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A Cognitive Approach for Performance Measurement in Flexible Manufacturing Systems using Cognitive Maps

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1. Introduction

Cognition is a process, which includes perceiving, storing, remembering, re-calling, and using the senses. In other words, cognition consists of the physical and mental activities of understanding, commenting on, and learning to perception of our world. The term cognitive approach comes from the behavioral science of psychology.

It was challenged around the beginning of the 1980s by the concept of cognitive ergonomics that mental work (thinking) is far more important than manual work (doing) (Hollnagel, 2001). Cognitive systems mean that the analysis cannot be based on a structural decomposition of human-machine systems, but have to be referred to the notion of acting system which means that humans and machines are seen together (Lang et al., 2000; Morray, 1998).

As computer-based systems (modern manufacturing systems) become more complex, performance of the human in such systems become more critical due to the assignment of cognitive and decision making tasks to the jobshop. The rapid development of manufacturing technology requires operators to learn new skills continuously. Since humans play a critical role, the interaction between tasks and human skills must be thoroughly understood so that corporations can adapt efficiently to new technologies (Brezocnik et al., 2003; Suwingnto et al., 2000). Besides, the classical performance measurement systems are insufficient to measure human and system performance factors.

Manufacturers face an increasingly uncertain external environment as the rate of the change in customer expectations, global competition and technology accelerates, hence manufacturing flexibility has become a critical dimension. A Flexible Manufacturing System (FMS) combines NC and CNC machines, a material handling system (MHS), and a computer system to control the work. These systems are appropriate for mid-volume and mid-variety manufacturing. The components of the systems are: (1) NC and CNC machines (2) Robots and (3) Direct control unit for material handling system and CNC machines (DNC) (Zhang et al., 2003).

A hierarchy is an efficient way to organize a complex system, as it is efficient structurally when representing the system and when controlling and passing information down the system. However, many decision-making problems like cognitive performance evaluation

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cannot be structured hierarchically because they involve the interaction and dependence between levels on the constructed cognitive maps. Structuring a problem involving functional dependence allows for feedback among clusters. These systems can be analyzed with a network structure like using cognitive maps. Besides, cognitive maps are expressed the positive and negative dependences (relationships) among factors together. The Multi-Criteria Decision Making (MCDM) methods are easy way to organize these systems.

The studies on the cognitive maps have begun several years ago, and ever increasingly continued in the last years. Cognitive maps have been used in several areas. Behavioral and neurosciences are the primary fields (Sato & Yamaguchi, 2009) and medicine, biology (Byrne et al., 2009; Gras et al., 2009), zoology, advanced manufacturing systems, risks and performances of projects, computers and artificial intelligence, fuzzy systems (Gras et al., 2009; Kim et al., 2008; Fekri et al., 2009), e-business (Xirogiannis & Glykas, 2007; Lee & Ahn, 2009), and education (Hossain & Brooks, 2008) can be given working areas as example. Nowadays, the studies on the advance manufacturing systems and performance of the models have been performed widely in the recent literature (Eraslan & Kurt, 2007; Kim et al., 2008; Kim et al., 2009; Lee et al., 2009; Fekri et al., 2009) but the combination of the MCDM methods and cognitive maps have not.

In this study, one of the biggest molding factories of Europe is selected and the cognitive maps which are specific to the FMS system performance structure are established. Developing quantitative models for determination of cognitive performance factors is studied using the combination of cognitive mapping technique and the MCDM methods which are Analytical Hierarchy Process (AHP) and Analytical Network Process (ANP) to identify these factors, express, prioritize and classify them quantitatively. The factors and subfactors affecting the system performance of Flexible Manufacturing Systems are prioritized and comparatively analyzed.

In the next section, the MCDM methods used in this study are briefly explained. In the third section, the application steps are stated and the prioritization with MCDM methods is performed. Finally, the research results and conclusion remarks are summarized in the conclusion and discussion section.

2. The Multi-Criteria Decision Making (MCDM) methods

In this section, the multi-criteria decision making (MCDM) methods which are used in this study are briefly explained.

