Journal of Applied Research on Industrial Engineering

Journal of Applied Research on Industrial Engineering

Vol. 1, No. 4 (2014) 230-249

Journal of
Applied Research on Industrial Engineering

Hybrid Approach of ANP and DEMATEL for Selecting Optimal Maintenance Strategy: a case study in the pharmaceutical industry

Ali Nakhjavani [a*], Naser Mollaverdi [b], Farimah Mokhatab Rafiei[c]

[a] Department of Industrial Engineering, Najafabad Branch, Islamic Azad University, Isfahan, Iran (Nakhjavani_n@yahoo.com)
[b] Department of Industrial Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran (naserm@cc.iut.ac.ir)
[c] Department of Industrial Engineering, Isfahan University of Technology , Isfahan 84156-83111, Iran (farimah@cc.iut.ac.ir)

A R T I C L E I N F O

Article history :
Received:
15 October 2014
Received in revised format:
20 October 2014
Accepted:
25 October 2014
Available online:
1 December 2014

Keywords :
Maintenance, Strategy Criteria, DEMATEL ANP

A B S T R A C T

Organizations' competitiveness and efficiency depend on the reliability, availability and productivity of their production equipment today. In order t o increase reliability and safety level with reasonable cost, it is vital for companies to select the appropriate maintenance strategy. Among all the duties of maintenance departments, having a proper maintenance strategy developed based on the needs of the organization and aligned with the organization's goals is a necessity. It is also considered the first and most important step toward the department's success. This paper presents a hybrid approach of analytical network process and DEMATEL to select optimal maintenance strategy. Results revealed that the best maintenance strategy for transformer equipments of Exir Pharmaceutical Company of Boroujerd is reliability centred maintenance.

1. Introduction

Manufacturing companies face great pressure to decrease their manufacturing costs continuously. One of the main expenditure items for these firms is maintenance cost which can reach 15–70% of production costs, varying according to the type of company (Bevilacqua and Braglia, 2000). Maintenance management has found new vigour and purpose to increase equipment capacity and capability due to increasing focus on lean manufacturing in today's competitive environment (Sawhney et al., 2009).

*Corresponding author name: Ali Nakhjavani E-mail address: Nakhjavani_n@Yahoo.com

The amount of money spent on maintenance in a selected group of companies is appraised to be about 600 billion dollars in 1989 (Wireman, 1990, cited by Chan et al., 2005). On the other hand, maintenance plays a significant role in keeping availability and reliability levels, product quality, and safety requirements. While minimum maintenance cost with good maintenance actions is ideal to all manufacturers, do more maintenance, will reduce chances of machine breakdowns but will produce more maintenance cost. Contrary, do less maintenance, will produce less maintenance cost but has more changes to face with machine breakdowns. Therefore, the optimal maintenance policy will be helpful for solving this problem (Wongmongkolrit and Rassameethes, 2011). Unfortunately, unlike production and manufacturing problems which have received great interest from researchers and practitioners, maintenance received little attention in the past. This is one of the reasons that results in low maintenance efficiency in industry at present. As indicated by Mobley (2002), one third of all maintenance costs are wasted as the result of redundant or unsuitable maintenance activities. Today, research in this area is on the rise. Moreover, the role of maintenance is changing from a 'necessary evil' to a 'profit contributor' and towards a 'partner' of firms to obtain world-class competitiveness (Waeyenbergh and Pintelon, 2002). Although the selection of the suitable maintenance strategy for each piece of equipment is importance for manufacturing companies, few studies have been done on this problem.

It is important to note that each maintenance strategy might have strength and weakness. Therefore, selection of the suitable strategy is one of the most significant problems for maintenance managers. The degree of importance of selecting a suitable maintenance strategy is different in various manufacturing systems. In continuous manufacturing systems, the issue of selecting suitable maintenance strategy is more critical than other systems, because failure of equipment leads to stoppage of manufacturing line.

In addition to the reviewed literature, Hadidi et al. (2012) has studied the literature on models addressing different aspects of integration in the areas of production planning, scheduling, maintenance and quality. They found that this integration is treated in two different ways. The first way is to present models where a model is considered for one function taking into account the other. These models are referred to as interrelated models. The second way is to simultaneously model two or more elements of the production system. These models are referred to as integrated models. It is important to note that each maintenance strategy might have strength and weakness. Therefore, selection of the appropriate strategy is one of the most important problems for maintenance managers. The degree of importance of selecting a suitable maintenance strategy is different in various manufacturing systems. In continuous manufacturing systems, the problem of selecting suitable maintenance strategy is more critical than other systems, because stoppage of equipment leads to stoppage of manufacturing line. Considering the reviewed literature it is apparent that selection of suitable maintenance strategy is almost a multi-criteria decision-making problem, and selection of optimum maintenance strategy needs consideration of various criteria.

