A multi-criteria approach to robot selection for a computer integrated manufacturing system

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Abstract -This paper describes a Multi-Criteri Decision-Making (MCDM) model designed to aid decision makers in selecting the most appropriate robots for a Computer Integrated Manufacturing (CIM) system. Existing methods for robot selection do not reflect interdependencies among criteria. The model mainly consists of two parts. The first part is called *qualitative model*, which narrows down all possible alternatives by using the Analytic Network Process (ANP). In first part when we evaluate alternative robots, we need to collect users' opinion. The second part uses a Mixed Integer Goal Programming (MIGP) model to find out the best candidate from the alternative robots. The proposed model takes into consideration multi-criteria, interdependence property and optimization for selecting robots, and helps managers explore and evaluate costs and benefits of various scenarios for each alternative separately by experimenting with different types of robots and degree of flexibility of systems.

I. INTRODUCTION

Today's high competitive global market requirements can be met by implementing of Computer Integrated Manufacturing (CIM) systems. The principal role of CIM in manufacturing organizations is to integrate the design, the manufacturing, the management, and the planning functions into a flexible system.

An industrial robot is a general-purpose, programmable machine possessing certain anthropomorphic characteristics [1]. It is utilized to move materials, parts, tools, or special devices through variable motions for the performance of a variety of operations. Robots are being used in a wide field of applications in manufacturing companies. Whatever the configurations the purpose of the robot is to perform a useful task [2]. Many companies use robots in the manufacturing sections of the CIM wheel and have integrated them into the CIM system [3]. Therefore, the selection of best robots will have a vital impact on the performance of the manufacturing companies.

Not all types of robot have been successful. There are enough case histories of misapplication, poorly selected robot, and no acceptance by company personnel to make a prospective user very careful, especially in an initial application. In view of the multiplicity of criteria inherent in such decision-making situations, the model of Multi-Criteria Decision-Making (MCDM) is used as the framework of selection method. Prior robot selection methods proposed are useful but have restricted application because they consider only independent robots or evaluation criteria. However, robot selection problems have interdependence property. When we consider robot evaluation problems, we need to collect CIM users' opinion because it is very dangerous to determine the criteria or the degree of interdependence for considering robot by one or two decision maker(s).

The objective of this paper is to suggest a solving method for robot selection problems that have interdependence property among evaluation criteria. In order to reflect the interdependencies property in robot selection in which exist multiple criteria, we used the Analytic Network process (ANP) model and Mixed Integer Goal Programming (MIGP) model. Specifically, we demonstrated how a combined ANP and MIGP model could be used as aid in robot selection problem.

II. REVIEW OF THE ROBOT SELECTION PROBLEM

A robot is characterized by its degree of freedom, number of joints, type of joints, joint placement, link lengths and shapes, and their orientation which influence its performances, namely, the workspace, manipulability, ease and speed of operation, etc. Several methods have been proposed to help manufacturing companies make good robot selection decisions. In [4] Goh et al. proposed a revised weighted sum decision model for robot selection using weights that are assigned by a group of experts. Many real-world problems have an interdependent property among the criteria or alternatives. Consideration for these interdependencies among criteria and multiple criteria provides valuable cost saving and greater benefits to manufacturing companies. Bhangale et al. [5] utilized dynamic model-based method for selecting robots. They did not consider interdependence property among criteria. Rivin [6], and Dorf and Nof [7] suggested a robot selection method based on the workspace and payload capacity. In [8] Yoshikawa utilized another measure like changing the position as a criterion. The above references considered only one criterion and not multiple criteria. In reality, it will be more appropriate to consider multiple criteria than to consider only one or two criteria in robot selection problems which have interdependence property.

No prior study reported in the literature has ever demonstrated the solving method of a robot selection that has all multiple criteria, interdependence property and optimization requirements. We will consider an interdependent robot selection problem having multiple criteria.

III. The ANP model for qualitative criteria

The initial study identified the multi-criteria decision-making (MCDM) technique known as the Analytic Hierarchy Process (AHP) to be the most appropriate for solving complicated problems. AHP was proposed by Saaty [9] and has been used to solve a wide range of MCDM problems. Many decision problems cannot be structured hierarchically because they involve the interaction and dependence of higher-level elements on a lower-level element. Saaty [10] suggested the use of AHP to solve the problem of independence on alternatives or criteria and the use of ANP to solve the problem of dependence among alternatives or criteria. The ANP addresses how to determine the relative importance of a set of activities in a MCDM problem. The process utilizes pair wise comparisons of the alternatives as well as pair wise comparison of the multiple criteria.