2.1 Analytical Hierarchy Process method (AHP)

The initial study identified the multi-criteria decision technique known as the Analytic Hierarchy Process (AHP) to be most appropriate for solving complicated problems. AHP was first introduced by Saaty and used in different decision-making process related to production (Bozdag et al., 2003; Buyukozkan et al., 2004), energy (Xiaohua & Zhenmin, 2002), investment (Suresh & Kaparathi, 1992), and location (Badri, 1999; Kuo et al., 2002). AHP is a comprehensive framework that is designed to cope with the intuitive, the rational, and the irrational when we make multi-objective, multi-criterion, and multi-actor decisions, with or without certainty for any number of alternatives. An advantage of the AHP over other MCDMs is that AHP is designed to incorporate tangible as well as intangible criteria especially where the subjective judgments of different individuals constitute an important

part of the decision process. The basic assumptions of AHP are that it can be used in functional independence of an upper part or cluster of the hierarchy from all its lower parts and the criteria or items in each level. AHP uses the Saaty’s 1-9 scale as shown in Table 1 (Saaty, 1996).

Low	1	Equal (low low)
	2	Between (medium low)
	3	Moderate (high low)
Medium	4	Between (low medium)
	5	Strong (medium medium)
	6	Between (high medium)
High	7	Very strong (low high)
	8	Between (medium high)
	9	Extreme (high high)

Table 1. Fundamental scale of absolute numbers for pairwise comparisons

2.2. Analytical Network Process method (ANP)

Many decision-making problems cannot be structured hierarchically because they involve the interaction and dependence of higher level elements on lower level elements (Saaty, 1986; Saaty, 1996). Structuring a problem involving functional dependence allows for feedback among clusters. This is a network system. Saaty 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, also introduced by Saaty, is a generalization of the AHP (Saaty, 1996). Whereas AHP represents a framework with a uni-directional hierarchical AHP relationship, ANP allows for complex interrelationships among decision levels and attributes. The ANP feedback approach replaces hierarchies with networks in which the relationships between levels are not easily represented as higher or lower, dominant or subordinate, direct or indirect (Meade & Sarkis, 1999). For instance, not only does the importance of the criteria determine the importance of the alternatives, as in a hierarchy, but also the importance of the alternatives may have impact on the importance of the criteria. Therefore, a hierarchical structure with a linear top-to-bottom form is not suitable for a complex system.

The ANP is a coupling of two parts. The first consist of a control hierarchy or network of criteria and subcriteria that control the interactions in the system. The second is a network of influences among the elements and clusters. The network varies from criterion to criterion and a supermatrix of limiting influence is computed for each control criterion. Supermatrix is a two-dimensional matrix of elements by elements. The priority vectors from the paired comparisons are placed in the appropriate column of the supermatrix. As the supermatrix is built in this way, the sum of each column corresponds to the number of comparison sets. Finally, each of these supermatrices is weighted by the priority of its control criterion and the results are synthesized through addition for all the control criteria. In addition, a problem is often studied through a control hierarchy or system of benefits, a second for costs, a third for opportunities, and a fourth for risks. The synthesized results of four control systems are

combined by taking quotient of the benefits times the opportunities to the costs times the risks to determine the best outcome. The process of ANP comprises of four major steps:

1. Model construction and problem structuring,
2. Pairwise comparisons matrices and priority vectors,
3. Supermatrix formation and determining limit supermatrix,
4. Synthesize the results.

Over the years, ANP, a comprehensive multi-purpose decision method, has been widely used in solving many complicated decision-making problems. Meade and Sarkis (1999) used ANP in a methodology they developed to evaluate logistic strategies and to improve production speed. Also in a separate study performed by Lee and Kim (2001), ANP is used in the interdependent information system project selection process. In addition to these studies Sarkis (2002), in a model he developed for the purpose of strategic supplier selection; Mikhailov and Singh (2003), in the development process of a decision support system; Yurdakul (2003), in a model he built in order to evaluate long term performances of production systems; Momoh and Zhu (2003), in specifying optimal production schedules; Niemira and Saaty (2004), in financial crisis forecasting, used ANP method.

