u>ScoreSpece</u> 10.36 13.82	RES Scoreldg 21.14 21.14	ScoreTotal 20.63 15.83	REST	ID 20 33	ScoreProdu 12.28 7.99	/EIGHT ScoreFlexbi 4.67 3.98	ED SCO ScoreSpace 0.52 0.69	Scowldgt	ScoreTot 20
Hot 10 20 33 81	Sert ScorePhodus 22.32 14.53 18.64	Order by PUF ScoreFleabi 18.67 15.91 13.02	y [4] RE SCO ScoreSpece 10.36 13.82 8.06	RES Score/dt 21.14 21.14 2.11	ScoreTatel 20.63 15.83 14.23	BEST	D 20 33 81	ScoreProdu 12.28 7.39 10.25	/EIGHT 5ccseFlexbi 4.67 3.98 3.26	ED SCO 500050000 0.52 0.69 0.4	DRES 5com/dapt 317 317 0.32	ScoreTot 20 15 14
Hot 10 20 33 81 77	Sert Sect 22.32 14.53 18.64 11.47	Order by PUF 5coreFlexibi 10.67 15.91 13.02 14.53	y Al RE SCO 5coer5pace 10.36 13.82 8.06 7.47	RES Scorolds 21.14 21.14 2.11 21.14	 ScoreTotal 20.61 15.83 14.23 13.48 	BEST	ID 20 33 81 77	ScoreProdu 12.20 7.39 10.25 6.31	EIGHT	ED SCO 5core5pace 0.52 0.65 0.4 0.37	DRES 5 covel dapt. 3.17 3.17 0.32 3.17	ScoreTot 20 15 14 13
Hot ID 20 33 81 77 75	Section 22.32 14.53 18.64 11.47 12.48	Order by PUE 5coreFlexibi 18.67 15.91 13.02 14.53 15.28	y [4] RE SCO 500005pace 10.36 13.82 8.06 7.47 14.32	RES Scorolds 21.14 21.14 2.11 21.14 21.14 11.52	 ScoreTotal 20.63 15.83 14.23 13.48 13.14 	BEST	ID 20 33 81 77 75	ScoreProdu 12.20 7.39 10.25 6.31 6.86	EIGHT 5ccceFlexbi 4.67 3.98 3.63 3.63 3.82	ED SCC 5core5pace 0.52 0.4 0.37 0.72	DRES 5combdapt 3.17 0.32 3.17 1.74	ScoreTot 20 15 14 13 13
Hoi 10 20 33 81 77 75 45	5 coreProdu 22.32 14.53 18.64 11.47 12.48 11.95	Order by PUF 5coreFlexbi 18.67 15.91 13.02 14.53 15.28 11.32	y Al ScoreSpace 10.36 13.82 8.06 7.47 14.32 9.72	RES Scoredul 21.14 21.14 2.11 21.14 21.14 11.52 11.22	 ScoreTotal 20.63 15.83 14.23 13.44 13.14 11.52 	WORST	ID 20 33 81 77 75 45	∑ 5correProdu 12.23 7.39 10.25 6.31 5.95 6.52	EIGHT 5ccceFlexibi 4.67 3.98 3.26 3.63 3.82 2.83	ED SCC 5cor5core 0.52 0.69 0.4 0.37 0.72 0.49	DRES 5 consideration 3.17 3.17 0.32 3.17 1.74 1.58	ScoreTot 20 15 14 13 13 13

Figure 4.18 Ranking of machines for Company X

n p	nd Con	Nev B	a R Dei	esc Pr		e Prevé	i ous	Next	Last	K7 Canod	Requery	Ē
		Sort Resul	t View	Results)	Search	Ŷ	_	. Y	Cost Analysi	s Power (Calculation	Sens
elect	pervicusly	defined weight	ts Modify w	eights or end	er your own	Solt Result	0 1	Ldaptability	Company We	ight:		
		. 1										
Nod	ily Weigl	Order	by AI		-							
Mod	illy Weigl Sort	Order	by Al		*							
Mod	ily Weigl Sort	Order	⊫y AI RE SCO	ORES	*	BEST		Ň	/EIGHT	ED SCO	ORES	
Hod	By Weigh Sert	Order PU	by AI	DRES	ScoreTotal	BEST	ID	ScoreProdu	/EIGHT	ED SCO	DRES	ScoreT
Mod ID 81	Sort Sort ScoreProd	0rder PU	by AI RE SCO 5 ScoreSpace 8.06	DRES x ScoreAds 30.49	ScoreTotal Z2.6	iest	ID 81	ScoreProdu 6.52	/EIGHT	ED SCO	ORES ScoreAdapt.	ScoreT
Hod 10 81 20	SorrePror 18.64 22.32	0rder PU 8# ScoreFlexi 13.02 18.67	by AI RE SCO 5 Soare5pac 8.05 10.35	DRES x ScoreAds 30.49 14.52	ScoreTotal 22.6 17.66	BEST	ID 81 20	SooreProdu 6.52 7.81	/EIGHT ScoreFlexibi 1.95 2.8	ED SC(DRES ScoreAdapt. 13.72 6.53	ScoreT
Hod 10 81 20 33	Sort Sort 18.64 22.32 14.53	0rder PU 5.5 ScoreFlexi 13.02 18.67 15.91	by A1 RE SCO 5 ScoreSpace 8.05 10.35 13.82	DRES x ScoreAd 30.49 14.52 14.52	500reTotal 22.6 17.66 14.7	BEST	ID 81 20 33	ScoreProdu 6.52 7.81 5.09	/EIGHT ScoreFlexibi 1.95 2.8 2.39	ED SC(ScoreSpace 0.4 0.52 0.69	ScoreAdapt 13.72 6.53 6.53	ScoreT
Mod 81 20 33 77	SorreProc 18.64 22.32 14.53 11.47	0rder PU 54 ScoreFlexi 13.02 14.53 14.53	by Al RE SCO 500re5pac 8.06 10.36 13.82 7.47	DRES x ScoreAd 30.49 14.52 14.52 14.52	ScoreTotal 22.6 17.66 14.7 13.1	BEST	ID 81 20 33 77	ScoreProdu 6.52 7.81 5.09 4.01	/EIGHT 1.95 2.8 2.39 2.10	ED SCC 500re5pace 0.4 0.52 0.53 0.53	DRES 5coreAdapt. 13.72 6.53 6.53 6.53	Score1
Hod 81 20 33 77 48	SorreProc 18.64 22.32 14.53 11.47 8.7	0rder PU 34 ScoreFlexi 13.02 18.67 15.91 14.53 11.27	by Al RE SCO 5.00re5pac 8.05 10.35 13.82 7.47 36.25	DRES 20 49 14 52 14 52 14 52 10 16	ScoreTotal 22.6 17.66 14.7 13.1 11.12		ID 81 20 33 77 48	ScoreProdu 6.52 7.81 5.09 4.01 3.05	/EIGHT 1.95 2.8 2.39 2.19 1.10	ED SCC 500re5pace 0.4 0.52 0.69 0.77 1.81	DRES 5coreAdapt. 13.72 6.53 6.53 6.53 6.53 4.57	Score1
Not 81 20 33 77 48 46	500rePtor 18.64 22.32 14.53 11.47 11.05	0rder PU 36 ScoreFlest 13.02 18.67 15.91 14.53 11.27 11.22	hy Al RE SCO 8.06 10.36 13.82 7.47 36.26 9.72	DRES 20 49 14 52 14 52 14 52 10 16 3 30	500reTotal 22.6 17.66 14.7 13.1 11.12 10.02	WORST	ID 81 20 33 77 48 46	ScoreProdu 6.52 7.81 5.09 4.01 3.05 4.15	/EIGHT 5coreFlexibi 1.95 2.8 2.78 2.78 2.18 1.69 1.7	ED SCC 5coreSpace 0.4 0.52 0.52 0.37 1.81 0.49	DRES ScoreAdapt. 13.72 6.53 6.53 6.53 6.53 6.53 4.57 4.49	Score1