Because, to determine the relationship of a network structure or the degree of interdependence is the most important function of ANP, we should collect data by CIM users discussion in general.

The process of solving interdependence robot selection problem (ANP model) is summarized as follows: In order to consider interdependence, the first is to identify the multiple criteria with consideration to robots components and CIM system requirements, and then draw a relationship between criteria that shows the degree of interdependence among the criteria. Next, determining the degree of impact or influence between the criteria. When comparing the robots for each criterion, the CIM user will respond to questions such as: "In comparing robots 1 and 2, on the basis of a given criterion, which robot is preferred?" The responses are presented numerically, scaled on the basis of Saaty's proposed 1-9 scale [9, 10] with reciprocals, in a robot comparison matrix. The final step in ANP model is to determine the overall prioritization of the alternative robots. The information obtained from the ANP is then used to formulate a MIGP model as a weight.

The robots selection problem can be decomposed in a network, shown in Fig. 1. The criteria, sub criteria and their level were obtained from a consensus of CIM users. Level 1 contains the goal, level 2 consists of three main criteria, level 3contains the sub criteria to the criteria in level 2, and level 4 consists of alternative robots. Fig. 1 illustrates also the interdependencies property among criteria.

The following ANP model utilizes pair wise comparisons of the robots as well as pair wise comparisons of the criteria. Since users' opinion is important for pair wise comparisons, the data utilized in the model should collect from CIM users in a given company. The comparison matrices for criteria and robots should be obtained separately from each user. We also should check the users responses by utilizing the ratio of consistency check.

The ANP model has the following steps:

Step1: When comparing the importance of the individual criteria (without dependence property), the question that must be asked of the users is: Which criterion should be emphasized more in an alternative robot? By comparing all criteria with one another with respect to the alternative robots, and aggregating this data with (1), and then using the process of averaging over normalized columns with (2), we will obtain the weight matrix of criteria (W_1).

$$a_{ij} = \frac{1}{3}\{\min_{k=1,\dots,K}(a_{kj}^{k}) + \mathrm{E}(a_{kj}^{k}) + \max_{k=1,\dots,K}(a_{ij}^{k})\} \qquad (1)$$

Where $\mathbf{i} < \mathbf{j}$, and $\mathbf{a}_{ij}^{k}$ is the response to attribute ij by user k ; the total number of users is K and the combined rating of attribute ij is $\mathbf{a}_{ij}$. In (2), w_i is the weighted priority for component $\mathbf{i}$; $\mathbf{J}$ is the index number of columns (components); and $\mathbf{I}$ is the index number of rows (components).

$$\mathbf{w}_i = \sum_{j=1}^{J}\left(\mathbf{a}_{ij} \Big/ \sum_{i=1}^{I}\mathbf{a}_{ij}\right) \Big/ \mathbf{J} \qquad (2)$$

Step2: The decision makers for robot selection rate the suitable robots on different multiple criteria assuming that there is no dependence among the alternative robots. We