In this research, first a list of maintenance objectives which are derived from the research literature is provided to the organization's experts, and then was asked of them to choose the organization's most important demands from these objectives, inquiring from the maintenance department in a way that objectives are proportional to the organization's needs. The Functional and Technical aspects of these objectives with the sub criteria of Maintenance Quality, Availability, Reliability, Maintainability, Overall Equipment Effectiveness (OEE), Productivity, and Output Quality are determined as the most important objectives for the maintenance department.

Also four strategies for maintenance based on Reliability Centered Maintenance (RCM), Total Productive Maintenance (TPM), Preventative Maintenance (PM), and Predictive Maintenance (Pdm) are selected for competition by the experts.

Ultimately, the DEMATEL method for determining the relationships between the sub criteria using analytic network process for selection of strategies of maintenance is used for optimal equipment manufacturing sector of the EXIR Pharmaceutical Factories in Boroujerd city.

This paper is organized as follows. First, literature review is written about maintenance and maintenance selection, then ANP and DEMATEL are overviewed and proposed model is introduced. The method is demonstrated through a case study from local industry in Boroujerd. Results are discussed and benefits are identified.

2. Literature review

Maintenance is classified into two main categories: corrective and preventive (Li et al., 2006; Waeyenberg and Pintelon, 2004). Corrective maintenance is performed after system failure and preventive maintenance is performed before its failure (Wang, 2002). Corrective maintenance, also called breakdown maintenance, is the oldest strategy in the industry (Waeyenberg and Pintelon, 2002; Mechefske and Wang, 2003; Wang et al., 2007). For large profit margin organizations, this policy can be seen as feasible strategy (Sharma et al., 2005).

Preventive maintenance, in practice, has two forms; periodic and predictive. In periodic maintenance, as the name suggests, maintenance is performed periodically to prevent sudden failure (Wang et al., 2007). This strategy is also called “time-based maintenance” and is used by many firms in the industry following manufacturer’s recommendations, which sometimes results in unnecessary maintenance activities. In predictive maintenance, maintenance decisions are made based on information collected from special measurement instruments like sensor systems, monitoring techniques, vibration monitoring, lubrication analysis and ultrasonic testing (Wang et al., 2007). This strategy is also known as condition-based maintenance. In addition to these, opportunistic maintenance is used by some large-scale industries such as petroleum and petrochemical industries. Bevilacqua and Braglia (2000) defined the opportunistic maintenance as “maintenance can lead to the whole plant being shut down at set times to perform all relevant maintenance interventions at the same time.”

Studies on maintenance systems in practice show that some managers are unaware of the different types of maintenance policies (Shorrocks, 2000; Shorrocks and Labib, 2000) and selection methods. Luce (1999), Okumura and Okino (2003) presented the maintenance selection method based on production loss and maintenance cost. Azadivar and Shu (1999) showed the effective methods of selecting appropriate (optimum) maintenance strategies for just in time production systems. Al-Najjar and Alsyouf (2003), Sharma et al. (2005) used fuzzy inference theory and fuzzy multiple criteria decision making methodology. Moreover, Mechefske and Wang (2003) showed a new method for selecting the optimum maintenance strategy and condition monitoring technique. Almeida and Bohoris (1995) developed a new method using decision-making theory especially the multi-attribute utility theory.

Triantaphyllou et al. (1997) presented AHP model with four maintenance criteria:

(1) Cost;

(2) Reparability;

(3) Reliability; and

(4) Availability.

In addition to these, Bertolini and Bevilacqua (2006) proposed a combined goal programming and AHP for maintenance selection. Wang et al. (2007) developed a fuzzy AHP model for selection of optimum maintenance strategy. Labib et al. (1998) developed a model of maintenance decision making, which includes AHP. In the first stage, criteria are identified and then in the second stage AHP is applied. Last, machines are ranked according to their importance. Arunraj and Maiti (2010) used AHP and goal programming for maintenance policy selection according to risk of failure and cost of maintenance in a chemical factory. They concluded that if risk is chosen as a criterion, predictive maintenance is preferred policy over periodic maintenance. Similarly, if cost is chosen as a criterion, corrective maintenance is preferred. Nevertheless, if both risk and cost are considered, AHP-GP results show that predictive maintenance and corrective maintenance are best for high-risk equipment and low-risk equipment, respectively.

