International Journal of Production Research

ISSN: 0020-7543 (Print) 1366-588X (Online) Journal homepage: https://www.tandfonline.com/loi/tprs20

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To cite this article: Z. Ayağ (2007) A hybrid approach to machine-tool selection through AHP and simulation, International Journal of Production Research, 45:9, 2029-2050, DOI: 10.1080/00207540600724856

To link to this article: https://doi.org/10.1080/00207540600724856

Published online: 16 Jul 2007.

International Journal of Production Research,
Vol. 45, No. 9, 1 May 2007, 2029–2050

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A hybrid approach to machine-tool selection through AHP and simulation

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(*Revision received January 2006*)

The selection process of a machine tool has been a critical issue for companies for years, because the improper selection of a machine tool might cause many problems having a negative effect on productivity, precision, flexibility, and a company's responsive manufacturing capabilities. Therefore, in this paper, to determine the best machine tool satisfying the needs and expectations of a manufacturing organization among a set of possible alternatives in the market, a hybrid approach is proposed, which integrates an analytic hierarchy process (AHP) with simulation techniques. The AHP as one of the most commonly used multiple criteria decision-making methods is used to narrow down all possible machine tool alternatives in the market by eliminating those whose scores (or weights) are smaller than a determined value obtained under certain circumstances. Then, a simulation generator is used first to automatically model a manufacturing organization, where the ultimate machine tool will be used, and second to try each alternative remaining from the AHP as a scenario on the generated model. Finally, the final alternative is selected by using the unit investment cost ratio, which is calculated by dividing the investment cost per year of each alternative by the additional number of produced units obtained from the simulation experiment of the relevant alternative.

Keywords: Machine-tool selection; Multiple-criteria decision-making; Analytic hierarchy process; Discrete-event simulation

1. Introduction

A major cost component during the initiation of a manufacturing plant is the capital investment in machinery and equipment. These investment decisions are critical to the profitability of the facility during its early stages of operation. A major decision involves the types and numbers of machines purchased. The types of machines selected depend on processing requirements of jobs that need to be performed. The number of machines of each type needed mainly depends on factors including the cost of machines, expected demand, and processing time. Therefore, a proper machine-tool selection has been a very important issue for manufacturing companies due to the fact that an improperly selected machine tool can have a negative effect on the overall performance of a manufacturing system. In addition, the outputs of

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International Journal of Production Research
ISSN 0020–7543 print/ISSN 1366–588X online © 2007 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/00207540600724856

a manufacturing system (i.e. the rate, quality, and cost) mostly depend on properly selected and implemented machine tools. On the other hand, the selection of a new machine tool can be a time-consuming and difficult process due to the fact that it requires advanced knowledge and experience of machine tools, manufacturing methods, financial evaluation, and so on. This can be a very hard task for engineers and managers in a company, so for a proper and effective evaluation, a decision-maker may need a large amount of data to be analysed and many factors to be considered. The decision-maker should be an expert or at least should be very familiar with the specifications of a machine tool to select the most suitable one. However, a survey conducted by Gerrard (1988a) reveals that the role of engineering staff in authorization for final selection is 6%; the rest belongs to middle and upper management (94%). Gerrard also indicated the need for a simplified and practical approach for the machine-tool selection process.

In this study, first the analytic hierarchy process (AHP) method developed by Saaty (1981) is selected: this is one of the well-known multiple-criteria decision-making (MCDM) methods, because the AHP consists of a systematic approach based on breaking the decision problem into a hierarchy of interrelated elements. The evaluation of selection attributes is done using a scaling system showing that each criterion is related with another. This scaling process is then converted to priority values to compare alternatives. It is a very useful tool to define the problem structure. The main advantages of AHP are the relative ease in handling multiple criteria and the fact that it can effectively handle both qualitative and quantitative data. The method also elicits preference information from the decision-makers in a way that they find easy to understand (Lootsma 1997). Second, the simulation technique is used because it is a powerful tool with which to model manufacturing systems. It is becoming one of the most commonly used methods, while state-of-art simulation packages with outstanding graphics capabilities in parallel with computer technology are being developed. As a further step, many simulation generators have been developed to facilitate the modelling efforts which take too much time. A simulation generator is an interactive software tool that translates the logic of a model described in a relatively general symbolism into the code of a simulation language and so enables a computer to mimic model behaviour. These are sometimes referred to as data-driven simulators which do not require any formal programming by the analyst.

In this paper, to determine the ultimate machine tool meeting the needs and expectations of a manufacturing organization among a set of possible alternatives in the market, a hybrid approach is proposed, which integrates the analytic hierarchy process (AHP) with simulation techniques. The AHP is used to narrow down all possible machine-tool alternatives on the market by eliminating those whose scores (or weights) are smaller than a determined value obtained under certain circumstances. Then, a simulation generator is used, first to automatically model a manufacturing organization, where the ultimate machine tool will be used, and second to try each alternative remaining from the AHP as a scenario on the generated model. Finally, the final alternative is selected by using the unit investment cost (UIC) ratio, which is calculated by dividing the investment cost per year of each alternative by the additional number of the produced units obtained from the simulation experiment of the relevant alternative.

In the final section, a case study is given to show the applicability of the approach on a real-life manufacturing organization of a mid-sized company, which designs and manufactures all kinds of cutting tools for many sectors in Turkey.

2. Related research

A decision is a choice made from two or more alternatives under certain criteria. The decision-making is a process of sufficiently reducing uncertainty and doubt about alternatives to allow a reasonable choice to be made among them. In the literature, researchers have studied different decision-making problems using various decision-making methods such as AHP, fuzzy MCDM, linear, 0–1 integer programming models and goal programming, and so on.

In this study, the AHP, as one of the well-known MCDM methods, is selected, because it has been widely used for MCDM selection problems in previous studies (i.e. Zahedı 1986, Ayağ 2002, 2005a, b, Scott 2002) since it was first introduced by Saaty (1981). In view of the significant number of applications it has already been developed in a similar context (Cagno *et al.* 1997). In the AHP, a multi-dimensional scaling problem is transformed in a one-dimensional scaling problem by using the AHP (Saaty 1999).

Next, several outstanding studies regarding the machine-tool selection problem are presented: Tabucanon *et al.* (1994) developed a decision support framework designed to aid decision-makers in selecting the most appropriate machines for flexible manufacturing systems (FMS). They first narrowed down all possible configurations using the AHP, called the pre-screening stage, and second used a goal-programming model to select the best machine tool. Gerrard (1988b) proposed a step-by-step methodology for the selection and introduction of new machine tools. Lin and Yang (1994) developed a model for the most suitable machine selection from a range of machines available for the manufacture of particular part types using the AHP method. Yurdakul (2004) presented a model which links machine alternatives to manufacturing strategy for machine-tool selection. In this study, the evaluation of investment in machine tools can model and quantify strategic considerations by using the AHP method. Arslan *et al.* (2004) proposed a multi-criteria weighted average (MCWA) method for machine-tool selection. They classified all of the machine tools in the market to create a database so that decision attributes can be easily determined for use in MCWA. Haddock and Hartshorn (1989) presented a decision-support system to match part characteristics to machine specifications by taking several attributes into account, such as processing time and cost, machine availability, and their location. Gopalakrishnan *et al.* (2004) described the design and development of a system for the selection and construction of vertical and horizontal machining-centre packages with a base machine and options format subject to budgetary constraints. Chan *et al.* (2001) suggested an integrated approach using an expert system with AHP for the design of the material-handling equipment-selection problem. Gındy and Ratchev (1998) proposed an integrated framework for selection of machining equipment in CIM, while Goh *et al.* (1995) presented a revised weighted sum decision model for robot selection. Oeltjenbruns *et al.* (1995) investigate the compatibility of AHP to strategic planning in manufacturing. The objective is to develop and explore different planning alternatives ranging from extending the life of existing machinery to total replacement with a new manufacturing system and to evaluate these alternatives through economical and technological criteria. Wang *et al.* (2000) suggest a fuzzy multiple-attribute decision-making model to assist the decision-maker in dealing with the machine selection problem for FMS.