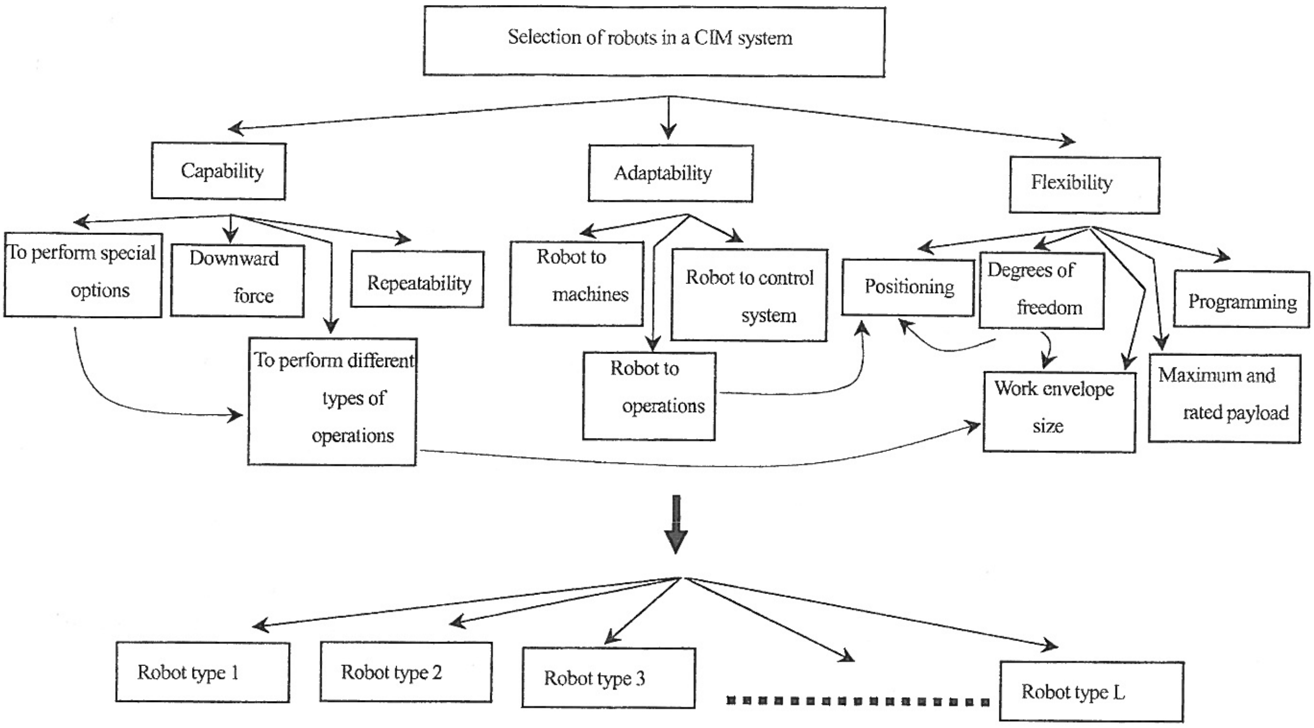

Fig. 1. The graphical representation of ANP model for robot selection in a CIM system

define the matrix W_2 by grouping together the l columns (alternatives) regarding normalized weight data.

Step3: Next, we considered interdependence among the criteria. When we select a robot, we cannot concentrate on just one criterion, we must also consider the other criteria related to it. Therefore, we need to examine the impact of all criteria on one another by using pair wise comparisons. In the matrix $\mathbf{W}_3$, we obtain the twelve sets of weight through users' aggregated data. In step 3, the decision makers rate these degrees by taking into consideration the criteria's relationships in fig. 1.

Step4: We then obtain the interdependence priorities of the criteria by (3).

$$W_4 = W_3 \times W_1 \tag{3}$$

Step5: Finally, the overall priorities of the alternative robots with respect to each of the criteria are calculated by (4).

$$W_5 = W_4 \times W_2 \tag{4}$$

The results of ANP can be calculated by EXCEL, and they are sufficient for selecting an appropriate robot, but for optimization other factors need to be taken into consideration. We must introduce a given company's specific limitations, constraints and quantitative data into a non-linear MIGP model in which the ANP results are weighed heavily.

IV. A MIGP model for quantitative criteria

In this section a MIGP model is utilized to select the best robot possible in a given manufacturing company or a CIM system. The selection of a robot requires several goals, and consists of both integer and non-integer variables. A MIGP model permits the consideration of CIM system resource limitations and other selection limitations that must be rigidly observed in the robot selection problems. Therefore, in order to consider all of the goals and variables for modeling this selection problem, we must use a MIGP model.

The following notations have been provided for the formulation of a MIGP model:

$B =$ The limited total investment for robots

$b_l =$ The investment required to install robot type l

$C_l =$ Total available time of robot type l for $l = 1, \ldots\ldots, L$

$S_{jl} =$ Busy time of robot type l on machine j

$V_{jl} =$ Setup time for robot type l on machine j

$Q_j =$ Number of machine j for $j = 1, \ldots\ldots, J$

$D_l =$ Number of robot type l

$R_{jl} =$ Binary integers for using robot type l on machine j

$D =$ The number of goals to be considered in this MIGP model

$L =$ The number of robot types or alternatives

y_d^+, y_d^- =The d th positive and negative deviation variables for $d = 1, \ldots, D$

$ANP_l =$ The final composite weight of the robot type l obtained from ANP model in matrix W_5

w_d = *The significant coefficient of deviation from* d *th goal*

M = *The significant coefficient of positive and negative deviation from* 5 *th goal= A large numeric figure.*

During robot selection for a CIM system, the goals within a MIGP model can be developed as follows:

$$\sum_{j=1}^{J} R_{jl} - (y_{l1}^+ - y_{l1}^-) = 1 \quad (5)$$

Equation (5) requires that each robot will be utilized at least on one machine.