Figure 4.19 Ranking of machines for Company Y

ETT 10	IENT MAD	HINE SELECTION	15 V 3.3 - [1	ntelligent	t Miachane Se	accion]					_ 0
e Opi	tions Help	p									_ 0
an D	nd Con	New Edi	Dyie	a A	ə 🔒	t Previ	us Next	Last	#7 Cancel	Requery	N. Dat
		Sort Result	ViewF	Results	Search			Cost Analysis	Power C	alculation	Sensitivity
P I i						0-4 D A		1			
Select	previously	defined weights	Modify we	ights or ena	er your own	2 OK PHILIN	: Adaptability	y Company We	pres		
Mod	ila Waish										
Mod	iily Weigh	Order b	v A		-						
Mod	Sily Weigh	Order b	A M		•						
Mod	iily Weigt Sort	Order b		RES	•	BEST		WEIGHT	ED SCO	ORES	
Mod	Sort	Order b	y AI	RES	•	BEST	0.000	WEIGHT	ED SCO	DRES	0
Hod	Sort	Order b PUE	y Al RESCO	DRES	ScoreTotal	BEST	D ScarePr	WEIGHT	ED SCO	DRES	ScoreTotal
Hod	Sort ScoreProd	Order b PUE	y Al RE SCO Scored pace	DRES ScowAda	ScoreTotal 19	IIEST	ID ScarePri 20 3.35	WEIGHT	ED SCC	ScoreAdapt	Score Total
Hod	Sort ScoeProd 22.32 14.53	Alta Order b PUF	y [4] RE SCO ScoreSpace 10.38 13.82 14.7	RES ScowAds 21.14 21.14 21.14	ScoelTotal 19 15.00	BEST	D ScorePri 20 3.35 33 2.18	WEIGHT	ED SCO Scorelipace 1.04	Scorekdapt 529 529	ScoreTotal 15 16.6
Hod	SeconProd 22.32 14.53 11.47	Max Order b PUF 18.67 15.91 14.53	y Al RE SCO 5configure 10.36 13.82 7.47 7.47	RES 21.14 21.14 21.14 21.14	ScoreTotal 19 16.8 15.02	BEST	ID ScorePr 20 3.35 33 2.18 77 1.72	WEIGHT odu ScoreFlexabil 9.34 7.96 7.27	ED SCC 5coreSpace 1.04 1.38 0.75	DRES 5.29 5.29 5.29	ScoreTotal 15 15.0 15.0
Hot 10 20 33 77 75	SeconProd 22.32 14.53 11.47 12.48	Arr Derder b PUI 18.67 15.91 14.53 15.28	y Al RE SCO Scontipace 10.36 13.62 7.47 14.32	RES ScowAds 21.14 21.14 21.14 21.14 11.62	ScoeTatal 19 16.8 15.02 13.85	BEST	10 ScorePr 20 3.35 33 2.18 77 1.72 75 1.87	WEIGHT 9.34 7.96 7.27 7.64	ED SCC ScoreSpace 1.04 1.38 0.75 1.43	DRES 529 529 529 529 291	ScoreTotal 15 15.0 13.05 13.05
Hot 10 20 33 77 75 48	SecondProd 22.32 14.53 11.47 12.48 8.7	Ar Order b PUI 1867 1867 1591 1453 1528 11.27	y Al ScoreSpace 10.36 13.82 7.47 14.32 36.26	RES 21.14 21.14 21.14 21.14 11.62 11.62	 ScowTotal 19 16.8 15.02 13.85 13.47 	WORST	D ScoreFr 20 3.35 33 2.18 77 1.72 75 1.87 48 1.31	WEIGHT 9.34 7.96 7.27 7.64 5.64	ED SCC 5core5pace 1.04 1.38 0.75 1.43 3.63	DRES 5.29 5.29 5.29 5.29 5.29 2.91 2.91	ScoreTotal 19 16.8 15.02 13.85 13.47
Hot 1203777 1548 45	ScoreProd 22.32 14.53 11.47 12.48 8.7 11.85	Au Score Fleebi 18.67 15.91 14.53 15.28 11.27 11.32	y All ScoreSpace 10.36 7.47 14.32 36.26 9.72	RES 21.14 21.14 21.14 21.14 11.62 11.62 11.23	 ScowTotal 19 16.8 15.02 13.85 13.47 11.22 	WORST	ID ScoreFr 20 3.35 33 2.18 77 1.72 75 1.87 48 1.31 46 1.78	WEIGHT 9.34 7.96 7.27 7.64 5.64 5.66	ED SCO 5consigners 1.04 1.38 0.75 1.43 3.63 0.97	DRES 529 529 529 291 291 281	ScoreTotal 19 16.8 15.02 13.85 13.47 11.22
Hot 12033 777 75 48 46 81	ScceeProd 22 32 14.53 11.47 12.48 8.7 11.85 18.64	Na Order b PUI 18.67 15.91 14.53 15.28 11.27 11.32 13.02	y All Scored pace 10.36 13.82 7.47 14.32 36.26 9.72 8.06	RES ScowAdr 21.14 21.14 21.14 11.62 11.62 11.23 2.11	 ScoreTatal 19 16.8 15.02 13.85 13.47 11.22 10.64 	WORST	ID ScorePri 20 3.35 33 2.18 77 1.72 75 1.87 48 1.31 46 1.78 81 2.8	WEIGHT 9.34 7.96 7.27 7.64 5.66 5.66 6.51	ED SCC 5contigues 1.04 1.38 0.75 1.43 3.63 0.97 0.81	ScoreAdapt 5.29 5.29 5.29 2.91 2.91 2.91 2.91 2.91 0.53	ScoreTotal 15 15.6 13.65 13.47 11.22 10.64
Hot 10 20 33 77 75 48 46 81	ScoreProc 22 32 14.53 11.47 12.48 8.7 11.65 18.64	Ma Order b PUF 1867 15.91 14.53 15.28 11.27 11.32 13.02	y Al ScoreGpace 10.36 7.47 14.32 36.26 9.72 8.06	PRES ScowAds 21.14 21.14 21.14 21.14 11.62 11.62 11.23 2.11	 ScceeTotal 19 15.8 15.02 13.85 13.47 11.22 10.64 	WORST	ID ScorePri 20 3.95 33 2.18 77 1.72 75 1.87 48 1.31 46 1.78 81 2.8	WEIGHT 9.34 7.96 7.27 7.64 5.64 5.66 6.51	ED SCC 1.04 1.38 0.75 1.43 3.63 0.97 0.81	DRES 529 529 529 529 529 291 291 291 281 053	ScoreTotal 19 16.6 15.00 13.69 13.40 11.22 10.64

Figure 4.20 Ranking of machines for Company Z

| Image: Second from the second f
 |
 | ie Options Help Con Ond Con New Cot Ond Con New Cot Ond Con New | ie Options Help Con End Con Con End Con New Con Con Con Con Con
 |
 | | | Options Help Development Search Development Development Search Development ScoreFlexable ScoreFlexab | Options Help Options O | Options Help Description Options South Result S | | Re Options Help Con Ond Con Next Cont Analysis Power Calculation Sett Containing Pure Containing Next Containing Next <t< th=""><th></th></t<> |
 |