In addition, in this study, the simulation technique is used because it has been widely used in solving problems in manufacturing systems. A great number of simulation studies have been done so far, while new simulation software with outstanding graphics capabilities in parallel with computer technology are developed. If summarized, some of these studies, (e.g. Aytug and Dogan 1998) stated that companies that are looking at methods to increase productivity and quality, and reduce costs, often find simulation studies inexpensive insurance against costly mistakes. O'Keefe and Haddock (1991) observed that simulation is now viewed as a tool that can be used directly by production and industrial engineers, and does not necessarily require specialists from operations research and computer programmers. The main trend in manufacturing simulation is the development of tools to deal with specific types of manufacturing systems, such as FMS or common sub-sets of manufacturing systems. The limited domain of these tools means that they can be data-driven. All they require is data that specify the components of the model, rather than program code that specifies the relationships between the components in the model. Aytug and Dogan (1998) also define a simulation generator as an 'interactive software tool that translates the logic of a model described in a relatively general symbolism into the code of a simulation language and so enables a computer to mimic model behaviour'. Simulation generators are sometimes referred to as data-driven simulators which do not require any formal programming by the analyst. They also define a data-driven generic simulation model as 'one which is designed to be applied to a range of systems with structural similarities'. Schroer (1989) presented a structured approach to modelling manufacturing systems. This structured approach is accomplished through a simulation assistant consisting of a set of pre-defined General Purpose System Simulator (GPSS) simulation macros, a user interface, and an automatic code generator.

In the literature, to the best of my knowledge, a few applications of the AHP and simulation together have been introduced to various MCDM problems. For example, Kivijarvi and Tuominen (1999) summarized studies in integrating AHP to the dynamic simulation of business systems. Ayağ (2002) developed an AHP-based simulation model for implementation and analysis of computer-aided systems (CAx). Levary and Wan (1999) developed a methodology using AHP and simulation for ranking entry mode alternatives encountered by individual companies considering foreign direct assessment. Chan *et al.* (2000) developed an integrated approach to develop intelligent decision-support tools to aid the design of FMS, which uses simulation and AHP together. Chan and Abhary (1996) presented an integrated approach to design and evaluate automated cellular manufacturing systems with simulation modelling and an AHP approach with a case study. Shang and Sueyoshi (1995) proposed a unified framework using AHP and simulation in order to facilitate decision-making in the design and planning of the most appropriate FMS for a manufacturing organization. Badiru *et al.* (1993) described a simulation-based decision-support system for AHP for hierarchical dynamic decision-making. Ayağ (2005a) used an integrated approach to evaluate concept alternatives in a new product-development environment through the AHP and simulation, and also used a fuzzy AHP-based simulation approach for solving the same problem (Ayağ 2005b).

3. Proposed approach

In this study, a hybrid approach, where the AHP and simulation techniques are used together, is proposed for the machine-tool selection problem. Figure 1 shows this approach step by step.

Both the AHP and simulation methods have fairly time-consuming steps, especially if they are carried out manually. For the AHP, as the numbers of attributes and alternatives increase, so the size of the problem naturally increases (e.g. an evaluation matrix with a great number of columns and lines). This entails a lengthy and laborious calculation process. Also, for a simulation study, building a model of manufacturing system manually takes considerable time and effort. To facilitate these efforts for both techniques, computer software was developed to make the process easier and quicker for the user. This software performs all the required and time-consuming calculations of the AHP automatically and models a whole manufacturing system of a company by using a simulation generator. The generator writes the required files automatically for the target simulation language, SIMAN, one of the most commonly used languages in simulation studies. It also allows the user, who does not have deep experience or knowledge of simulation, modelling, and computer programming, to understand the results of simulation experiments.

This software has three different modules:

1. the *user-interface module* connected to the user bi-directionally, allowing the user to carry out the AHP and to construct the model and experimental files for the SIMAN simulation language;
2. the *AHP module*; and
3. the *model and experimental file generator module*.

With the user-interface part, the user only enters all the requested data for the study through a data-driven interactive tool in a user-friendly environment after reading the instructions given in detail on the screen. These modules are given in figure 2. Next, this hybrid approach is presented step by step in more detail.

3.1 *Data acquisition and entry*

In this section, first, a related part of manufacturing organization to which the final alternative (or machine tool) will be adapted should be analysed in more detail, to provide all the required data for the user who enters them into a simulation generator (which automatically models the system under certain assumptions). The data (i.e. route matrix, set-up times, process times, scrap, and rework rates) for use in simulation experiments for each machine-tool alternative can be easily obtained from either the vendor or the manufacturer, or experienced operators working on a similar machine tool.

Second, a list of alternatives and attributes should be prepared by taking into account the ideas of everyone who will be involved in running and maintaining