Since there are a limited number of robots in a CIM system, the total robot using time for each machine should not exceed the total available time of the corresponding robots.

$$\sum_{j=1}^{J} Q_j \times S_{jl} \times R_{jl} - (y_{l2}^+ - y_{l2}^-) = C_l \times D_l \quad (6)$$

$$(\sum_{j=1}^{J}\sum_{l=1}^{L} (S_{jl} + V_{jl}) \times R_{jl}) - (y_3^+ - y_3^-) = \sum_{j=1}^{J}\sum_{l=1}^{L} S_{jl} \quad (7)$$

Equation (7) satisfies the condition that each robot can be utilized after the busy time of it.

According to operation and machine constraints, total number of robots must be enough:

$$(\sum_{l=1}^{L} D_l \times R_{jl}) - (y_4^+ - y_4^-) = Q_j \quad (8)$$

In order to select only one type of robot:

$$\sum_{l=1}^{L}\sum_{j=1}^{J} R_{jl} - (y_5^+ - y_5^-) = 1 \quad (9)$$

$$\sum_{l=1}^{L}\sum_{j=1}^{J} b_l \times R_{jl} - (y_6^+ - y_6^-) = B \quad (10)$$

In order to select the most appropriate robot with the largest composite weight possible in the ANP model:

$$\sum_{j=1}^{J} R_{jl} + y_{6+l}^- = 1 \quad (11)$$

$$y_6^+ = 0 \text{ or } 1 \text{ and } y_d^- = 0 \text{ or } 1 \text{ for } d = 6, \ldots, 6+L \quad (12)$$

$$y_d^+ \geq 0 \text{ and } y_d^- \geq 0 \text{ for } d = 1, \ldots, 5 \quad (13)$$

By considering all of the goals mentioned above and utilizing the composite weights obtained from ANP, the following MIGP objective function is achieved:

$$\textbf{Minimize} Z = w_1(\sum_{l=1}^{L} y_{l1}^-) + w_2\sum_{l=1}^{L} y_{l2}^+ + w_3y_3^+ + w_4y_4^- + M(y_5^+ + y_5^-) + w_6y_6^+ + w_7(\sum_{l=1}^{L} ANP_l \times y_{6+l}^-) \quad (14)$$

After data from a given company or CIM system is entered into the model above, the LINDO program can be utilized to solve the MIGP model.

V. Case study

We applied the ANP within a MIGP model to two companies, one in Iran and one in Japan, by utilizing their data, goals and available alternative robots. The following case study is based on the Iranian company and the Japanese case study is still in progress. The Iranian company located in the city of Tehran manufactures storage shelves and rocks. They needed robots for one type machine in their CIM system. For this case study, we developed a questionnaire in order to obtain the necessary data and available types of robot. Four types of robot were available for the company. First we applied the ANP model, and then we utilized the ANP results and alternative robots' data along with the company's goal to formulate the following MIGP model in Table I. The ANP result showed the 3rd robot was best alternative, because it has the largest weight in $W_5 = (0.118, 0.182, 0.436, 0.264)$.

By applying the MIGP model, we were able to conclude that the 4th robot was the most suitable robot type for a CIM system for this particular company. As we see the results of ANP (qualititative) and MIGM (quantitative) are different Because of optimization requirement in company, the MIGP result is final solution.