3. Prioritization of the cognitive factors utilizing MCDM methods for FMS system performance

In this section, AHP and ANP models are developed to prioritize of the performance measurement factors. At the beginning, a systematic way must be put forward to consider, determine and calculate the cognitive performance factors. The hierarchical structures could be established via cognitive maps' specifications, and the factors of cognitive performance for the FMS system could be designated. In this study, the steps stated below are followed and each step is explained briefly in the following sections:

- i. Determine the cognitive performance factors for the FMS system and their importance levels via brainstorming with system experts and managers.
- ii. Establish the hierarchy levels for individual and system performance using the factors' importance and experts' view.
- iii. Determine the effects of dependences among factors, i.e., the interrelations among the factors using cognitive maps.
- iv. Examine the vertical relations with AHP method i.e., establish the cognitive performance decision matrices (CPDM) via pairwise comparisons and calculate the weights.
- v. Determine the dependences of the factors for each level and examine the new effects with ANP method.
- vi. Calculate the global weights with both MCDM methods, compare each other, and analyze the differences.

3.1 Determination of the cognitive system performance factors

The criteria in the developed model are determined with an expert team including the participations of related department managers, production chiefs, and the authors of this study. Firstly, the team members propose criteria to use in the performance model. Later, the proposed criteria are evaluated together and the final criteria to put into model are determined. Totally 22 factors and subfactors are determined. The structure of the model about decision problem is stated, and adding the connections between the factors and the Cognitive Map (network model) was developed (Eraslan&Kurt, 2007).

3.2 Establishing the hierarchy of the factors using cognitive maps

The developed model consists of four main criteria and 18 subfactors in 3 levels which are shown in Fig. 1. At the top of the hierarchy, there exists the goal of the problem which determines the prioritization of cognitive factors affects FMS system performance. Expert team decides that flexibility (FLEX), production speed (PS), product variety (PV), and customer satisfaction (CS) have some importance levels for the determined goal in the first level. Material (MF), operation (OF), material handling (MHF), and rotating flexibilities (RF) are the subfactors of the flexibility; flow rate (FR) and the buffers (BU) are the subfactors of the production speed; product quality (PQ) and total cost (TC) are the subfactors of the customer satisfaction in the second level. The subfactors of material handling are robots (RO), AS/RS Systems (ASRS), and Automated Guided Vehicles (AGV); the subfactors of flow rate are NC (NC), CNC (CNC), and DNC (DNC); and finally the subfactors of total cost are setup cost (SC), purchasing cost (PC), labor cost (LC), and production volume (VO) stated in the third level.