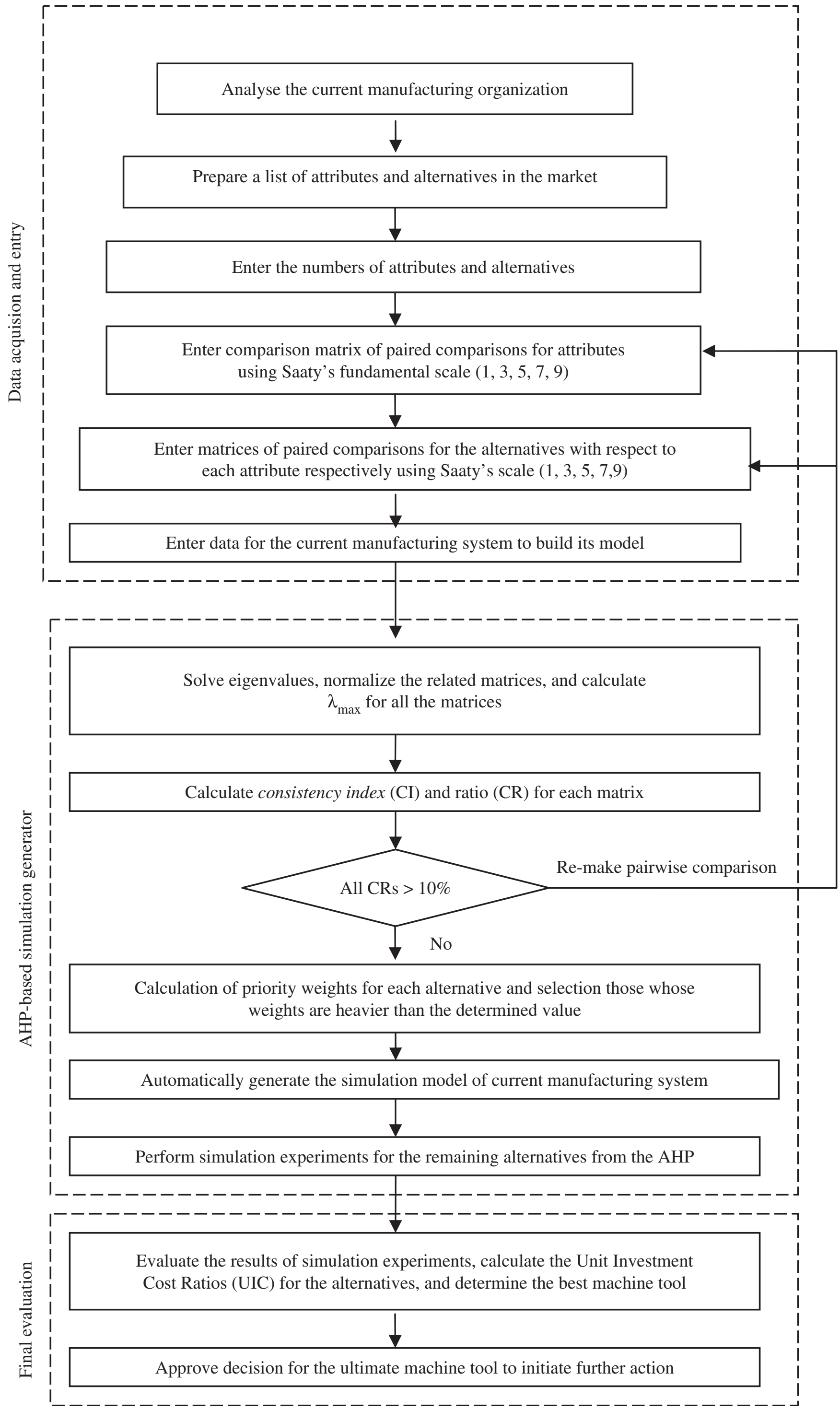

Figure 1. Hybrid approach for the machine-tool selection problem.

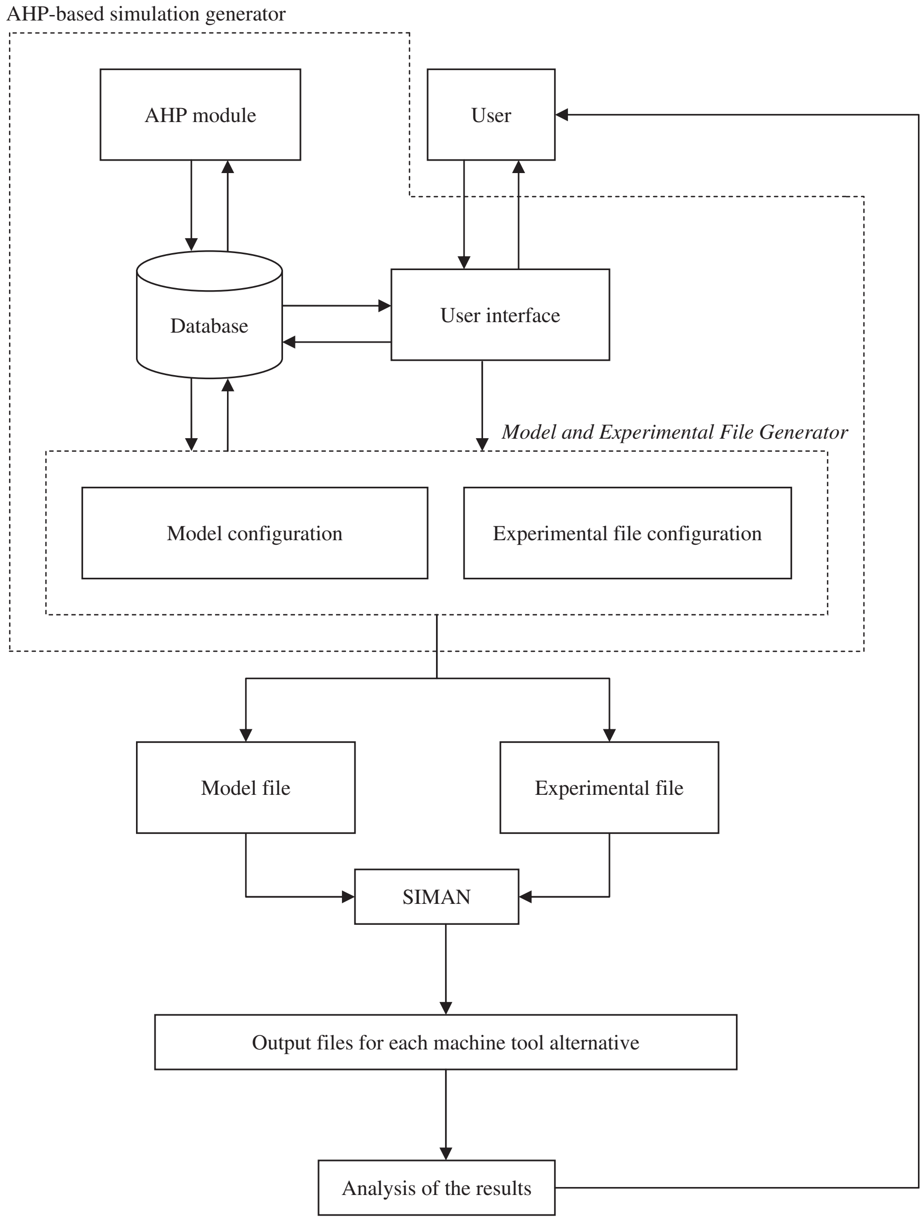

Figure 2. AHP-integrated simulation analysis with a simulation generator.

a machine tool. Shop supervisors, manufacturing engineers, machine operators, setup people and maintenance staff should participate in the development of this list, which may include: (1) the size of the working 'envelope' (depending on the type of machine, this may include characteristics such as table size, tool clearance, chuck size, and tool swing); (2) the tool capacity; (3) the type of tool holders used; (4) the machine horsepower (for cutting force); (5) the type of machine control;

(6) the compatibility with existing CAM software (or programs already written); and (7) the number of available machining axes (generally between three and five). Thus, most attributes used in evaluating machine-tool alternatives depend on the number of machine-tool properties (general, spindle, tooling, work support axis, and physical). For example, productivity is a function of spindle speed and power, maximum cutting feed, rapid traverse speed, etc. Furthermore, flexibility depends on the speed range, number of axes, number of pallets, etc. Adaptation is the degree of a machine tool's ability to fit an 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.

3.2 *AHP-based simulation generator*

Here, the AHP method together with an integrated simulation generator is employed as a multiple-criteria evaluation approach for a machine-tool selection problem. The AHP breaks down the complex structure of the decision process to a hierarchical sequence to determine the relative importance of each alternative through pairwise comparisons, while the simulation technique is used to measure the benefits of each selected alternative from the AHP on the generated model of a real-life manufacturing system of a company. This section brings two popular techniques together, AHP and simulation, to determine the best machine tool satisfying the needs and expectations of a manufacturing organization.

3.2.1 AHP method. This method was developed by Saaty (1981) and consists of a systematic approach based on breaking down the decision problem into a hierarchy of interrelated elements. The evaluation of selection attributes is done using a scaling system showing that each criterion is related with another. This scaling process is then converted to priority values to compare alternatives. Table 1 shows this nine-point scale scheme.