--
---|---
--
--	---	---	---
---	--		
Option Option<	Cont Con New Colours Press Previous Next Last Concer Requery Sect Result View Results Search Cost Analysis Power Calculation Service Sect Result View Results Search Cost Analysis Power Calculation Service Sect Previously defined weights Modify weights or enter your own Sot Results Adaptability Company Weights Sect Previously defined weights Or enter your own Sot Results Adaptability Company Weights Define by All Sect Define by All Sect Previous Sector Previous	Continue of the second se	Image: Second Flexibility North Image: Second Flexibility Next Least Image: Second Flexibility Next Next Least Image: Second Flexibility Next Least Image: Second Flexibility Next Next Least Image: Second Flexibility Next Next Least Image: Second Flexibility Next Next Least Next Least Next Least Next Next Least Next <th>Image: Second Fields Second</th> <th>Image: Second Fields Second</th> <th>Image: Second Score Final Score Space Score Add Score Total Image: Score Final Score Space Score Add Score Total Image: Score Final Score Space Score Add Score Total Image: Score Final Score Space Score Add Score Total Image: Score Final Score Final Score Space Score Add Score Total Image: Score Final Score Final Score Space Score Add Score Total Image: Score Final Score Final</th> <th>Control Con New Color Preside Score/Fields Score/Fie</th> <th></th> <th>Continue of the second of</th> <th></th> <th>or Design Design<th>Containing weights Order by Ad Process Proces</th></th>
Sett Nearth View Pretriet Settion Contrargets Power Calculatory Settion Setect previously defined weights Modily weights or enter your own Sot Results Adaptability Company Weights Company Weights Modily Weights Order by Ad • Modily Weights Company Weights Company Weights Bert PURE SCORES EEST WEIGHTED SCORES EEST WEIGHTED SCORES 10 ScoreProdu Scorent Produ Scorent Produ Scoren	Select previously defined weights Modify weights or enter your own Set Results Adaptability Company Weights Select previously defined weights Modify weights or enter your own Set Results Adaptability Company Weights Modify Weights Order by Al • WEIGHTED SCORES ID ScoreProdu ScoreProdu </th <th>Select previously defined weights Modify weights or enter your own Set Plenultz Adaptability Company Weights Select previously defined weights Modify weights or enter your own Set Plenultz Adaptability Company Weights Modify Weights Order by Ali • • • Sert PURE SCORES erst WEIGHTED SCORES • 10 Score/Fredu Sc</th> <th>Select previously defined weights Modify weights or enter your own Sot Pieruits Adoptability Company Weights Select previously defined weights Modify weights or enter your own Sot Pieruits Adoptability Company Weights Modify Weights Order by Ad Image: Company Weights Modify Weights Bart PURE SCORES EEST WEIGHTED SCORES ID ScoreFlexibi ScoreSpace ScoreFlexibi ScoreSpace 10 ScoreFlexibi ScoreSpace ScoreFlexibi ScoreSpace 11 Sore 11.62 24.7 12 14.53 15.91 13.62 21.54 15.69 13 19.94 2.32 13.32 14.3 15.93</th> <th>Select previously defined weights Modily weights or enter your own Sof Pierrults Adaptability Company Weights Select previously defined weights Modily weights or enter your own Sof Pierrults Adaptability Company Weights Modily Weights Order by Ad Image: Company Weights Image: Company Weights Bert PURE SCORES erst WEIGHTED SCORES ID ScoreFlexibility ScoreFlexibility ScoreFlexibility 10 ScoreFlexibility ScoreFlexibility ScoreFlexibility 23 14.53 15.51 13.82 21.14 23 14.53 15.91 13.82 21.14</th> <th>Select previously defined weights Modily weights or enter your own Sof Piezults Adaptability Company Weights Select previously defined weights Modily weights or enter your own Sof Piezults Adaptability Company Weights Modily Weights Order by Ad Image: Company Weights Modily Weights Bert PURE SCORES REST WEIGHTED SCORES ID ScoreFlexibili ScoreSpace ScoreFlexibili ScoreSpace ScoreFlexibili ScoreSpace 10 ScoreFlexibili ScoreSpace ScoreFlexibili ScoreSpace ScoreFlexibili ScoreSpace 23 14.53 15.91 13.82 21.14 15.61 33 2.18 1.59 7.6 4.23</th> <th>Select previously defined weights Modily weights or enter your own Sort Plexuits Adaptability Company Weights Select previously defined weights Modily weights or enter your own Sort Plexuits Adaptability Company Weights Modily Weights Order by Ali • Bent PURE SCORES arst WEIGHTED SCORES 10 ScoreFlexibility ScoreFlexibility ScoreFlexibility 11 11 12 36.26 11.62 148 8.7 11.27 36.26 11.62 24.7 131 15.91 13.82 21.14 15.69 7.6 4.23</th> <th>Seet Needer Vervenen Seaton Contribution Power Calculation Sentin Select previously defined weights Modily weights or enter your own Sot Plexaits Adaptability Company Weights Sect Under by All PURE SCORES D ScoreProdul ScoreFlexible ScorePower ScoreAdapt ScoreTatal 43 87 1127 35.25 11.52 129 12 129 12</th> <th>Select previously defined weights Modily weights or enter your own Sort Planults Adaptability Company Weights Select previously defined weights Modily weights or enter your own Sort Planults Adaptability Company Weights Modily Weights Order by All * Bert PURE SCORES arst WEIGHTED SCORES 10 ScoreFlexbill ScoreSpace ScoreSpace ScoreSpace 48 8.7 11.27 36.26 11.62</th> <th>Seet Needer Vervienden Seeten ContAnagen Power Calculation Seeten Select previously defined weights Modily weights or enter your own Sot Plexult: Adaptability Company Weights Order by All Define ScoreFlexable ScoreFlexabl</th> <th>Seet Needel Very Petrale Seaton Con Wrappin Power Calculation Series Select previously defined weights Modily weights or enter your own Soft Piezults Adaptability Company Weights Modily Weights Order by Ad Modily Weights Order by Ad Modily Weights Order by Ad Modily Rest WEIGHTED SCORES ID ScoreProdul Score/Feedel Score/Adapt Score/Feedel Score/Feeded</th> <th>Select previously defined weights Modify weights or enter your own Sort Presults Adaptability Company Weights Select previously defined weights Modify weights or enter your own Sort Presults Adaptability Company Weights Modify Weights Order by All * Bent PURE SCORES arst WEIGHTED SCORES</th> <th>Select previously defined weights Modily weights or enter your own Soft Persuits Adaptability Company Weights Select previously defined weights Modily weights or enter your own Soft Persuits Adaptability Company Weights Modily Weights Ordier by All * Sert PURE SCORES serst WEIGHTED SCORES</th>	Select previously defined weights Modify weights or enter your own Set Plenultz Adaptability Company Weights Select previously defined weights Modify weights or enter your own Set Plenultz Adaptability Company Weights Modify Weights Order by Ali • • • Sert PURE SCORES erst WEIGHTED SCORES • 10 Score/Fredu Sc	Select previously defined weights Modify weights or enter your own Sot Pieruits Adoptability Company Weights Select previously defined weights Modify weights or enter your own Sot Pieruits Adoptability Company Weights Modify Weights Order by Ad Image: Company Weights Modify Weights Bart PURE SCORES EEST WEIGHTED SCORES ID ScoreFlexibi ScoreSpace ScoreFlexibi ScoreSpace 10 ScoreFlexibi ScoreSpace ScoreFlexibi ScoreSpace 11 Sore 11.62 24.7 12 14.53 15.91 13.62 21.54 15.69 13 19.94 2.32 13.32 14.3 15.93
Set Set Persuitz Adaptability Company Weights Modify Weights Order by Aligned Image: Company Weights Set Order by Aligned Image: Company Weights D Conder by Aligned Image: Company Weights D SconeFlexible SconeFlexible SconeFlexible D	Modily Weights Order by Add Sort PURE SCORES BEST WEIGHTED SCORES 10 ScoreFlexibi ScoreFlexi	Modily Weights Modily weights or enter your own Sort Piezults Adaptability Company Weights Modily Weights Order by Adaptability Company Weights Company Weights Sort PURE SCORES BEST WEIGHTED SCORES 10 ScoreFlexibiti ScoreSpaces ScoreFlexibiti	Modify Weights Modify weights or enter your own Sof Results Adaptability Company Weights Modify Weights Order by Ad Image: Company Weights Image: Company Weights Sort PURE SCORES REST WEIGHTED SCORES ID ScoreFredul ScoreFlexibility ScoreFredul ScoreFlexibility ScoreFredul ScoreFlexibility 10 ScoreFredul ScoreFlexibility ScoreFlexibility ScoreFlexibility ScoreFlexibility 11 ScoreFlexibility ScoreFlexibility ScoreFlexibility ScoreFlexibility 12 ScoreFlexibility ScoreFlexibility ScoreFlexibility ScoreFlexibility ScoreFlexibility 13 14 ScoreFlexibility ScoreFlexibility ScoreFlexibility ScoreFlexibility 13 14 ScoreFlexibility ScoreFlexibility ScoreFlexibility ScoreFlexibility ScoreFlexibility 13 14 ScoreFlexibility ScoreFlexibility ScoreFlexibility ScoreFlexibility ScoreFlexibility 14 ScoreFlexibility ScoreFlexibility ScoreFlexibility Score
Select previously defined weights Modify weights or enter your own Sort Result: Adaptability Company Weights Modify Weights: Order by Adaptability Image: Company Weights Image: Company Weights Sert PURE SCORES Image: Company Weights Image: Company Weights ID Score/Fields Score/Fields Score/Fields Score/Fields ID Score/Fields Score/Fields Score/Fields Score/Fields Score/Fields ID Score/Fields Score/Fields Score/Fields Score/Fields Score/Fields Score/Fields ID Score/Fields Score/Fields <th>Modily Weights Order by Add Born PURE SCORES Best WEIGHTED SCORES 10 ScoreFloods/ScoreFlexibil ScoreSpace/ScoreAda ScoreFloods/ScoreFlexibil ScoreSpace/ScoreAda ScoreFloods/ScoreFlexibil ScoreSpace/ScoreAda ScoreFloods/ScoreFlexibil ScoreSpace/ScoreAda ScoreFlexibil ScoreSpace/ScoreAda ScoreFlexibil ScoreSpace/ScoreFlexibil ScoreSpace/ScoreFlexibi</th> <th>Modily Weights Order by Au Soft Finants Adaptability Company Weights Box PURE SCORES Exst WEIGHTED SCORES 10 ScoreFrodu ScoreFrod</th> <th>Modily Weights Order by All Image: Company Weights Modily weights Bart Order by All Image: Company Weights Image: Company Weights<!--</th--><th>Select previously defined weights Modify weights or enter your own Sort Pierrultz Adaptability Company Weights Modify Weightz: Order by Al Sert PURE SCORES sert WEIGHTED SCORES 10 ScoreProdu/ Score/Fields/ Score</th><th>Select previously defined weights Modify weights or enter your own Sort Pierrultz Adaptability Company Weights Modify Weights Order by All Burnels PURE SCORES sets WEIGHTED SCORES 10 ScoreProdu/ScoreFlexibil ScoreSpace/ScoreAds/ScoreTotal 0 ScoreProdu/ScoreFlexibil ScoreSpace/ScoreAds/ScoreTotal 48 8.7 11.27 36.26 11.62 24.7 32 14.53 15.91 13.82 21.14 15.6</th><th>Select previously defined weights Modify weights or enter your own Sort Pierratic Adaptability Company Weights Modify Weights Order by All Sort PURE SCORES serst WEIGHTED SCORES 1D ScoreProdu ScoreFlexibil ScoreSpace ScoreAdapt ScoreTotal 10.5 ScoreProdu ScoreFlexibil ScoreSpace ScoreAdapt ScoreTotal 11.52 24.7 32 14.53 15.91 13.82 21.14 15.61 1.59 7.6 4.23</th><th>Modily Weights Order by All Bort PURE SCORES REST WEIGHTED SCORES 10 ScoreProdu/ScoreFlexibil ScoreSpace/ScoreAdapt ScoreTatal 10 ScoreProdu/ScoreFlexibil ScoreSpace/ScoreAdapt ScoreTatal 48 8.7 11.27 36.26 11.62 24.7 20 14.62 15.64 12.02 14.5 12.02</th><th>Select previously defined weights Modify weights or enter your own Soft Fierrult: Adaptability Company Weights Modify Weights: Order by Al Sert PURE SCORES arst WEIGHTED SCORES ID ScoreFredul ScoreFlexibil ScoreSpace ScoreAdapt ScoreTotal ID ScoreFredul ScoreFlexibil ScoreSpace ScoreAdapt ScoreTotal</th><th>Select previously defined weights Modify weights or enter your own Soft Flexult: Adaptability Company Weights Modify Weights Order by All Sort PURE SCORES erst WEIGHTED SCORES ID Score/Fredu Score/Fields Score/Fredu Score/Fields Score/Fredu Score/Fields</th><th>Select previously defined weights Modify weights or enter your own Soft Pierrultz Adeptability Company Weights Modify Weights Order by AI * PURE SCORES BEST WEIGHTED SCORES ID ScoreProdual Score/Fiestbil Score/Space Score/Adet Score/Fiestbil Score/Fiestbil Score/Fiestbil Score/Fi</th><th>Select previously defined weights Modily weights or enter your own Soft Pierrule: Adeptability Company Weights Modily Weights: Sort Order by All </th><th>Select previously defined weights Modily weights or enter your own Soft Fiercultz Adaptability Company Weights Modily Weights Order by All Y Sert PURE SCORES erst WEIGHTED SCORES</th></th>	Modily Weights Order by Add Born PURE SCORES Best WEIGHTED SCORES 10 ScoreFloods/ScoreFlexibil ScoreSpace/ScoreAda ScoreFloods/ScoreFlexibil ScoreSpace/ScoreAda ScoreFloods/ScoreFlexibil ScoreSpace/ScoreAda ScoreFloods/ScoreFlexibil ScoreSpace/ScoreAda ScoreFlexibil ScoreSpace/ScoreAda ScoreFlexibil ScoreSpace/ScoreFlexibil ScoreSpace/ScoreFlexibi	Modily Weights Order by Au Soft Finants Adaptability Company Weights Box PURE SCORES Exst WEIGHTED SCORES 10 ScoreFrodu ScoreFrod	Modily Weights Order by All Image: Company Weights Modily weights Bart Order by All Image: Company Weights Image: Company Weights </th <th>Select previously defined weights Modify weights or enter your own Sort Pierrultz Adaptability Company Weights Modify Weightz: Order by Al Sert PURE SCORES sert WEIGHTED SCORES 10 ScoreProdu/ Score/Fields/ Score</th> <th>Select previously defined weights Modify weights or enter your own Sort Pierrultz Adaptability Company Weights Modify Weights Order by All Burnels PURE SCORES sets WEIGHTED SCORES 10 ScoreProdu/ScoreFlexibil ScoreSpace/ScoreAds/ScoreTotal 0 ScoreProdu/ScoreFlexibil ScoreSpace/ScoreAds/ScoreTotal 48 8.7 11.27 36.26 11.62 24.7 32 14.53 15.91 13.82 21.14 15.6</th> <th>Select previously defined weights Modify weights or enter your own Sort Pierratic Adaptability Company Weights Modify Weights Order by All Sort PURE SCORES serst WEIGHTED SCORES 1D ScoreProdu ScoreFlexibil ScoreSpace ScoreAdapt ScoreTotal 10.5 ScoreProdu ScoreFlexibil ScoreSpace ScoreAdapt ScoreTotal 11.52 24.7 32 14.53 15.91 13.82 21.14 15.61 1.59 7.6 4.23</th> <th>Modily Weights Order by All Bort PURE SCORES REST WEIGHTED SCORES 10 ScoreProdu/ScoreFlexibil ScoreSpace/ScoreAdapt ScoreTatal 10 ScoreProdu/ScoreFlexibil ScoreSpace/ScoreAdapt ScoreTatal 48 8.7 11.27 36.26 11.62 24.7 20 14.62 15.64 12.02 14.5 12.02</th> <th>Select previously defined weights Modify weights or enter your own Soft Fierrult: Adaptability Company Weights Modify Weights: Order by Al Sert PURE SCORES arst WEIGHTED SCORES ID ScoreFredul ScoreFlexibil ScoreSpace ScoreAdapt ScoreTotal ID ScoreFredul ScoreFlexibil ScoreSpace ScoreAdapt ScoreTotal</th> <th>Select previously defined weights Modify weights or enter your own Soft Flexult: Adaptability Company Weights Modify Weights Order by All Sort PURE SCORES erst WEIGHTED SCORES ID Score/Fredu Score/Fields Score/Fredu Score/Fields Score/Fredu Score/Fields</th> <th>Select previously defined weights Modify weights or enter your own Soft Pierrultz Adeptability Company Weights Modify Weights Order by AI * PURE SCORES BEST WEIGHTED SCORES ID ScoreProdual Score/Fiestbil Score/Space Score/Adet Score/Fiestbil Score/Fiestbil Score/Fiestbil Score/Fi</th> <th>Select previously defined weights Modily weights or enter your own Soft Pierrule: Adeptability Company Weights Modily Weights: Sort Order by All </th> <th>Select previously defined weights Modily weights or enter your own Soft Fiercultz Adaptability Company Weights Modily Weights Order by All Y Sert PURE SCORES erst WEIGHTED SCORES</th>
Modily Weights Order by Al Sort PURE SCORES sest WEIGHTED SCORES 10 ScoreFlexbil ScoreSpace ScoreFlexbil Score			
 | Modily Weights Order by Al Sert PURE SCORES sest WEIGHTED SCORES 1D ScoreFrodu ScoreFlexibil ScoreSpace ScoreAds ScoreTatal 10 ScoreFrodu ScoreFlexibil ScoreSpace ScoreAds ScoreTatal 48 8.7 11.27 38.26 11.82 24.7 32 14.53 15.91 13.62 21.14 15.6 20 22.32 18.67 10.36 21.14 15.14
 | Modily Weights Order by All Sert PURE SCORES sers WEIGHTED SCORES 10 ScoreFrodus | Modily Weights: Order by All Sert PURE SCORES sest WEIGHTED SCORES 10 ScoreProdu
 | Modily Weights Order by All Sort PURE SCORES sest WEIGHTED SCORES 10 ScoreFredul ScoreFlexibil ScoreSpace ScoreFredul ScoreFlexibil ScoreSpace ScoreFredul ScoreSpace | Modily Weights Order by All Sort PURE SCORES sest WEIGHTED SCORES 10 ScoreFredul ScoreSpace ScoreFredul ScoreSpa | Modily Weights Order by Al Bort PURE SCORES sest WEIGHTED SCORES 1D ScoreFrodu | Modily Weights Order by Al Sert PURE SCORES arst WEIGHTED SCORES 10 ScoreProdul ScoreProdu ScoreProdul ScoreProdul ScoreProdu ScoreProdul ScoreProdul Score | Modily Weights Order by All Sort PURE SCORES sest WEIGHTED SCORES 10 ScoreFredula ScoreFlexibil ScoreSpace ScoreAdapt ScoreTital ID ScoreFredula ScoreFlexibil ScoreSpace ScoreAdapt ScoreTital 43 8.7 11.27 36.26 11.62 24.7
 | Modily Weights Order by All Sert PURE SCORES start WEIGHTED SCORES ID ScoreProdul ScoreFlexibil ScoreSpace ScoreAdept ScoreTatal ID ScoreProdul ScoreFlexibil ScoreSpace ScoreAdept ScoreTatal | | Modily Weights
Sort Order by All T
PURE SCORES BEST WEIGHTED SCORES | Modily Weights
Order by Au PURE SCORES BEST WEIGHTED SCORES
 |
| Modily Weights Order by Al Sort PURE SCORES sext WEIGHTED SCORES 10 SconeProdus SconeProdus< | Modily Weights Order by Al Sert PURE SCORES sest WEIGHTED SCORES 10 ScoreProdu | Modily Weights Order by Al Sert PURE SCORES sest WEIGHTED SCORES 10 ScoreProdu | Modily Weights Order by Al Sort PURE SCORES sest WEIGHTED SCORES 10 ScoreFlexibil ScoreSpace ScoreFlexibil Sco | Modily Weights Order by Al Sort PURE SCORES sest WEIGHTED SCORES 10 ScoreProdul ScoreSpace ScoreProdu ScoreSpace ScoreProdu ScoreSpace ScoreSpace 10 ScoreProdu ScoreSpace ScoreProdu ScoreSpace ScoreProdu ScoreSpace ScoreProdu ScoreSpace 11 11.27 36.26 11.62 24.7 13 19.94 2.32 2.3 32 14.53 15.91 13.62 21.14 15.6 32 2.18 15.9 7.6 4.23 1 | Modily Weights Order by All Sort PURE SCORES sest WEIGHTED SCORES 10 ScoreFredul ScoreSpace ScoreFredul ScoreSpa | Modily Weights Order by All Image: Construction of the state | Modily Weights Order by Al * Sert PURE SCORES sers WEIGHTED SCORES 10 ScoreProdul ScoreFlexibil ScoreSpace ScoreFlexibil ScoreSpace ScoreFlexibil ScoreSpace 20 14.10 11.52 24.7 11.52 23.24 20 14.52 11.52 24.7 11.52 23.24 | Modily Weights Order by All Sort PURE SCORES sest WEIGHTED SCORES 10 ScoreProdue Score/Fiesbil Score/Space ScoreAdapt Score/Total ID Score/Fiesbil Score/Space ScoreAdapt Score/Total 48 8.7 11.27 36.26 11.62 24.7 | Modily Weights Order by All Sort PURE SCORES sest WEIGHTED SCORES ID ScoreProdul ScoreFinabili ScoreSpace ScoreAdapt ScoreTatal ID ScoreProdul ScoreFinabili ScoreSpace ScoreAdapt ScoreTata | Modily Weights
Sort Order by AI P PURE SCORES REST WEIGHTED SCORES ID ScoreProdul ScorePr | Modily Weights
Sert PURE SCORES BEST WEIGHTED SCORES | Modily Weights
Sort Order by All PURE SCORES BEST WEIGHTED SCORES |
| 48 8.7 11.27 36.26 11.82 24.7 33 14.53 15.91 13.82 21.14 15.6 30 22.32 18.67 10.36 21.14 15.14 75 12.48 15.28 11.62 13.6 77 11.47 14.53 7.47 21.14 11.51 46 11.85 11.32 9.72 11.23 10.5
 | 48 8.7 11.27 36.26 11.62 24.7 33 14.53 15.91 13.82 21.14 15.6 20 22.32 18.67 10.36 21.14 15.14
 | 48 8.7 11.27 36.26 11.62 24.7 33 14.53 15.91 13.82 21.14 15.6 20 22.32 18.67 10.36 21.14 15.14 | 48 8.7 11.27 38.28 11.82 24.7 48 1.31 1.13 19.94 2.32 33 14.53 15.91 11.82 21.14 15.6 33 21.18 1.59 7.6 4.23 30 23.92 19.62 19.92 21.44 15.6 33 2.18 1.59 7.6 4.23 10