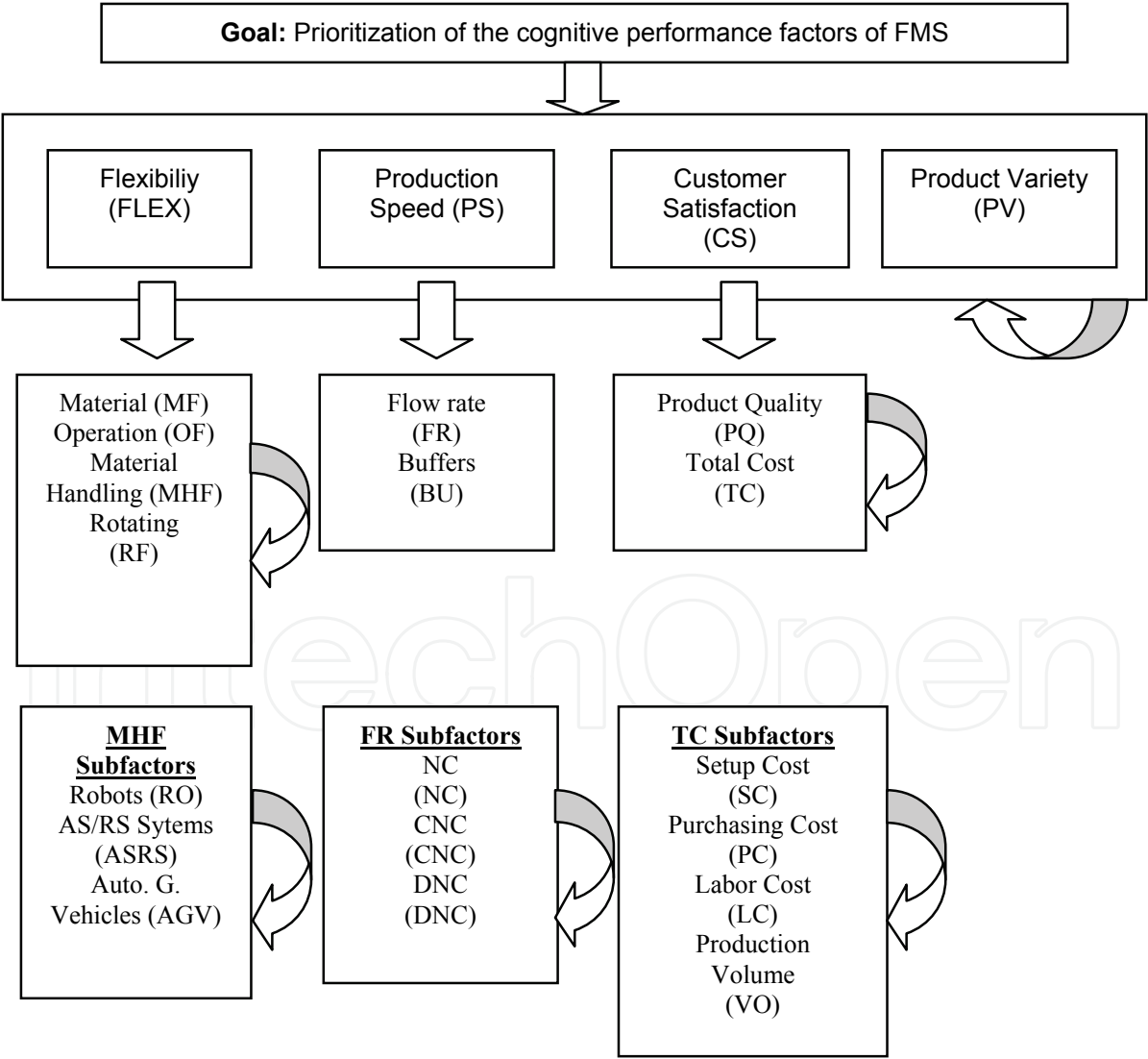


Fig. 1. The Cognitive Map of FMS System Factors

3.3 Prioritization of the performance factors with AHP method

After setting up the cognitive map and required connections, pairwise comparisons are performed. In order to do the pairwise comparisons, a questionnaire is designed and the views of expert team members are taken therein. While taking the judgment for each individual in expert team, interviews were made separately each other by using questionnaire technique. The scale that takes integer values between 1 and 9 were used in the recommended technique (Saaty, 1996). The valuation scales in the pairwise comparisons are those, where 1 is equal importance, 3 is moderate importance, 5 is strong importance, 7 is very strong or demonstrated importance, and 9 is extreme importance. Even numbered values will fall in between importance levels as shown in Table 1.

Pairwise comparisons were based on upper level main criteria. Weights of the criteria must be determined first. For this reason, the expert team made their pairwise comparisons about strategic criteria and notified their judgments according to overall goal. As a result, pairwise comparison matrix is obtained to determine the criteria priorities. The pairwise comparison matrices are obtained for second and third level in the hierarchy without taking into consideration the relationships among factors. Then, overall weights are calculated as shown in Table 2.

Level	Factors	FLEX	PS	CS	PV
1	Weights	0.526	0.249	0.085	0.141
Level 2	Subfactors	MF	OF	MHF	RF
	Weights	0.070	0.508	0.193	0.229
	Subfactors	FR	BU	PQ	TC
	Weights	0.667	0.333	0.750	0.250
Level 3	Subfactors	RO	ASRS	AGV	
	Weights	0.633	0.106	0.260	
	Subfactors	NC	CNC	DNC	
	Weights	0.074	0.283	0.643	
	Subfactors	SC	PC	LC	VO
	Weights	0.079	0.151	0.254	0.516

Table 2. Overall weights of the main criteria and the subfactors

3.4 Prioritization of the performance factors with ANP method using the dependences among factors

This network consists of four kinds of subnetworks: flexibility (FLEX), production speed (PS), product variety (PV), and customer satisfaction (CS) each of which represents the relationship of its own clusters and elements as shown in Fig. 2.