Using the AHP method in the MCDM process, one has to be aware that the result obtained allows compensatory rules. This means that a bad performance of a certain criterion can be completely compensated by a good performance of another criterion. In the AHP, the alternatives that are deficient with respect to one or more objectives can be compensated by their performance with respect to other objectives. So the AHP model gives the best choice of alternatives compared, which are the acceptable or passing grade performance with the actual performance, means allowing compensation of bad performance indicators by good indicators. So, the AHP is a popular method for tackling multicriteria analysis

Table 1. Fundamental scale used in a pairwise comparison (Saaty 1989).

1	Equal importance for both elements compared
3	Element A is moderately important compared with Element B
5	Element A is strongly important compared with Element B
7	Element A has demonstrated importance compared with Element B
9	Element A is extremely important compared with Element B

problems involving qualitative data and has been applied successfully to many actual decision situations.

The steps of the AHP method are as follows:

Step 1: Define the problem and determine its goal.

Step 2: Structure the hierarchy from the top (the objectives from a decision-maker's viewpoint) through the intermediate levels (criteria on which subsequent levels depend) to the lowest level which usually contains the list of alternatives.

Step 3: Construct a set of pairwise comparison matrices (size $n \times n$) for each of the lower levels with one matrix for each element in the level immediately above by using the relative scale measurement. The pairwise comparisons are done in terms of which element dominates the other.

Step 4: There are $n(n-1)$ judgements required to develop the set of matrices in Step 3. Reciprocals are automatically assigned in each pairwise comparison.

Step 5: Hierarchical synthesis is now used to weight the eigenvectors by the weights of the criteria, and the sum is taken over all weighted eigenvector entries corresponding to those in the next lower level of the hierarchy.

Step 6: Having made all pairwise comparisons, the consistency is determined by using the eigenvalue $\lambda_{\max}$, to calculate the consistency index, CI, as follows:

$$\mathrm{CI} = \frac{(\lambda_{\max} - n)}{n - 1}, \tag{1}$$

where n is the matrix size. Judgement consistency can be checked by taking the consistency ratio (CR) of CI with the appropriate value.

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}. \tag{2}$$

The CR is acceptable, if it does not exceed 10%. If it is more, the judgement matrix is inconsistent. To obtain a consistent matrix, judgements should be reviewed and improved. RI is the average index for randomly generated weights (Saaty 1981). Steps 3–6 are performed for all levels in the hierarchy.

The priority weight of each alternative can be obtained by multiplying the matrix of evaluation ratings by the vector of attribute weights and summing over all attributes. Expressed in conventional mathematical notation (Saaty 1981):

$$\text{Weighted evaluation for alternative: } k = \sum_{i=1}^{t} (\text{attribute weight}_i \times \text{evaluation rating}_{ik}) \tag{3}$$

for $i = 1, 2, \ldots, t$ (t = total number of attributes).

After calculating the weight of each alternative, the overall consistency index is calculated to make sure that it is smaller than 10% for consistency on judgements. After the AHP, the alternatives in the list, whose weights are smaller than a determined value, are eliminated, and the remainder are considered for further analysis in the detailed simulation study. Determination of the value depends on several parameters (i.e. the number of attributes, the AHP score). For this study, a scale system is assumed to determine this value as follows: (1) if the number of alternatives is between two and six, there is no need to use a constant value and no need to reduce alternatives; (2) if the number of alternatives is between seven and 12, discard the alternatives that have scores less than 0.10; (3) if the number of alternatives is between 13 and 24, discard the alternatives that have scores less than 0.05.

3.2.2 Simulation generator. In this section, a simulation generator based on the AHP is developed to analyse the remaining alternatives from the AHP after eliminating those whose weights (or scores) are smaller than a determined value as explained above. For this purpose, the selected alternatives are tried as scenarios respectively on an automatically generated model of a real-life manufacturing system to measure their benefits for the entire system.

To model a whole system, in figure 3, a typical *operation-centre structure* is defined as a cornerstone of a typical manufacturing system. An operation-centre as a member of an *operation-centre group* could be a machining, assembling, or testing centre, etc. (the main functions of a manufacturing system). In addition, the route matrices of existing products are used to define the priorities among the operation-centres. It can be assumed that a manufacturing organization consists of the operation-centre groups, and their operation-centres with input and output values and the tasks carried out by these centres. In table 2, the notations used in this study are presented.

All required data for building the system are entered into the system via a data-driven interactive tool by the user. Next, the simulation generator automatically builds the system and writes both of the model and experimental files for the target simulation language, SIMAN. Then, the generated model is run for the selected alternatives, and the results are compared and presented to the decision-maker (manufacturing engineers or managers) for the final decision to determine the best machine tool.

A database and user interface are designed and implemented. The database comprises two major components: the AHP and the simulation. Table 3 shows the components of the database and the data in each component. Input is via the

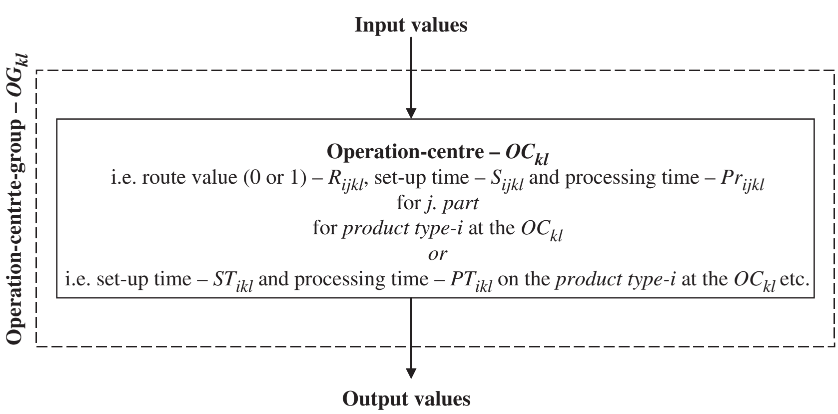

Figure 3. Operation-centre (OC_{kl}) with input–output values in the operation-centre group (OG_{kl}) as a cornerstone of a typical manufacturing organization.

Table 2. Summary of notations.

P_i	Product type: i ($i = 1, 2, 3, \ldots, m$)
P_{ij}	j. Part of the product type: i ($j = 1, 2, 3, \ldots, n$)
m	Number of products
n	Number of parts in the product
t	Number of operation-centre groups: all
y	Number of operation-centre groups: machining
v	Number of operation-centres: all
z	Number of operation-centres: machining
OG_k	Type of operation-centre group ($k = 1, 2, 3, \ldots, t$)
OC_{kl}	Type of operation-centre in the operation-centre group: OG_k ($l = 1, 2, 3, \ldots, v$)
R_{ijkl}	Route value (0 or 1) for j. Part for product type i at the operation-centre: OC_{kl}
S_{ijkl}	Set-up time for j. Part for product type i at the operation-centre: OC_{kl}
Pr_{ijkl}	Processing time for j. Part for product type i at the operation-centre: OC_{kl}
TO_{kll}	Transfer time between operation-centres at the same operation-centre group
TG_{kk}	Transfer time between operation-centre groups
ST_{ikl}	Set-up time of product i at the operation-centre: OC_{kl}
PT_{ikl}	Processing time of product i at the operation-centre: OC_{kl}
SR_{kl}	Scrap rate at the operation-centre: OC_{kl}
RR_{kl}	Rework rate at the operation-centre: OC_{kl}
BR_{kl}	Breakdown of the operation-centre: OC_{kl}

keyboard from the user to supply the simulation generator with the necessary information. The process of simulation analysis with the simulation generator is illustrated in figure 2. Both the database and the user interface were tested and validated extensively for different cases. Some operational data are generated from the basic descriptions after the user completes data entry. All data are gathered from a real-life system under certain assumptions. Assumptions relate the model behaviour to the physical system behaviour by serving two purposes: (1) to identify system details not included in the model because they do not influence performance; (2) to define how the included details are represented in the model. The following is a list of key assumptions made for this study: (1) only material flow is modelled; (2) absence of employees is not included; and (3) rework is not included.