 | 48 8.7 11.27 36.26 11.62 24.7 48 1.31 1.13 19.94 2.32 23 33 14.53 15.91 13.82 21.14 15.61 33 2.18 1.59 7.6 4.23 | 48 8.7 11.27 36.26 11.62 24.7 48 1.31 1.13 19.94 2.32 2 33 14.53 15.91 13.82 21.14 15.61 33 2.18 1.59 7.6 4.23 | 48 8.7 11.27 36.26 11.62 24.7 48 1.31 1.13 19.94 2.32 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 | 48 8.7 11.27 36.26 11.62 24.7 48 1.31 1.13 19.94 2.32 20 14.62 15.64 15.62 20.14.62 21.9 1.69 7.6 4.23 | 48 8.7 11.27 36.26 11.62 24.7 48 1.31 1.13 19.94 2.32
 | | | D ScowProdu ScowPeeds ScowSpace ScowAdi ScowTetal D ScowProdu ScowPeeds ScowSpace ScowAdapt ScowTetal | ID ScoreProdu ScorePredu ScorePre |
| 33 14.53 15.91 13.82 21.14 15.61 20 22.32 18.67 10.36 21.14 15.61 75 12.48 15.23 11.62 13.66 20 3.35 1.67 5.7 4.23 11 77 11.47 14.53 7.47 21.14 11.51 worst 75 1.77 1.78 1.53 7.88 2.32 11 45 11.85 11.32 9.72 11.23 10.51 worst 46 1.78 1.13 5.36 2.25 11
 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 11 20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 15
 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1 | 33 1453 1591 1382 21.14 156 33 218 159 7.6 4.23