Table I. A MIGP model for case study

B=10000 Euro	D=10	$ANP_1 = 0.118$	$ANP_2 = 0.182$	$ANP_3 = 0.436$	$ANP_4 = 0.264$	$w_1 = 0.098$
$w_2 = 0.174$	$w_3 = 0.029$	$w_4 = 0.119$	$M = 10^7$	$w_6 = 0.00014$	$w_7 = 2.52$	
J=1	L=4	Q=11	$D_1 = 15$	$D_2 = 14$	$D_3 = 9$	$D_4 = 12$
$S_1 = 5.1$ hours	$S_2 = 4.3$ hours	$S_3 = 2.6$ hours	$S_4 = 2.8$ hours	$V_1 = 3.2$ hours		
$V_2 = 4.3$ hours	$V_3 = 5.3$ hours	$V_4 = 5.4$ hours	$b_1 = 8000$ *Euro*	$b_2 = 9000$ *Euro*	$b_3 = 12500$ *Euro*	
$b_4 = 10500$ *Euro*						

(1) $R_1 - (y_{11}^+ - y_{11}^-) = 1$ (2) $R_2 - (y_{21}^+ - y_{21}^-) = 1$ (3) $R_3 - (y_{31}^+ - y_{31}^-) = 1$ (4) $R_4 - (y_{41}^+ - y_{41}^-) = 1$

(5) $11 \times 5.1 R_1 - (y_{12}^+ - y_{12}^-) = 17 \times 15$ (6) $11 \times 4.3 R_2 - (y_{22}^+ - y_{22}^-) = 20 \times 14$ (7) $11 \times 2.6 R_3 - (y_{32}^+ - y_{32}^-) = 24 \times 9$

(8) $11 \times 2.8 R_4 - (y_{42}^+ - y_{42}^-) = 21 \times 12$

(9) $(5.1+3.2)R_1 + (4.3+4.3)R_2 + (2.6+5.3)R_3 + (2.8+5.4)R_4 - (y_3^+ - y_3^-) = 5.1+4.3+2.6+2.8$

(10) $15R_1 + 14R_2 + 9R_3 + 12R_4 - (y_4^+ - y_4^-) = 11$ (11) $R_1 + R_2 + R_3 + R_4 - (y_5^+ - y_5^-) = 1$

(12) $8000\, R_1 + 9000\, R_2 + 12500\, R_3 + 10500\, R_4 - (y_6^+ - y_6^-) = 10000$

(13) $R_1 + y_7^- = 1$ (14) $R_2 + y_8^- = 1$ (15) $R_3 + y_9^- = 1$ (16) $R_4 + y_{10}^- = 1$

(17) $\min Z = 0.098(\sum_{l=1}^{L} y_{l1}^-) + 0.174\sum_{l=1}^{L} y_{l2}^+ + 0.029y_3^+ + 0.119y_4^- + 10^7(y_5^+ + y_5^-) + 0.00014y_6^+ + 2.52(0.118y_7^- + 0.182y_8^- + 0.436y_9^- + 0.264y_{10}^-)$

The MIGP results are summarized as follows:

$R_4 = 1$, $y_{11}^- = y_{21}^- = y_{31}^- = y_7^- = y_8^- = y_9^- = y_4^+ = 1$,

$y_{42}^- = 221.2$, $y_{12}^- = 255$, $y_{13}^- = 280$, $y_{32}^- = 216$,

$y_3^- = 6.6$, $y_6^+ = 500$ and other variables are zero.

The results indicate that the best alternative will cost 500 ($y_6^+ = 500$) more Euro than the initial 10000 Euro with respect to total investment.

VI. CONCLUSIONS

The proposed model provides a way for researcher finding method in a robot selection problem having interdependent relationships.

Prior researches mainly focused on problems assuming independence. Although there are many prior researches in independent problem using AHP or other MCDM methods, there are no studies or researches on interdependent robot selection problem. It is seen that AHP is most appropriate in situations where robot costs and benefits are not known, CIM system resource constraints do not exist, robots interdependencies do not exist and an optimal solution is not needed. Although there are lots of difficulties for solving problems considering interdependent property, most of real-world problems especially, robot evaluation problems, have interdependent property. However, it is very difficult to judge whether they are having interdependent property or not. Therefore, group decision-making is more helpful to determine such an interdependent property than to decide by only one or two decision maker(s). Group discussion is more needed to determine the degree of impact among the considered criteria or alternatives because the degree of impact is varied according to decision maker.

In robot selection problem, it is very important to consider the interdependent relationship among alternative robots or criteria because of the characteristics of interdependence that exist in real problem. In addition, the cost of difficulty in data gathering for modeling is not so critical than the risk in selecting the wrong robot without considering the interdependencies.

In this paper we developed a new MCDM method for interdependent robot selection.

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