The simulation generator needs data such as: the matrices of route, setup, and process times for the entire products in the current system. These data are acquired from the real-life system of a company and fitted to certain parametric distributions for the simulation analysis to generate random variables during the experiments. The generator creates custom report specifications within the experimental file. The results of a simulation run are divided into three major sections with the following headings: tally variables, discrete-change variables, and counters. Under the tally variables section, observation-based statistics are listed. The average coefficient of variation, minimum, maximum, and number of observations are reported for each item. The discrete-change variables section lists time-based statistics. The average coefficient of variation, minimum, maximum, and final values are reported for each variable. The final section reports counter-variables such as the number of orders completed, number of units designed, and number units manufactured (Pegden 1990).

Various steps were taken to verify and validate the SIMAN simulation programs generated, and the results obtained from the simulation runs. Several examples were

Table 3. Components of the database.

AHP

Number of attributes (2–50)
Names of attributes
Number of machine tool alternatives (2–24)
Names of machine tool alternatives
Matrix of paired comparison for attributes
Matrixes of paired comparison of machine tool alternatives for each attribute
Scaling system

Simulation

Customer order
Interval time (days): exponential
Lot size of order: uniform (1–10)
Type of the order (or product): discrete

Product tree
Number of parts in a product: uniform (1–24)
Number of levels (1–12)
Branching value at any level (1–12)

Operation-centre-groups
Types of the groups for all (i.e. machining, inspecting and assembling groups)
Numbers of the groups (1–12)
Types of the groups for machining (i.e. lathe, milling, and grinding groups)
Numbers of the groups for machining (1–24)
Transportation times between operation-centre groups: constant (5 min.)

Operation centres
Types of operation-centres in each group (i.e. lathe, milling, grinding, testing, and assembling)
Capacities of operation-centres in each group
Numbers of operation-centres in each group (1–24)
Initial buffer and buffer capacity (for input and output queue) on each operation-centre in group
Transportation times between operation-centres in the same group (constant)
Set-up time matrix of *j*. part for product *i* at the operation-centre-machining (Normal distr.)
Processing time matrix of *j*. part for product *i* at the operation-centre-machining (Normal distr.)
Route value matrix of *j*. part for product *i* at the operation-centre machining (0 or 1)
Set-up time matrix of product: *i* at the operation-centre
Processing time matrix of product: *i* at the operation-centre
Rework rate at the operation-centre (%)
Scrap rate at the operation-centre (%)
Interval time for breakdown at the operation-centre (reliability of the machine tool) (exponential)
Production rate of the operation-centre (productivity of the machine tool) (units per hour)

Experiments
Simulation date, model and user's name
Maximum number of concurrent entities in the system
Number of simulation runs to execute
Warm-up period of simulation
Beginning time of the first run
Maximum length of each run
Option for initializing the system status between runs (yes/no)
Option for discarding previous observations between runs (yes/no)
Option for detailing trace report of the processing entities (yes/no)

generated using the user interface. The programs generated were verified manually for their logical and structural correctness. If data taken via the user interface are employed to describe a product organization system, then the simulation generator creates the files for the SIMAN simulation language. Several performance measures such as queue lengths, resource utilization, and cycle times are included as standard items in the output results to validate the simulation models. Finally, the model logic is validated using the trace capability of SIMAN. All results indicated a valid and robust simulation generator.

The simulation generator is written in QBasic. It has no model size restrictions and generates simulation programs that can be run in all versions of SIMAN. The advantages of simulation generators are well known but there are also several limitations. O'Keefe and Haddock (1991) indicate that the disadvantages for the user occur in three areas: (1) perceived ease of use, (2) weaknesses resulting from the underlying language, and (3) limitations of the generator. Furthermore, if the assumptions made in developing a simulation generator are not explicitly stated by the developer and not understood by the user, the results can be invalid. The simulation generator is easy to use, but it requires a large amount of data. It also requires basic statistical skills. The same arguments can be made for the design of the simulation experiment and for the analysis of the simulation results. There are a few weaknesses resulting from the underlying language, SIMAN. SIMAN does not have real subroutine capabilities, so several modules must be repeated many times, producing large model files. However, this can be viewed as an advantage, since the code is more readable in its current form.

3.3 *Evaluation of the AHP and simulation results*

In this study, the UIC ratio is defined to determine the ultimate machine tool. This ratio is calculated by dividing the investment cost per year of each alternative by the additional number of the produced units obtained from the simulation experiment of the relevant alternative. The additional number of units for an alternative is calculated by subtracting the number of units manufactured in the current system, from the number of units manufactured in the alternative system in which the relevant alternative is employed. By comparing the UIC ratios of all the alternatives, the final machine tool with the lowest UIC is found out, and then it is presented to the company's management for approval to initiate further actions.

4. Case study

As a case study, a cutting-tool manufacturer that designs and manufactures all kinds of cutting tools (i.e. twist drills, taps, and reamers) for various sectors in Turkey was taken into consideration. First of all, the current manufacturing organization of the company was analysed, along with all the manufacturing operations, as specified in figure 1. The products designed and manufactured in-house are classified into three groups such as: standard (N), semi-standard (S), and custom (P).

In this case study, the twist-drill manufacturing department was taken into consideration due to the fact that the company has product-based manufacturing organization. The lot size for each group of twist drills (N, S, and P) was generated by using a uniform distribution (1–50). This department consists of five different machining centres such as: a material-cutting machine for material preparation (M1), a semi-automated lathe machine tool (M2), heat treatment (M3), a CNC cylindrical grinding machine tool (M4), and a sharpening machine tool (M5), with the numbers of 1, 2, 1, 3, and 1, respectively.

After a while, the department manager and plant manager of the company noticed that a new kind of CNC lathe machine tool for turning operations of the twist drills with a diameter over 12.1 mm for all three groups was needed because the existing tools (M2) were old-fashioned and not CNC-controlled. Thus, they were inadequate in meeting demand and caused a bottleneck in manufacturing. The purchase of a new tool with an outstanding manufacturing ability would also cut the queue in front of the existing machine tools and would be positioned in the section of the department where the others were. Therefore, they decided to purchase a new CNC lathe machine tool to make the manufacturing faster and also to maintain the tight leadtimes requested by customers. The managers made a short list of possible machine-tool alternatives in the market and, based on their experience of machine tools and operations carried out in each machine tool, narrowed them down to seven (A1–A7).

Second, the attributes and their sub-attributes for evaluating machine-tool alternatives were defined for the AHP in table 4 (Arslan *et al*. 2004). Then, the AHP method was carried out using the aforementioned software program (figure 2). The data were entered by the user, e.g.: (1) the number of attributes [19]; (2) the number of alternatives [7]; (3) the matrix of paired comparisons for attributes; (4) the matrix of paired-comparison results for alternatives with respect to

Table 4. Attributes with their sub-attributes used in the AHP (Arslan *et al*. 2004).