 | 33 1453 1531 1382 21.14 156 33 218 159 7.6 4.23 1 | 33 1453 1591 13.82 21.14 156 33 218 1.59 7.6 4.23 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 | 33 14 E3 1E 91 13 02 31 14 152 32 31 9 |
 | 48 8.7 11.27 36.26 11.62 24.7 48 1.31 1.13 19.94 2.32 | 48 8.7 11.27 36.26 11.62 24.7 48 1.31 1.13 19.94 2.32 | 48 8.7 11.27 36.26 11.62 24.7 48 1.31 1.13 19.94 2.32 | 48 8.7 11.27 36.26 11.62 24.7 48 1.31 1.13 19.94 2.32
 |
| 20 22.32 18.67 10.36 21.14 15.14 75 12.48 15.23 14.32 11.62 13.6 77 11.47 14.53 7.47 21.14 11.51 45 11.86 11.32 9.72 11.23 10.51
 | 20 22 32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 15
 | 20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1 | 30 31 32 30 40 47 40 30 31 44 40 40 44 30 30 30 5 4 67 6.7 4 33 91

 | | | | 23 14 23 12 21 12 02 21 14 12 12 12 12 12 12 12 12 12 12 12 12 12 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23
 | | | | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23
 |
| 75 12.48 15.28 14.32 11.62 13.6 77 11.47 14.53 7.47 21.14 11.51 46 11.85 11.32 9.72 11.23 10.5
 |
 | | 20 22 22 10.01 10.20 21.14 12.14 20 3.23 1.0/ 3.7 4.23 0

 | 20 22 32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1 | 20 22 32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1 | 20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 17 | 30 31 32 40 32 40 30 24 64 45 44 25 44 26 26 6 27 5 2 4 23 5 |
 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 |
 |
| 77 11.47 14.53 7.47 21.14 11.51 WORST 77 1.72 1.45 4.11 4.23 11 46 11.85 11.32 9.72 11.23 10.5 45 1.78 1.13 5.35 2.25 11
 | 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32
 | 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32 | 75 1248 15 29 14 22 11 62 13 6 75 1 87 1 53 7 68 2 32