On the basis of the dependences shown in Fig. 2., dependence matrix is organized utilizing pairwise comparison matrices. The dependent weights (CPDM_{GOAL}) are obtained multiplying with the first weights of the factors and pairwise comparison matrix given in Table 2.

$$CPDM_{GOAL} = \begin{bmatrix} 1 & 1/3 & 0 & 1/2 \\ 0 & 2/3 & 1/3 & 0 \\ 0 & 0 & 1/3 & 0 \\ 0 & 0 & 1/3 & 1/2 \end{bmatrix} * \begin{bmatrix} 0.526 \\ 0.249 \\ 0.085 \\ 0.141 \end{bmatrix} = \begin{bmatrix} 0.650 \\ 0.213 \\ 0.046 \\ 0.094 \end{bmatrix}$$

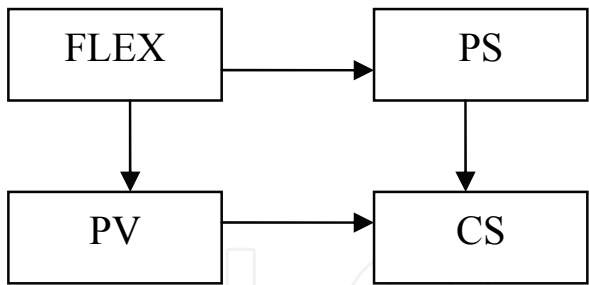


Fig. 2. Dependences (interrelations) among main factors in the first level (main criteria: GOAL).

It is shown that a significant difference is appeared when compare with the weights without using dependences (AHP) more particularly for FLEX and PV.

In the next step, the dependences among the subfactors in the second level of the cognitive map are analyzed. These dependences are viewed in the Fig. 3.

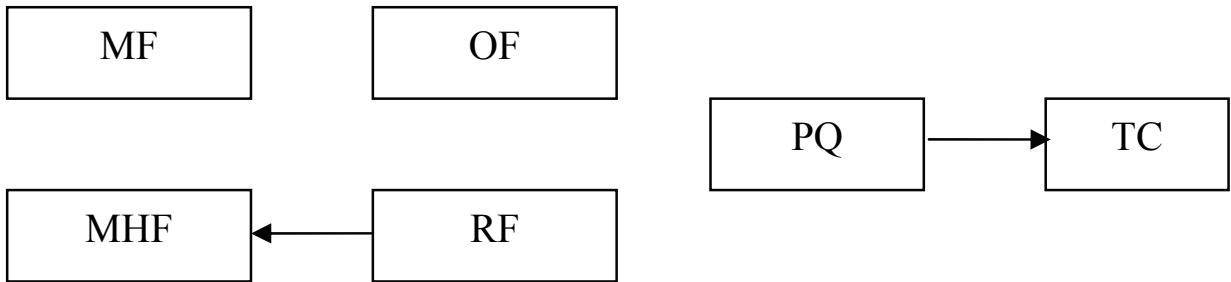


Fig. 3. Dependences among subfactors in the second level (FLEX, CS).