No.	Attributes	No.	Sub-attributes
A	Productivity	1	Spindle speed
		2	Power
		3	Cutting feed
		4	Traverse speed
B	Flexibility	5	Number of tools
		6	Rotary table
C	Space	7	Machine dimensions
D	Adaptability	8	CNC type
		9	Taper no.
E	Precision	10	Repeatability
		11	Thermal deformation
F	Reliability	12	Bearing failure rate
		13	Reliability of drive system
G	Safety and environment	14	Mist collector
		15	Safety door
		16	Fire extinguisher
		17	Training
H	Maintenance and service	18	Repair service
		19	Regular maintenance

each attribute, respectively. A fundamental scale system of Saaty (1989) given in table 1 was used to rate both the alternatives with respect to one criterion at a time and the attributes.

The following steps can be done automatically by using the AHP module in figure 2: (1) synthesizing the pairwise comparison matrix; (2) calculating the priority vector of a criterion such as spindle speed; (3) calculating the consistency ratio (CR); (4) calculating λ_{max}; (5) calculating the consistency index (CI); (6) selecting the appropriate value of the random consistency ratio; and (7) checking the consistency of the pairwise comparison matrix to check whether the decision-maker's comparisons were consistent or not.

The pairwise comparison matrix was produced by dividing each element of the matrix by its column total. The priority vector in table 5 can be obtained by finding the row averages.

Next, the consistency ratio for the matrix of pairwise comparisons of alternatives for the attribute-*spindle speed* was calculated by using equations (1) and (2) as follows (table 6):

$$\mathrm{CI} = \frac{7.617 - 7}{6} = 0.103, \quad \mathrm{RI} = 1.32, \quad \mathrm{CR} = \frac{0.103}{1.32} = 0.078 < 0.10.$$

For the matrices of pairwise comparisons of alternatives for the 18 remaining attributes, the consistency ratios were calculated in the same way, and it was clearly found that they were all less than 10%. Similarly, the consistency study for the matrix of pairwise comparison of attributes for each level was calculated as follows:

$$\lambda_{max} = 21.09, \quad \mathrm{CI} = \frac{21.09 - 19}{18} = 0.116, \quad \mathrm{RI} = \frac{1.98 \times 17}{19} = 1.77, \quad \mathrm{CR} = 0.066 < 0.1.$$

Based on these calculations, the consistencies of the judgements in all comparison matrices were also acceptable. Thus, the overall priority weights for A1–A7, respectively, were determined equation (3) as follows:

$$\sum_{i=1}^{19} (\text{attributeweight}_i \times \text{evaluationrating}_{ij}) \quad i = 1, 2, 3, \ldots, 19 \text{ and } j = 1, 2, 3, \ldots, 7.$$

Also, the overall consistency index was calculated as 0.085. Because it is smaller than 0.10, all of the judgements are consistent (table 7).

Only three machine-tool alternatives with scores higher than 0.100 were taken into consideration for the simulation experiments. The others were eliminated. These three alternatives, A1–A3, were taken as scenarios respectively by the simulation generator. All the data gathered from the real-life manufacturing system were entered to the generator to model current manufacturing organization. After that, each machine-tool alternative as a scenario was taken, and its data such as the matrices of set-up and process time were entered into the system for its simulation experiment. Each machine-tool alternative and its related data were added to the simulation generator as another type of machine tool (M6) addition to the existing

Table 5. Matrix of paired comparison results of seven alternatives in decimal values with respect to the criterion 'spindle speed' (consistency ratio = 0.078).

Productivity spindle speed	A1	A2	A3	A4	A5	A6	A7	Priority vector
A1	1.000	3.000	5.000	9.000	3.000	9.000	9.000	0.422
A2	0.333	1.000	1.000	3.000	3.000	7.000	3.000	0.172
A3	0.200	1.000	1.000	3.000	3.000	5.000	3.000	0.154
A4	0.111	0.333	0.333	1.000	1.000	3.000	7.000	0.092
A5	0.333	0.333	0.333	1.000	1.000	5.000	3.000	0.095
A6	0.111	0.143	0.200	0.333	0.200	1.000	1.000	0.029
A7	0.111	0.333	0.333	0.143	0.333	1.000	1.000	0.036
Total								1.000
							λ_{max}	7.617
							CI	0.103
							RI	1.32
							CR	0.078 < 0.1 OK

machine tool (M1, M2, M3, M4, M5). Next, the generated files for each alternative were run by SIMAN, and then the results were obtained.

The routing data of all kinds of groups for the current twist-drill manufacturing system consisting of five different machine tools are the same and are listed in table 8. Also, the route matrix of the groups used in simulation experiments for each alternative is given in table 9. This matrix was introduced into the generator for each alternative by modifying the route matrix of the current manufacturing system. The scrap rate for entire products at each machine tool is assumed to be 5%, and the rework rate is also assumed to be 3% for the entire products. In addition, the interval time of breakdown for each machine tool is accepted as 43 days, based on an exponential distribution.

For verification and validation of the generated model, all the required data were acquired from the real-life system of company to produce its simulation model. To prove its accuracy, the TRACE command, one of the SIMAN output commands, was used to verify the model. This allows the user to watch step by step, running the generated model on the time basis to see how well it represents the real-life systems under certain assumptions determined by the author, while building the generator.

In addition, to check the validity of the generated model of the manufacturing system, extreme conditions from the real-life system were taken into consideration to understand how correctly the model represents the real-life system under these conditions. Formal, qualitative, and observation characteristics were examined in the model (Birta and Ozmizrak 1996). Furthermore, the *t* distribution was used to prove the validity of the generated model using 'the average product cycle time' variable at a 95% confidence level. The simulation duration was selected to be 300 working days, so that the data from the simulation experiments would be statistically meaningful. The results were exported to Excel as an ASCII file by using a SIMAN output command to

Table 6. Matrix of paired comparisons for the sub-attributes[1] (consistency ratio = 0.066).

Attribute	Sub-attribute	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Priority vector
	1	1	0.2	5	1	0.333	0.111	5	5	0.333	0.2	0.2	0.111	3	7	9	0.2	0.222	0.111	0.333	0.039
	2		1	7	9	7	0.143	0.2	1	3	7	5	3	0.333	3	1	0.111	7	0.111	5	0.068
A	3			1	0.333	3	0.2	0.333	5	0.111	0.2	0.2	5	7	7	5	3	0.333	0.2	5	0.041
	4				1	0.111	3	9	0.2	0.143	1	3	7	0.2	5	0.111	7	7	7	3	0.061
B	5					1	1	0.143	7	5	0.143	5	9	5	7	7	1	9	0.143	5	0.068
	6						1	0.111	9	0.43	0.2	7	0.143	7	1	0.143	0.2	7	0.111	0.333	0.054
C	7							1	7	5	5	7	0.111	5	0.2	7	3	9	0.2	9	0.087
D	8								1	0.333	3	0.111	0.2	0.143	5	5	7	5	3	5	0.043
	9									1	0.111	0.333	5	9	3	1	0.143	3	0.143	0.2	0.044
E	10										1	9	7	1	7	0.111	0.2	5	0.333	7	0.07
	11											1	3	3	0.2	9	1	3	3	5	0.048
F	12												1	5	0.111	5	0.143	7	0.2	0.111	0.048
	13													1	3	0.333	5	5	7	0.2	0.041
G	14														1	5	0.2	9	0.143	0.2	0.034
	15															1	3	5	3	5	0.052
	16																1	7	0.143	3	0.058
H	17																	1	9	0.333	0.022
	18																		1	0.2	0.084
	19																			1	0.038
																					Total: 1.000

[1] Only the upper part of the matrix is shown. $\lambda_{max} = 21.09$; CI = 0.116; RI = 1.77; CR = 0.066 < 0.1 OK.