 | | | | 20 22 22 10.0 10.0 21.14 12.14 20 3.35 1.6/ 5./ 4.23 1 | 20 22 32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1
 | 23 1453 1591 13.82 21.14 15.6 33 218 1.59 7.6 4.23
20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1 | 20 22 32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1
 |
| 46 11.85 11.32 9.72 11.23 10.5 46 1.78 1.13 5.35 2.25
 |
 | | 12 16-12 1240 11-06 11-06 12-07 12-07 1-02 1-06

 | 75 12 48 15 28 14 32 11 82 136 75 1.87 1.53 7.88 2.32 | 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32 | 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32 | 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32 | 20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32
 | 23 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32 | 20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32
 |
|
 | 77 11.47 14.53 7.47 21.14 11.51 wrights 77 1.72 1.45 4.11 4.23 11
 | 77 11.47 14.53 7.47 21.14 11.51 with \$77 1.72 1.45 4.11 4.23 1 | 77 11.47 14.53 7.47 21.14 11.51 whest 77 1.72 1.45 4.11 4.23 1

 | 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32 17.7 11.47 14.53 7.47 21.14 11.51 wtbest 77 1.72 1.45 4.11 4.23 1 | 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32 177 11.47 14.53 7.47 21.14 11.51 writest 77 1.72 1.45 4.11 4.23 11 | 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32 77 11.47 14.53 7.47 21.14 11.51 wmpsr 77 1.72 1.45 4.11 4.23 1 | 20 22.02 10.07 102.00 21.14 15.14 20 5.7 4.23 1 75 12.46 15.23 14.32 11.62 12.6 75 12.4 15.73 1.50 5.7 4.23 1 77 11.47 14.53 7.47 21.14 11.51 wrmeer 77 1.45 4.11 4.23 1 | 20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32 77 11.47 14.53 7.47 21.14 11.51 wmpst 77 1.72 1.45 4.11 4.23 1
 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 20 22.32 18.67 10.36 21.14 15.14 20 23.95 1.867 5.7 4.23 1 75 12.48 15.23 14.32 11.62 13.6 75 1.87 5.7 4.23 1 77 11.47 14.53 7.47 21.14 11.51 wrment 77 1.45 4.11 4.23 1 | 33 14.53 15.91 13.82 21.14 15.6 20 22.32 18.67 10.36 21.14 15.14 75 12.48 15.28 14.32 11.62 13.6 77 11.47 14.53 7.47 21.14 11.51 wrtnest | 33 14.53 15.91 13.82 21.14 15.6 33 218 15.9 7.6 4.23 20 22.32 18.67 10.36 21.14 15.14 20 335 1.87 5.7 4.23 1 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32 77 11.47 14.53 7.47 21.14 11.51 wmpst 77 1.72 1.45 4.11 4.23 1 | 20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1 75 12.48 15.28 14.32 11.62 12.6 75 1.87 1.53 7.88 2.32 77 11.47 14.53 7.47 21.14 11.51 wrth 5.7 1.72 1.45 4.11 4.23 1
 |
| 81 18.64 13.02 8.06 2.11 8.95 81 2.8 1.3 4.43 0.42
 | 77 11.47 14.53 7.47 21.14 11.51 WORST 77 1.72 1.45 4.11 4.23 11 46 11.85 11.32 9.72 11.23 10.5 46 1.78 1.13 5.35 2.25 11
 | 77 11.47 14.53 7.47 21.14 11.51 WORST 77 1.72 1.45 4.11 4.23 1 46 11.85 11.32 9.72 11.23 10.5 46 1.78 1.13 5.35 2.25 | 77 11.47 14.53 7.47 21.14 11.51 worst 77 17.1 1.43 5.35 2.35 46 11.85 11.32 9.72 11.23 10.5 worst 77 1.13 5.35 2.25

 | 75 12.48 15.23 14.32 11.62 13.6 75 1.53 7.88 2.32 77 11.47 14.53 7.47 21.14 11.51 w0est 77 1.72 1.45 4.11 4.23 1 46 11.85 11.32 9.72 11.23 10.5 46 1.78 1.13 5.35 2.25 | 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32 77 11.47 14.53 7.47 21.14 11.51 w0RST 77 1.72 1.45 4.11 4.23 1 46 11.85 11.32 9.72 11.23 10.5 46 1.78 1.13 5.35 2.25 | 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32 77 11.47 14.53 7.47 21.14 11.51 WURST 77 1.72 1.45 4.11 4.23 1 46 11.85 11.32 9.72 11.23 10.5 46 1.78 1.13 5.35 2.25 | 20 22.02 10.07 10.00 21.14 15.14 20 3.13 1.07 57 4.23 1 75 12.48 15.28 14.32 11.62 13.61 57 4.23 1 77 11.47 14.53 7.47 21.14 11.51 worst 77 1.72 1.45 4.11 4.23 1 46 11.85 11.32 9.72 11.23 10.5 worst 77 1.13 5.35 2.25 | 20 22.32 18.67 10.36 21.14 15.14 75 12.48 15.28 14.32 11.62 13.6 77 11.47 14.53 7.47 21.14 11.51 46 11.85 11.32 9.72 11.23 10.5
 | 33 14.53 15.91 13.82 21.14 15.6 20 22.32 18.67 10.36 21.14 15.14 75 12.48 15.28 14.32 11.62 13.6 77 11.47 14.53 7.47 21.14 11.51 46 11.85 11.32 9.72 11.23 10.5 | 33 14.53 15.91 13.82 21.14 15.6 20 22.32 18.67 10.36 21.14 15.14 75 12.48 15.28 14.32 11.62 13.6 77 11.47 14.53 7.47 21.14 11.51 46 11.65 11.32 9.72 11.23 10.5 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 20 22.32 18.67 10.36 21.14 15.14 15.14 15.24 16.77 5.7 4.23 1 77 11.47 14.53 7.47 21.14 11.51 15.77 1.53 7.68 2.32 77 11.47 14.53 7.47 21.14 11.51 wttest 77 1.72 1.45 4.11 4.23 1 46 11.65 11.32 9.72 11.23 10.5 11.13 5.36 2.25 | 20 12.2.32 18.67 10.36 12.1.14 15.14 75 12.48 15.28 14.32 11.62 13.6 77 11.47 14.53 7.47 21.14 11.51 45 11.165 11.32 9.72 11.23 10.55
 |
| 17 11.47 14.53 7.47 21.4 11.51 77 1.72 1.45 4.11 4.23 11 46 11.86 11.32 9.72 11.23 10.5 44 1.73 1.13 5.35 2.26 1
 | 27 40 40 40 00 44 00 44 00 40 00 10 00 0
 | 75 10 40 45 00 44 00 44 00 40 0 | 27 1 22 22 1001 1020 21.09 12.09 20 20 20 20 20 20 20 20 20 20 20 20 20

 | 20 22 52 18.57 10.35 21.14 15.14 20 3.33 1.67 5.7 4.23 1 | 20 22 32 1051 10 35 21.14 15.14 20 3.73 1.67 5.7 4.23 1 | 20 22 32 18.57 10.35 21.14 15.14 20 3.35 1.67 5.7 4.23 1 | |
 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 |
|
 | 77 11 47 14 53 7 47 21 14 11 51 mmm 77 1 72 1 45 4 11 4 23 11
 | 77 11 47 14 53 7 47 21 14 11 51 monter 77 1 72 1 45 4 11 4 23 1 | 77 1147 1453 747 2114 1151 200 77 172 145 411 423 1

 | 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32 177 11.47 14.53 7.47 21.14 11.51 mmm 77 1.72 1.45 4.11 4.23 1 | 75 12.48 15.28 14.32 11.62 13.6 75 1.87 1.53 7.88 2.32 177 11.47 14.53 7.47 21.14 11.51 mmm 77 1.72 1.45 4.11 4.23 1 | 75 1248 1528 1432 11.52 13.6 75 1.87 1.53 7.88 2.32
77 11.47 14.53 7.47 21.14 11.51 77 1.72 1.45 4.11 4.23 1 | 201 22.22 10.97 10.30 [21.19] 10.19 201 3.17 1.60 57 4.23 1 75 12.46 15.28 14.32 11.62 13.6 75 1.87 1.58 2.32 1 77 11.47 14.63 7.47 21.14 11.51 arrays 77 1.45 4.11 4.23 1 | 20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1 75 12.48 15.28 14.32 11.82 13.6 75 1.87 1.53 7.88 2.32 77 11.47 14.63 7.47 21.14 11.51 77 1.72 1.45 4.11 4.23 1
 | 33 14.53 15.91 13.82 27.14 15.6 33 2.18 1.59 7.6 4.23 20 22.32 18.67 10.36 21.14 15.14 12.14 15.14 14.32 1 75 12.48 15.28 14.32 11.62 13.6 27 1.87 1.53 7.68 2.32 1 77 11.47 14.653 7.47 21.14 11.51 14.51 4.11 4.23 1 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.67 5.7 4.23 1 75 12.48 15.23 11.62 13.6 7 1.53 7.68 2.32 77 11.47 14.53 7.47 21.14 15.19 77 1.53 7.68 2.32 | 33 14.53 15.91 13.82 21.14 15.6 33 2.18 1.59 7.6 4.23 20 22.32 18.67 10.36 21.14 15.16 20 3.35 1.87 5.7 4.23 1 75 12.48 15.28 11.62 13.6 13.67 5.7 4.23 1 77 11.47 14.53 7.47 21.14 11.51 7.7 1.53 7.88 2.32 | 20 22.32 18.67 10.36 21.14 15.14 20 3.35 1.87 5.7 4.23 1 75 12.48 15.28 14.32 11.62 13.61 75 1.87 1.53 7.88 2.32 1 77 11.47 14.53 7.47 21.14 11.51 11.61 77 1.87 1.53 7.88 2.32
 |