Labib (2004) also developed a model for maintenance policy selection using a computerized maintenance management system. In this study, fuzzy logic and AHP are used. HajShirmohammadi and Wedley (2004) used an AHP model for maintenance management for centralization and decentralization. Centralized system means that all maintenance systems are managed from a centrally administered location. However, decentralized system implies that each production area manages its own maintenance systems. Shyjith et al. (2008) developed a model using AHP and TOPSIS for maintenance selection in textile industry and then Ilangkumaran and Kumanan (2009) integrated fuzzy AHP and TOPSIS algorithm to select the maintenance policy for textile industry. Shahin et al. (2012) used ANP for maintenance policy selection according to Reliability, Availability, maintainability and cost of maintenance in Chadormalu Mining-Industrial Company. Pourjavad et al. (2013) used ANP and TOPSIS for maintenance policy selection. The main aim of this study is to recommend an efficient method to determine the most suitable maintenance strategy. The main purpose of this study is to develop an analytic network process ANP method and the technique for order preference by similarity to an ideal solution TOPSIS for selecting suitable maintenance strategy. Shahin et al. (2013) used decision making grid, Sigma level, and process capability index for Determining appropriate maintenance strategy. For this purpose, decision making grid (DMG) has been developed. Sigma level and process capability indexes have been used based on the metric of mean time between failures (MTBF). The proposed approach has been examined on 26 equipments of a steel manufacturing company.

Hong Ding et al. (2014) developed a model for optimal maintenance policy selection. This paper focuses on developing a model to select the optimal maintenance policy with integration of failure modes and effect analysis and technique for order preference by similarity to idea solution. the main objective of this paper is to propose a maintenance policy selection model that could assist maintenance personnel in identifying an optimal maintenance policy systematically.

3. Integrated methods combined DEMATEL and ANP

In this section, an integrated method, combined DEMATEL method, and a novel cluster-weighted ANP method is developed. The procedures that are used in the proposed method are described as follows.

3.1. The DEMATEL method

The DEMATEL method is based upon graph theory, enabling us to plan and solve problems visually, so that we may divide multiple criteria into a cause-and-effect group, to better understand causal relationships to plot a network relationship map. Directed graphs (also called digraphs) are more useful than directionless graphs, because digraphs will demonstrate the directed relationships of sub-systems.

A digraph may typically represent a communication network, or some domination relationships between individuals. The methodology can confirm interdependence among variables/criteria and restrict the relations that reflect characteristics within an essential systemic and developmental trend (Chiu, Chen, Tzeng, & Shyu, 2006; Hori & Shimizu, 1999; Tamura, Nagata, & Akazawa, 2002). The end product of the DEMATEL process is a visual representation by which the respondent organizes his or her action in the world (Tzeng et al., 2007), e-learning evaluation (Tzeng et al., 2007), airline safety measurement (Liou et al., 2007), and innovation policy portfolios for Taiwan's SIP Mall (Huang & Tzeng, 2007).

The DEMATEL method can be summarized in the following steps:

Step 1: Find the average matrix.

Suppose we have H experts in this study and n criteria to consider. Each expert is asked to indicate the degree which represents he or she believes a criterion i affects criterion j. These pairwise comparisons between any two criteria are denoted by a_{ij} and are given an integer score ranging from 0, 1, 2, 3, and 4, representing 'No influence (0),' 'Low influence (1),' 'Medium influence (2),' 'High influence (3),' and 'Very high influence (4),' respectively. The scores by each expert will give us a n × n non-negative answer matrix $X^k = [x_{ij}^k]_{n\times n}$, with $1 \le k \le H$. Thus, $X^1, X^2, \ldots, X^H$ are the answer matrices for each of the H experts, and each element of X^k is an integer denoted by x_{ij}^k. The diagonal elements of each answer matrix X^k are all set to zero. We can then compute the n × n average matrix A for all expert opinions by averaging the H experts' scores as follows:

$$A= [a_{ij}]_{n\times n} = \frac{1}{H}\sum_{k=1}^{H}[X_{ij}]_{n\times n} \qquad (1\text{-}3)$$

The average matrix $A = [a_{ij}]_{n\times n}$ is also called the initial direct relation matrix. A show the initial direct effects that a criterion exerts on and receives from other criteria. Furthermore, we can map out the causal effect between each pair of criteria in a system by drawing an influence map (if $a_{ij} \le 1$ for ∀i,j, we can identify among all criteria are independent; otherwise, we can identify all criteria are non-independent). Fig. 1 below is an example of such a network influence map. Each letter represents a criterion in the system. An arrow from c to d shows the effect that c has on d, and the strength of its effect is 4. DEMATEL can convert the structural relations among the criteria of a system into an intelligible map of the system.