Using the dependences of Fig. 3, the dependence matrices are obtained for both groups with pairwise comparison matrices. Then, dependent weights of subfactors are calculated multiplying the first weights of subfactors. These calculations are given below ($CPDM_{FLEX}$, $CPDM_{CS}$):

$$CPDM_{FLEX} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 2/3 & 0 \\ 0 & 0 & 1/3 & 1 \end{bmatrix} * \begin{bmatrix} 0.070 \\ 0.508 \\ 0.193 \\ 0.229 \end{bmatrix} = \begin{bmatrix} 0.070 \\ 0.508 \\ 0.129 \\ 0.293 \end{bmatrix}$$
$$CPDM_{CS} = \begin{bmatrix} 1 & 2/3 \\ 0 & 1/3 \end{bmatrix} * \begin{bmatrix} 0.750 \\ 0.250 \end{bmatrix} = \begin{bmatrix} 0.920 \\ 0.080 \end{bmatrix}$$

After the calculations of $CPDM_{FLEX}$, $CPDM_{CS}$ matrices, it is shown that the weights of the subfactors of MF and OF are remained same expectedly in the FLEX group but the weights of MHF and RF is significantly changed. In the CS group, the weight of the subfactor PQ is increased but the TC is decreased.

In the third step, the dependences of the subfactors in the third level of the cognitive map are determined and analyzed. The interrelations of the subfactors are shown in Fig. 4.

On the basis of Fig. 4, the dependence matrices are constituted for three groups utilizing pairwise comparison matrices. Multiplying the first weights of subfactors and dependence matrices, dependent weights of subfactors are calculated. These calculations are given below ($CPDM_{MHF}$, $CPDM_{FR}$, $CPDM_{TC}$):

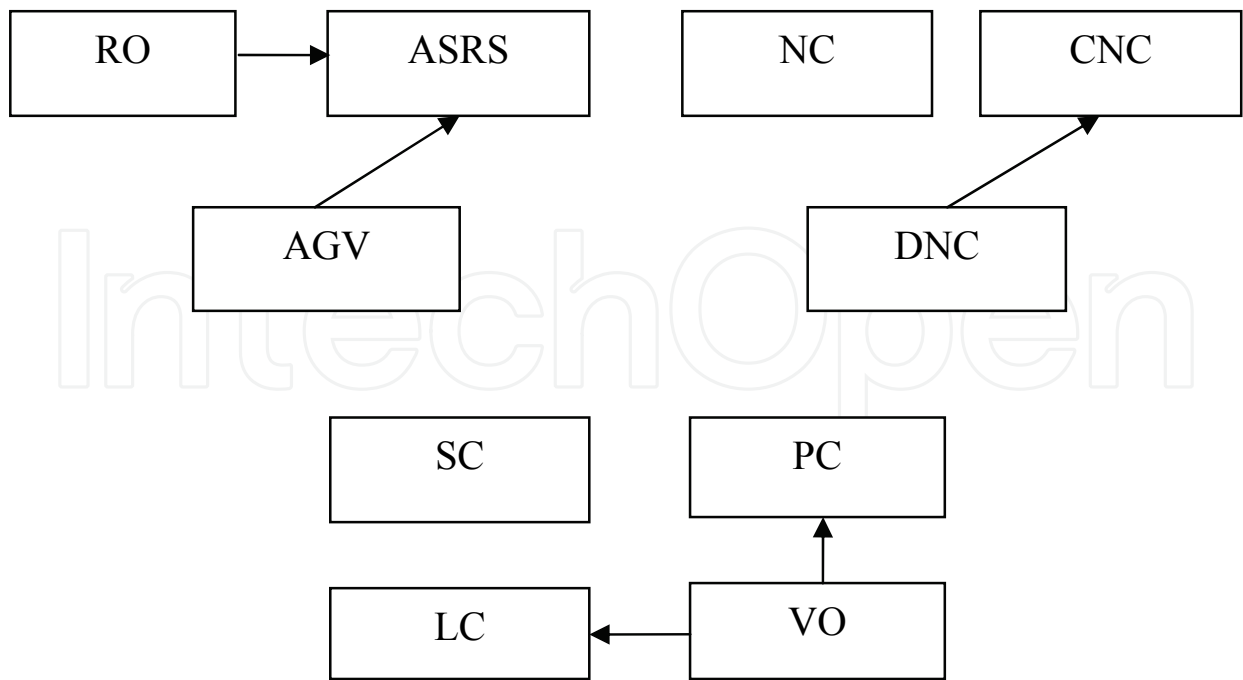


Fig. 4. Dependences among subfactors in the third level (MHF, FR, TC).