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.

n 12	d Can		i *? key Edit	Del	da.	Real Prot	Prev	aus	Next L		v) ansi	Reque	ry
1. 11		Ϋ́	Sort Result	View	Results	Search	1			Cost Analysis	Power	Calculat	ion Sen
	S	enakiv	iy .	Υ	Top A	Ing Critical	Υ		Threshold)	Тор М	lost Critical
1	01 ←	\rightarrow	ID2 ID1 a	nd ID.2 www	erses their	rankings]		New	r Weights			
	ID1	ID2	Productivity	Flexibility	Space	Adaptability	ID1	102	Info	Productivity	Flexibility	Space	Adaptability
	48	33	·1046.67	-1978.26	73.76	-476.44	48	33	Productivity	66.93	3.89	21.4	7.78
	-40	20	-468.94	-1291.09	67.15	-500.52	48	30	Flexibility	5.04	63.78	18.47	6.72
	-43	75	-1983.46	-2775	92.06	0	48	33	Space	25.24	16.83	24.29	33.65
	48	77	-3219.22	-4121.88	83.34	-690.58	48	33	Adaptability	7.68	5.12	28.16	59.03
	48	46	-3023.29	0	97.34	0	48	20	Productivity	50.1	5.87	32.29	11.74
	43	81	-1057.75	-5254.71	0	0	48	20	Flexibility	6.54	60.73	24	8.73
							-40	20	Space	23.78	15.06	20.65	31.71
Π.	_	_					48	20	Adaptability	7.5	5	27.49	60.02
-							48	75	Productivity	78.62	2.52	13.84	5.03
						-	48	75	Flexibility	3.97	76.16	14.57	5.3
							49	75	Space	30.38	20.25	8.85	40.51
							-48	77	Productivity	85.42	1.72	9.44	3.43
						-	48	77	Flexibility	2.93	82.43	10.74	3.9
						-	48	77	Space	27.69	18.46	16.92	36.92
						-	48	77	Adaptability	6.3	4.2	23.1	55.4
						-	40	46	Productivity	94.64	1.01	9.94	3.61
						-	48	48	Space	32.29	21.52	3.14	43.05
						-	48	81	Productivity	67.14	3.87	21.26	7.73
						-	48	B1	Flexibility	1.45	91.23	5.36	1.95

Figure 4.22 Percent top sensitivity analyses for Company T

File Options	Help										
Con End Con	N	1 47 W Edit	00	eta I	C Prot	Previous	Next	Last	k7 Cancel	Requi	ny Ed
	Υī,	Sort Result	View	Resulto	Search	<u> </u>	- Y	Cost Analysi	0 Pove	er Calcula	tion Sensitiv
4			<u> </u>	T 4	en Critical	<u> </u>	Theart	oH	γ	Tonk	In all Collins I
D1 6	\rightarrow 1	р D2 ID1 и	nd ID2 nev	eroez their i	anking:	1	N	ew Weigh			fest Callodi
		p D2 ID1 a Productivity	nd ID2 revo	eroes their r	anking:		N 12 Tinto	ew Weigh	ts Feability	Soace	Adversality
	→ I 102 33	Productivity	nd ID2 nevr	space	ankings Adaptability	101 E	N 2 Into 3 Space	ew Weight	ta Flesibility	Space 60.61	Adaptability 6.22
101 ÷	→ I 102 33 81	Productivity 0 0	nd ID2 revi Flexibility 0 0	space	Adaptability	101 ID 20 32 20 7	N 2 Into 3 Space 5 Space	ew Weigh Poductvity 22.8 13.15	ts Flesibility 10:37 8.7	5pace 60.61 66.93	Adaptability 6.22 5.22
101 ÷	> 1 102 33 81 77	Productivity 0 0 0	nd ID2 nevr	space -28223.81 0	Adaptability	101 10 20 33 20 79 20 44	N 2 Into 3 Space 5 Space 8 Space	ew Weight Productivity 22.8 19.15 40.23	ts Fleability 10.37 8.7 18.29	Space 60.61 66.93 30.51	Adaptability 6.22 5.22 10.97
101 20 20 20 20 20 20 20	> 1 102 33 81 77 75	Productivity 0 0 0 0	Flexibility 0 0 0 0	1 ap x aross their 1 -2823.81 0 0 -3745.37	Adaptability	101 10 20 32 20 77 20 4	N 2 Into 3 Space 5 Space 8 Space	ew Weight Productivity 22.8 13.15 43.23	ts Flexibility 10.37 8.7 18.29	5pace 60.61 66.93 30.51	Adigitability 6.22 5.22 10.97
101 ÷	> 1 102 33 81 77 75 46	Productivity 0 0 0 0 0 0	Flexibility 0 0 0 0 0	Space -2823.81 0 -3745.37 0	Archantability	101 ID 20 33 20 77 20 4	N 2 Into 3 Space 5 Space 8 Space	ew Weigh Poducivity 22.8 19.15 40.23	ts Flexibility 10.37 8.7 18.29	5pace 60.61 66.93 30.51	Adigstability 6.22 5.22 10.37