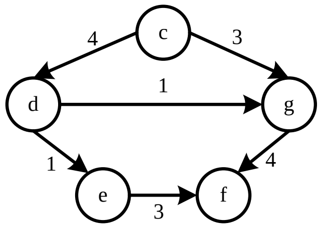

Fig. 1. *Example of an influence map.*

Step 2: Calculate the normalized initial direct-relation matrix.

The normalized initial direct-relation matrix D is obtained by normalizing the average matrix A in the following way:

Let s = max $\left(\max_{1\le i\le n} \sum_{j=1}^{n} a_{ij}\ ; \max_{1\le i\le n} \sum_{i=1}^{n} a_{ij}\right)$ (2-3)

Then D = $\frac{A}{S}$ (3-3)

Since the sum of each row i of matrix A represents the total direct effects that criterion i gives to the other criteria, $\max_{1\le i\le n} \sum_{j=1}^{n} a_{ij}$ represents the total direct effects of the criterion with the most direct effects on others. Likewise, since the sum of each column j of matrix A represents the total direct effects received to other criteria by criterion i, $\max_{1\le j\le n} \sum_{i=1}^{n} a_{ij}$ represents the total direct effects that the criterion j receives the most direct effects from other criteria. The positive scalar s takes the smaller of the two as the upper bound, and the matrix D is obtained by dividing each element of A by the scalar s. Note that each element d_{ij} of matrix D is between ero and less than 1.

Step 3: Compute the total relation matrix.

A continuous decrease of the indirect effects of problems along the powers of matrix D, e.g. D^2, D^3, . . . , D^∞, guarantees convergent solutions to the matrix inverse similar to an absorbing Markov chain matrix. Note that $\lim_{m\to\infty} D^m = [0]_{n\times n}$ and $\lim_{m\to\infty} (I + D + D^2 + D^3 + \cdots + D^m) = (I - D)^{-1}$, where 0 is the n × n null matrix and I is the n × n identity matrix. The total relation matrix T is an n × n matrix and is defined as follow:

T= $[t_{ij}]$ $\quad i, j = 1,2, \ldots , n$ (4-3)

T = $(D + D^2 + D^3 + \cdots + D^m) = D(I + D + D^2 + D^3 + \cdots + D^{m-1}) =$ (5-3)

$D[(I + D + D^2 + D^3 + \cdots + D^{m-1})(1 - D)](1 - D)^{-1} = D(I - D)^{-1}$

as $m\to\infty$ and $[(I + D + D^2 + \ldots + D^{m-1})(1 - D)] = I - D^m$

We also define r and c as n ×1 vector representing the sum of rows and sum of columns of the total relation matrix T as follows:

r = $[r_i]_{n\times 1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1}$ (6-3)

c = $[c_j]'_{1\times n} = \left[\sum_{i=1}^{n} t_{ij}\right]_{1\times n}$ (7-3)

where superscript ′ denotes transpose.

Let $r_i = \sum_{j=1}^{n} t_{ij}$ be the sum of ith row in matrix T. Then r_i shows the total effects, both direct and indirect, given by criterion i to the other criteria j = 1, 2. . . n. Let $c_j = \sum_{i=1}^{n} t_{ij}$ denotes the sum of jth column in matrix T. Then c_j shows the total effects, both direct and indirect, received by criterion j from the other criteria i = 1, 2. . . n. Thus when j = i, the sum ($r_i + c_i$) gives us an index representing the total effects both given and received by criterion i.

In other words, ($r_i + c_i$) shows the degree of importance (total sum of effects given and received) that criterion i plays in the system. In addition, the difference ($r_i - c_i$) shows the net effect that criterion i contributes to the system. When ($r_i - c_i$) is positive, criterion i is a net causer, and when $(r_i - c_i)$ is negative, criterion i is a net receiver (Tamura et al., 2002; Tzeng et al. 2007).

Step 4: Set a threshold value and obtain the network relationship map (NRM).

In order to explain the structural relation among the criteria and keep the complexity of the system to a manageable level at the same time, it is necessary to set a threshold value p to filter out some negligible effects in matrix T. Only some criteria, whose effect in matrix T is greater than the threshold value, should be chosen and shown in a network relationship map (NRM) for influence (Tzeng et al., 2007). In this paper, the threshold value has been decided by experts through discussions. After the threshold value is decided, the final influence result of criteria can be shown in a NRM. To clearly represent the procedures of the DEMATEL method, a simple example is developed to show how the NRM can be obtained and as well as how the relationships of criteria discussed above can be determined. For example, suppose a system contains three criteria C_1, C_2 and C_3, the total-influence matrix T can be derived by running from step1 to step 4.