Table 7. Final ranking of the alternatives (A1–A7).

Alternatives	1 −0.039	2 −0.068	3 −0.041	4 −0.061	5 −0.068	6 −0.054	7 −0.087	8 −0.043	9 −0.044	10 −0.07	11 −0.048	12 −0.048	13 −0.041	14 −0.034	15 −0.052	16 −0.058	17 −0.022	18 −0.084	19 −0.038	Overall priority vector
A1	0.422	0.411	0.423	0.374	0.371	0.382	0.387	0.377	0.368	0.411	0.408	0.422	0.426	0.369	0.337	0.338	0.332	0.321	0.332	0.379[1]
A2	0.172	0.167	0.171	0.265	0.262	0.267	0.239	0.254	0.225	0.188	0.188	0.141	0.125	0.197	0.224	0.222	0.229	0.231	0.235	0.214[1]
A3	0.154	0.175	0.151	0.111	0.108	0.113	0.137	0.152	0.189	0.17	0.181	0.191	0.176	0.187	0.151	0.15	0.128	0.112	0.114	0.148[1]
A4	0.092	0.086	0.112	0.065	0.083	0.068	0.066	0.053	0.051	0.065	0.076	0.09	0.112	0.091	0.119	0.102	0.147	0.157	0.124	0.091
A5	0.095	0.1	0.069	0.11	0.108	0.091	0.084	0.076	0.087	0.083	0.071	0.077	0.092	0.071	0.079	0.077	0.075	0.073	0.085	0.085
A6	0.029	0.028	0.037	0.036	0.03	0.037	0.045	0.06	0.051	0.051	0.04	0.04	0.034	0.044	0.049	0.076	0.048	0.072	0.074	0.047
A7	0.036	0.033	0.037	0.039	0.038	0.042	0.042	0.028	0.029	0.032	0.036	0.039	0.035	0.041	0.041	0.035	0.041	0.034	0.036	0.036
CR	0.078	0.093	0.097	0.086	0.09	0.067	0.085	0.085	0.09	0.092	0.094	0.088	0.063	0.062	0.084	0.1	0.084	0.094	0.074	0.085[2]
Total	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

[1] Selected alternatives whose score are bigger than 0.100 for the simulation study.
[2] Overall consistency index: $0.085 < 0.100$ OK.

Table 8. Route matrix of the groups for modelling the current manufacturing system.

Product groups	Machine tools				
	M1 (1)	M2 (2)	M3 (1)	M4 (3)	M5 (1)
Twist drills (for N, S, and P types: all groups)					
Diameter: 0.1–12.0 mm	1	1	1	1	1
Diameter: 12.1–	1	1	1	0	1

Table 9. Route matrix of the groups used in simulation experiments.

Product groups	Machine tools					
	M1 (1)	**M2 (2)**	**M6[1] (1)**	M3 (1)	M4 (3)	M5 (1)
Twist drills (for N, S, and P types: all groups)						
Diameter: 0.1–12.0 mm	1	**1**	**0**	1	1	1
Diameter: 12.1–	1	**0**	**1**	1	0	1

[1] M6: a new machine tool was added to the current system to eliminate the bottleneck in M2.

Table 10. Results of simulation experiments for each machine tool alternative[1].

Performance criteria	Current system	Scenario I (A1)	Scenario II (A2)	Scenario III (A3)
Product cycle time for all types (days)	43.4	36.1	44.2	41.5
Total number of units for all types	15 531	21 232	17 893	21 152
M1 utilization	0.81	0.94	0.89	0.94
M2 utilization	1.92	1.92	1.79	1.91
M3 utilization	0.72	0.89	0.89	0.82
M4 utilization	2.81	2.91	2.88	2.77
M5 utilization	0.89	0.92	0.89	0.94
M6 utilization	0.00	0.96	0.93	0.96

[1] Results were obtained from the data after truncating the warm-up period data.

evaluate the results much faster. To find the warm-up period or transition period, the PLOT command was used on 'the average product cycle time', and the period was found as 95 days. To calculate the confidence intervals, FILTER and INTERVALS commands were also used for each performance criterion (Ayağ 2002).

Table 10 shows the results of the simulation experiments carried out for each machine-tool alternative. All the results in the table were obtained from the data after truncating the warm-up period data.

The final alternative was found by using the UIC ratio analysis. As can be seen in table 11, Alternative 1 (A1) with the lowest UIC ratio is considered the best. The return of investment of each machine-tool alternative was assumed to be 5 years.

Table 11. UIC analysis for machine-tool alternatives (A1–A3).

	Investment cost ($)[1]	Increase in the average number of units per year[2]	Unit investment cost (UIC) ($/year)[3]
Machine tool alternatives	(*a*)	(*b*)	(*c*) = [(*a*)/ROI)/(*b*)]
A1 (final alternative)	100 000	5701	3.51
A2	115 000	2362	9.74
A3	135 000	5621	4.80

[1] Investment cost (*a*) includes all kinds of costs (procurement cost, fixture costs etc.) for each alternative.
[2] This value (*b*) was obtained by subtracting the average number of units generated from the simulation experiment of current system, from the average number of units generated from the simulation experiment of each alternative.
[3] The unit investment cost per year for each alternative (*c*) was obtained by dividing its investment cost per year (*a*)/ROI by the number of units increased per year (*b*) by adding a new machine tool. The ROI of each alternative was assumed to be 5 years.

5. Conclusion

One of the most important challenges in a machine-tool selection process is the lack of both reliable data for possible alternatives of machine tools and an expert with in-depth experience of machine specifications and manufacturing processes and so on. Therefore, this problem negatively affects most companies because of inappropriate selection of a machine tool that causes many problems in their manufacturing systems, because they have critical effects not only on the productivity, precision, and flexibility of manufacturing systems, but also on its responsive manufacturing capabilities.

In this paper, a hybrid approach has been proposed for the machine-tool selection problem using the AHP and simulation methods. The AHP is used to narrow down all possible machine-tool alternatives in the market by eliminating those whose scores (or weights) are worse than a pre-determined value obtained under certain circumstances. Then, a simulation generator is used first to automatically model a manufacturing organization, where the ultimate machine tool will be used, and second to try each alternative remaining from the AHP as a scenario on the generated model. Lastly, the final alternative is selected by using the UIC ratio, which is calculated by dividing the investment cost per year of each alternative by the additional number of the produced units obtained from the simulation experiment with the relevant alternative.

In the literature, there are different methods which produce different solutions. In this case, another problem arises as to which method produces the correct ranking of machine tools. Most MCDM methods can lead a decision-maker to make a wrong decision, because a decision-maker's requirements for evaluating the alternatives may always have ambiguity and multiplicity of meaning. Furthermore, it is also recognized that human assesment on qualitative attributes is always subjective and thus imprecise, due to the vagueness and uncertainty in the judgements of the decision-maker. In my opinion, the best aspect of the proposed approach is in helping a decision-maker make a purchase decision for a machine tool, especially an expensive one (i.e. a multi-axis special-purposed turning system), by analysing its performance in a real-life system by simulation, before it is physically obtained. In other words, the proposed approach provides a valuable tool for a decision-maker to make the best purchase decision.