$$CPDM_{MHF} = \begin{bmatrix} 1 & 1/3 & 0 \\ 0 & 1/3 & 0 \\ 0 & 1/3 & 1 \end{bmatrix} * \begin{bmatrix} 0.633 \\ 0.106 \\ 0.260 \end{bmatrix} = \begin{bmatrix} 0.668 \\ 0.037 \\ 0.295 \end{bmatrix}$$

$$CPDM_{FR} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 3/4 & 0 \\ 0 & 1/4 & 1 \end{bmatrix} * \begin{bmatrix} 0.074 \\ 0.283 \\ 0.643 \end{bmatrix} = \begin{bmatrix} 0.075 \\ 0.212 \\ 0.713 \end{bmatrix}$$

$$CPDM_{TC} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 3/4 & 0 & 0 \\ 0 & 0 & 9/10 & 0 \\ 0 & 1/4 & 1/10 & 1 \end{bmatrix} * \begin{bmatrix} 0.079 \\ 0.151 \\ 0.254 \\ 0.516 \end{bmatrix} = \begin{bmatrix} 0.079 \\ 0.114 \\ 0.228 \\ 0.579 \end{bmatrix}$$

Depend on the interrelations of the third level, some particular changes of the subfactors are observed. The significant changes are calculated for subfactor ASRS in MHF group; for subfactors CNC and DNC in FR group; and for subfactor VO in TC group.

3.5 Comparison of the results

First, the global weights of factors/subfactors are calculated with AHP method accepting that the subfactors are independent each other or in the same level. Then, the interrelations among factors/subfactors are considered using the feature of the ANP method. Thus, the new and more sensitive weights are calculated and more accurate results are obtained. These results are comparatively analyzed (Saaty, 2006) and given in the Table 3.

Level 1	Factors	FLEX	PS	CS	PV
	AHP	0.526	0.249	0.085	0.141
	ANP	0.650	0.213	0.046	0.094
Level 2	Subfactors	MF	OF	MHF	RF
	AHP	0.070	0.508	0.193	0.229
	ANP	0.070	0.508	0.129	0.293
	Subfactors	FR	BU	PQ	TC
	AHP	0.667	0.333	0.750	0.250
	ANP	0.667	0.333	0.920	0.080
Level 3	Subfactors	RO	ASRS	AGV	
	AHP	0.633	0.106	0.260	
	ANP	0.668	0.037	0.295	
	Subfactors	NC	CNC	DNC	
	AHP	0.074	0.283	0.643	
	ANP	0.075	0.212	0.713	
	Subfactors	SC	PC	LC	VO
	AHP	0.079	0.151	0.254	0.516
	ANP	0.079	0.114	0.228	0.579

Table 3. The comparison the weights of factors/subfactors for AHP and ANP Methods

4. Conclusion and discussion

In this study, a cognitive approach for the factors effecting performance of FMS system have been developed and explained using cognitive maps. The benefits of this approach show four new improvements:

- The complex structure of cognitive performance is established for a specific FMS system by cognitive mapping technique.
- The MCDM methods i.e., AHP and ANP have been applied to the dynamic structure of the system and the decisions of the production managers and related stuffs are included in decision processes. The results are comparatively analyzed; more sensitive results are obtained utilizing interrelations for factors and subfactors.
- The dynamic nature of the internal and external environments of jobshop has been included to the performance measurement system.
- The factors that affect performance can be identified; their effects can be quantified effectively by this approach.

According to the results, comparing the AHP and ANP matrices, the 17 of the global weights of the cognitive performance factors/subfactors are changed, 5 of them are remained stable.

The proposed model can help managers to evaluate the levels of the impact to each factor and make the interrelations clearly on overall performance. Therefore this model can be

regarded as a detailed Decision Support System (DSS) to monitoring and determine the cognitive problems in workplace for modern manufacturing systems in future studies.

The overall effect of factors can be designed a investigating system by using performance charts to follow the dynamic behavior of cognitive systems in certain periods, since they have to be monitored frequently or occasionally and do not remains stable.

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