Figure 4.23 Percent top sensitivity analysis for Company X

Ne Op	ptions	Help	IN SULT	un v 3.3 -	- Envirende	ne Plachase Sei	ection	u.						
Carl I			New R		V	A Find	P	¢ eviou	Next	Lest	K3 Gencel	Req.	ary I	X
		Υ	Sot Result	Vie	w Results	Search	Υ		Y	Cost Analys	ie Pov	ver Calcui	ation Sens	itivi
_	1	Servait	ivity	1	Top A	ny Ditical	Υ		Theest	valid	<u> </u>	Top	Most Critical	
		_		1.00.0										
	ID1 e		Productivity	and ID2 re	Spece	rankings Adaptability		102	Itilo	Productivity	vts Findbiltz	Space	Adaptability	
	ID1 (1D2 49	Productivity	end ID2 re Flexibility 0	Spece 	Adaptability	ID1	10.2	Info Productivity	Productivity 72.23	Rexbility 6.41	Space 214	Adaptability 19.22	
	1D1 (1D2 43 46	ID2 ID1 Productivity 0 0	Flexibility 0 0	Space -814.27 -13090.19	Adaptability 0 0	1D1 81 81	102 20 20	Info Productivity Fleability	Productivity 72.23 18.7	Hexbilly 5.41 54.59	Space 2.14 2.67	Adaptability 19.23 24.04	
	ID1 (ID1 81 61 81	102 48 46 75	ID2 ID1 Productivity 0 0 0	Flexibility 0 0 -3709.2	5pace 614.27 -13090.19 -3941.02	Adaptability 0 0 0	1D1 81 81 81	102 20 20 20	Info Productivity Fleability Space	Productivity 72.23 18.7 11.44	Heodolity 6.41 54.53 4.9	Space 2.14 2.67 68.94	Adaptability 19.23 24.04 14.71	
	1D1 (1D1 81 81 81 01	1D2 48 46 75 20	102 101 Productivity 0 0 0 -382 90	Flexibility 0 0 -3709.2 -511.23	Space 914.27 -13090.19 -3941.02 -4117.00	Adaptability 0 0 0 0 0 0 0	11D1 81 81 81	1D2 20 20 20 20	N Productivity Pleability Space Adaptability	Productivity 72.23 18.7 11.44 90.66	Flexibility 6.41 54.53 4.9 21.71	Space 2.14 2.67 68.94 7.24	Adaptability 19.23 24.04 14.71 20.4	
	1D1 4 81 81 81 81 81 81	48 46 75 20 33	02 101 Productivity 0 0 0 -382.50 0	end ID2 m Flexibility 0 -3709.2 -501.23 -1795.63	Space 614.27 -13090.19 -3941.02 -4117.00 -2724.41	Adaptability 0 0 0 0 0 0 0 0 0 0 0	1D1 81 81 91 01 81	102 20 20 20 20 20 33	Info Productivity Pleability Space Adaptability Fleability	Productivity 72.23 18.7 11.44 50.65 9.48	Heshilty 6.41 54.55 4.9 21.71 76.99	Space 2.14 2.67 68.94 7.24 1.35	Adaptability 18.23 24.04 14.71 20.4 12.18	
	101 (81 81 81 81 81 81 81 81 81	48 46 75 20 33 77	102 101 Productivity 0 0 -382 50 0 0 0	end ID2 m Flexibility 0 -3709.2 -501.23 -1795.63 -4130.85	Space 814.27 -13090.19 -3941.02 -4117.00 -2724.41 D	Adaptability 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	1D1 81 81 81 81 81 81	102 20 20 20 20 33 33	Info Productivity Flexibility Space Adaptability Flexibility Space	Productivity 72.23 18.7 11.44 50.95 9.48 14.82	Headbilly 5.41 54.53 4.9 21.71 76.99 5.35	Space 2.14 2.67 68.94 7.24 1.35 59.78	Adaptability 18.23 24.04 14.71 20.4 12.18 18.05	
	101 (81 81 81 81 81 81 81 81 81	48 46 75 20 33 77	ID2 ID1 Productivity 0 0 0 -382.98 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	end ID2 or 0 0 -3709.2 -501.23 -1795.63 -4130.85	Space 814.27 -13090.19 -3941.02 -4117.00 -2724.41 D	Adaptability 0 0 0 0 0 0 0 0 0 0	1D1 81 81 81 81 81 81 81	102 20 20 20 20 33 33 33 77	N Productivity Fleability Space Adaptability Fleability Space Fleability	Productivity 72.23 18.7 11.44 50.66 9.48 14.82 4.85	Heodbilly 6.41 54.53 4.9 21.71 76.99 6.25 88.13	Space 2.14 2.67 68.94 7.24 1.35 59.78 0.69	Adaptability 18.23 24.04 14.71 20.4 12.18 18.05 6.25	
	101 (101 81 81 81 81 81 81 81 81 81	48 48 46 75 20 33 77	ID2 ID1 Productivity 0 0 0 -302 50 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	end ID2 m 0 0 -3709.2 -501.23 -1795.63 -4130.95	Space 814.27 -13090.19 3941.02 -4117.00 2724.41 0	Adaptability 0 0 60.60 0 0 0 0	1D1 81 81 81 81 81 81 81 81	102 20 20 20 20 33 33 77 48	N Productivity Fleability Space Adaptability Space Fleability Space	Productivity 72.23 18.7 11.44 50.66 9.48 14.82 4.86 24.87	rts Flexibility 54.53 4.9 21.71 76.99 5.35 88.19 10.66	Space 2.14 2.67 68.94 7.24 1.35 59.78 0.69 32.49	Adaptability 18.23 24.04 14.71 20.4 12.18 18.05 6.25 31.98	
	ID1 (81 81 81 81 81 81 81	48 48 75 20 33 77	ID2 ID1 Productivity 0 0 0 -302.50 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	and ID2 m Flexibility 0 -3709.2 -501.23 -1795.63 -4130.95	Space 4714.27 -13090.19 -3941.02 -4117.00 -2724.41 0	Adaptability 0 0 0 0 0 0 0 0 0 0	101 81 81 81 81 81 81 81 81	102 20 20 20 20 33 33 33 33 77 48 48 46	N Productivity Fleability Space Adaptability Fleability Space Fleability Space Space	Productivity 72.23 18.7 11.44 90.66 9.48 14.82 4.86 24.87 4.64	rts Flexibility 6.41 54.53 4.9 21.71 76.99 6.35 88.19 10.66 1.90	Space 214 2.67 68.94 7.24 1.35 59.78 0.69 32.49 87.41	Adaptability 19.23 24.04 14.71 20.4 12.18 13.05 6.25 31.06 5.96	
	ID1 (81 81 81 81 81 81 81	48 46 75 20 33 77	ID2 ID1 Productivity 0 0 -302.90 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	and ID2 te Flexibility 0 -3709.2 -501.23 -1795.63 -4130.95	Space 4714.27 -13090.19 -3941.02 -4117.00 -2724.41 D	Adaptability 0 0 0 0 0 0 0 0 0 0	101 81 81 81 81 81 81 81 81 81 81	102 20 20 20 33 33 77 48 46 75	N Productivity Plaubility Space Adaptability Space Flaubility Space Space Space Space Flaubility	Productivity 72.23 18.7 11.44 90.66 9.48 14.82 4.88 24.97 4.64 5.33	NS Flexibility 6.41 54.53 4.9 21.71 76.99 6.75 88.19 10.66 1.99 87.05	214 2.67 68.94 7.24 1.35 59.78 0.69 32.49 87.41 0.76	Adaptability 19.23 24.04 14.71 20.4 12.18 19.05 6.25 31.98 5.96 6.85	

Figure 4.24 Percent top sensitivity analysis for Company Y

File Option	ns Help											, i
Con Etd	Con	New B		teter j	a Crost	Pri	¢	Next	1 Last	NT Carcel	Reque	ny D
	n	Sof Result	View	Repuls	Search	Υ			Cost Analys	e Pove	er Calcula	tion Sensiti
	Sensi	inty	\neg	Top Ar	y Dillical	m		The	rhokd	<u></u>	Top N	fast Critical
	D1 103	2 Productivi	y Flexibility	Space	Adaptability	ID1	102	Into	Productivity	Reability	Space	Adaptability
	D1 ID3	2 Productivi	ly Flexibility	Space	Adaptability	ID1	102	Info	Productivity	Flexibility	Space	Adaptability
2	20 33	0	0	-647.71	0	20	33	Space	9.1	30.35	45.38	15.17
	0 77	0	0	0	0	- 40	10	Space	5.45	21.53	61.24	18.77
	20 /5	0	0	-1321.83	0	20	46	Space	12.36	41.2	12.05	20.6
	00 49 00 40	0	0	-914.13	0							
	20 45	0	0	0	0							

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.

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	Р	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	Т	10	years
MARR	i	15	%
Tax Rate	r	33	%
Annual Production	X	?	parts

Table 4.2Notation and data for the analysis

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 $12000 \in$. In this process rotary table option eliminates the need of an additional fixture at a cost of $500 \in$ 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 multicriteria 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 Manufacturing*, 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



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. <u>cagdasarslan@su.sabanciuniv.edu</u>

* 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 <u>AS</u> <u>SOON AS POSSIBLE (PREFERABLY NOT LATER THAN 10 DAYS) TO THE</u> FOLLOWING E-MAIL ADDRESS: <u>cagdasarslan@su.sabanciuniv.edu</u>

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:
- 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?

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.
- 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.

Please select one

Please specify if different :

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



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 :

2. Total number of employees:

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	Weight
	1 st Choice	2 nd 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 1 st Choice	Weight 2 nd 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 Elovibility	Weight	Weight	
2. Flexibility		1 st Choice	2 nd Choice
1. L	J Axis	%0	%0
2. A	Articulated Axis	%0	%0
3. N	lo of Pallets	%0	%0
4. R	Rotary Table	%0	%0
5. T	otal # of tools	%0	%0
6. H	lead Changer	%0	%0
7. N	Iain Spindle Power	%0	%0
8. Ir	ndex Table	%0	%0
9. D	Dual Axis Rotary Table	%0	%0
10. N	/ax. Speed	%0	%0
11.C	CNC or not?	%0	%0
12.C	CNC Control Type	%0	%0
13.		%0	%0
14.		%0	%0
	Total weight should give %100	%100	%100

4. Adaptability	Weight	Weight
	1 st Choice	2 nd 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

Total weight should	l give %100
---------------------	-------------

%100

5. Precision	Weight	Weight
	1 st Choice	2 nd 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	Weight
	1 st Choice	2 nd 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

0 Maintonance and Service	Weight	Weight
	1 st Choice	2 nd 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