In my study, both methods yield the same results. The results could be the same, if only ideal conditions are provided; for example, if the AHP is used more efficiently, and the judgement matrices of the decision-makers are well structured, the results for both methods could be the same. But in practice, the results for both methods are generally different because the human assesment in qualitative attributes is always subjective and thus imprecise. From this point of view, the simulation approach can also be thought of as an analysis tool to verify the results of the AHP.

The proposed approach should be especially used by the decision-makers (i.e. the manufacturing manager and/or engineer) to decide on what kind of machine tool is most suitable for the needs and goals among a set of alternatives. In particular, if the cost of the machine tool and its level of impact on a manufacturing system are high, the selection process becomes more complicated for decision-makers to reach the most satisfactory decision. The simulation method provides more reliable results (i.e. production rate and cycle time) for decision-makers to determine the ultimate machine tool. They can also analyse how each alternative affects their system in terms of queue capacities, work-in process, routing priorities and so on, before it is physically integrated to the real system. In short, the proposed approach produces more information for decision-makers to help them to find the best machine tool in the selection process.

In future studies, a knowledge-based or expert system can be integrated to help decision-makers make pairwise calculations more concisely and interpret the results at each step of the AHP and simulation.

References

Arslan, M.C., Catay, B. and Budak, E., A decision support system for machine-tool selection. *J. Manuf. Technol. Manage.*, 2004, **15**, 101–109.

Ayağ, Z., An analytic-hierarchy-process based simulation model for implementation and analysis of computer-aided systems. *Int. J. Prod. Res.*, 2002, **40**, 3053–3073.

Ayağ, Z., An integrated approach to evaluating conceptual design alternatives in a new product development environment. *Int. J. Prod. Res.*, 2005a, **43**, 687–713.

Ayağ, Z., A fuzzy AHP-based simulation approach to concept evaluation in a NPD environment. *IIE Trans.*, 2005b, **37**, 788–803.

Aytug, H. and Dogan, C.A., A framework and a simulation generator for kanban-controlled manufacturing systems. *Comput. Ind. Eng.*, 1998, **34**, 337–350.

Badiru, A.B., Pulat, P.S. and Krang, M., DDM: decision support system for hierarchical dynamic decision-making. *Decis. Support. Syst.*, 1993, **10**, 1–18.

Birta, L.G. and Ozmizrak, F.N., A knowledge-based approach for the validation of simulation models: the foundation. *ACM Trans. Modell. Comput. Simul*, 1996, **6**, 76–98.

Cagno, E., Caron, F. and Perego, A., Competitive bidding: A multi-criteria approach to assess the probability of winning, in *Deuxieme Congress International Franco-Quebecois de Genie Industrie—ALBI*, 1997.

Chan, F.T.S. and Abhary, K., Design and evaluation of automated cellular manufacturing systems with simulation modelling and AHP approach: a case study. *Integr. Manuf. Syst.*, 1996, **7**, 39–52.

Chan, F.T.S., Ip, R.W.L. and Lau, H., Integration of expert system with analytic hierarchy process for the design of material handling equipment selection system. *J. Mater. Process. Technol.*, 2001, **116**, 137–145.

Chan, F.T.S., Jiang, B. and Tang, N.K.H., The development of intelligent decision support tools to aid the design of flexible manufacturing systems. *Int. J. Prod. Econ*, 2000, **65**, 73–84.

Gerrard, W., Selection procedures adopted by industry for introducing new machine tools, in *Advances in Manufacturing Technology III, Proceedings of 4th National Conference on Production Research*, 1988a, pp. 525–531.

Gerrard, W., A strategy for selecting and introducing new technology/machine tools, in *Advances in Manufacturing Technology III, Proceedings of 4th National Conference on Production Research*, 1988b, pp. 532–536.

Gındy, N. and Ratchev, S.M., Integrated framework for selection of machining equipment in CIM. *Int. J. Comput. Integr. Manuf*, 1998, **11**, 311–325.

Goh, C.H., Tung, Y.C.A. and Cheng, C.H., A revised weighted sum decision model for robot selection. *Comput. Ind. Eng.*, 1995, **30**, 193–199.

Gopalakrishnan, B., Yoshii, T. and Dappili, S.M., Decision support system for machining center selection. *J. Manuf. Technol. Manage.*, 2004, **15**, 144–154.

Haddock, J. and Hartshorn, T., A decision support system for specific machine selection. *Comput. Ind. Eng.*, 1989, **16**, 277–286.

Kivijarvi, H. and Tuominen, M., Integrating AHP and dynamic simulation: experiences, conceptualizations and business experiments, in *Proceedings of the ISAHP, Kobe, Japan*, 1999, pp. 386–392.

Levary, R.R. and Wan, K., An analytic hierarchy process based on simulation model for entry mode decision regarding foreign direct investment. *Omega*, 1999, **27**, 661–677.

Lin, Z.C. and Yang, C.B., Evaluation of machine selection by the AHP method. *J. Mater. Process. Technol.*, 1994, **57**, 253–258.

Lootsma, F.A., *Fuzzy Logic for Planning and Decision-Making*, 1997 (Kluwer Academic: Dordrecht).

Oeltjenbruns, H., Kolarik, W.J. and Schnadt-Kirschner, R., Strategic planning in manufacturing systems-AHP application to an equipment replacement decision. *Int. J. Prod. Econ.*, 1995, **38**, 189–197.

O'Keefe, R.M. and Haddock, J., Data-driven generic simulators for flexible manufacturing systems. *Int. J. Prod. Res.*, 1991, **29**, 1795–1810.

Pegden, D., *Introduction to the SIMAN*, 1990 (System Development Corp.: Santa Monica, CA).

Saaty, T.L., *The Analytical Hierarchical Process*, 1981 (McGraw Hill: New York).

Saaty, T.L., Decision-making, Scaling, and number crunching. *Decis. Sci.*, 1989, **20**, 404–409.

Saaty, T.L., Fundamentals of the analytic network process, in *Proceedings of the ISAHP*, Kobe, 1999, p 14.

Schroer, B.J., A simulation assistant for modelling manufacturing systems. *Simulation*, 1989, **53**, 201–204.

Scott, M., Quantifying certainty in design decisions: examining AHP, in *Proceedings of the 14th Conference on Design Theory and Methodology*, September, Montreal, Canada, 2002.

Shang, J. and Sueyoshi, T., A unified framework for the selection of a flexible manufacturing system. *Eur. J. Oper. Res.*, 1995, **85**, 297–315.

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). *Comput. Ind.*, 1994, **25**, 131–143.

Wang, T.Y., Shaw, C.F. and Chen, Y.L., Machine selection in flexible manufacturing cell: a fuzzy multiple attribute decision-making approach. *Int. J. Prod. Res.*, 2000, **38**, 2079–2097.

Yurdakul, M., AHP as a strategic decision-making tool to justify machine-tool selection. *J. Mater. Process. Technol.*, 2004, **146**, 365–376.

Zahedı, F., The analytic hierarchy process: a survey of the method and its application. *Interfaces*, 1986, **16**, 96–108.