Next, based on the threshold value p, we can filter the minor effects in the elements of matrix T. The values of elements in matrix T are zero if their values less than p. That is, there are lower influences with other criteria when their values are less than p. Thus, a new total-influence matrix T_p can be obtained and the NRM can also be shown as Figure. 2 below.

$$\mathbf{T_p} = \begin{array}{c} \\ \mathbf{c_1} \\ \mathbf{c_2} \\ \mathbf{c_3} \end{array} \begin{array}{c} \begin{array}{ccc} \mathbf{c_1} & \mathbf{c_2} & \mathbf{c_3} \end{array} \\ \begin{bmatrix} \mathbf{0} & t^p_{12} & t^p_{13} \\ t^p_{21} & \mathbf{0} & t^p_{23} \\ \mathbf{0} & \mathbf{0} & t^p_{33} \end{bmatrix} \end{array}$$

3.2. The ANP method

The ANP is an extension of AHP, and it is the general form of analytic hierarchy process (AHP). The ANP handles dependence within a criterion (inner dependence) and among different criteria (outer dependence). AHP models a decision making framework using a unidirectional hierarchical relationship among criteria, but ANP allows more complex interrelationships among criteria. A major difference between the two techniques is the existence of a feedback relationship among criteria within this framework.

The method of the ANP can be described as follows. The first step of the ANP is to compare the criteria in whole system to form the super-matrix. This is done through pair-wise comparisons by asking ‘‘How much importance/influence does a criterion have compared to another criterion with respect to our interests or preferences?” The relative importance value can be determined using a scale of 1–9 to represent equal importance to extreme importance (Saaty, 1980, 1996). The general form of the super-matrix can be described as follows:

$$
\mathbf{W} = \begin{array}{cc} & \begin{array}{cccc} C_1 & C_2 & & C_n \\ e_{11} \cdot e_{1m1} & e_{21} \cdot e_{1m2} & & e_{n1} \cdot e_{nm} \end{array} \\ \begin{array}{c} C_1 \; e_{11}, e_{12}, \ldots, e_{1m} \\ C_2 \; e_{21}, e_{22}, \ldots, e_{2m} \\ \vdots \\ C_n \; e_{n1}, e_{n2}, \ldots, e_{nm} \end{array} & \begin{bmatrix} W_{11} & W_{12} & \cdots & W_{1n} \\ W_{21} & W_{22} & \cdots & W_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ W_{n1} & W_{n2} & \cdots & W_{nn} \end{bmatrix} \end{array}
$$

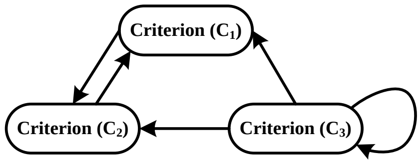

Fig. 2. *The NRM of the system*

where C_n denotes the nth cluster, e_{nm} denotes the mth element in nth cluster, and W_{ij} is the principal eigenvector of the influence of the elements compared in the jth cluster to the ith cluster. In addition, if the jth cluster has no influence to the ith cluster, then W_{ij} = [0].

After, the weighted super-matrix is obtained by multiplying the total-influence matrix, which is derived according to DEMATEL method. Traditional, the weighted super-matrix is derived by transforming all columns sum to unity exactly. This step is much similar to the concept of Markov chain which ensures the sum of these probabilities of all states equals to 1. However, we know each criterion's affect the other criteria may be different according to the results of the DEMATEL method. If the influence degrees of these criteria are regarded as equal, that is, using average method to obtain the weighted super-matrix. The results of the assessed weights would be higher or lower than the real situation. It would be irrational and unsuitable in real situation. For this reason, we intend adopt the DEMATEL method to overcome the shortcomings, and suppose that the total-influence matrix T_p has been determined according to the DEMATEL method result. Because the influence degrees between criteria in the total-influence matrix T_p are different, all criteria of the total-influence matrix T_p should be normalized. The normalized elements of the total-influence matrix T_p are $t_{ij}^{z} = \frac{t_{ij}^{p}}{\sum_{i=1}^{n} t_{ij}^{p}}$ and the normalized total-influence matrix T_z is represented as follows:

$$
\mathbf{T_z} = \begin{bmatrix} \mathbf{T}^{z}_{11} & \cdots & \mathbf{T}^{z}_{1j} & \cdots & \mathbf{T}^{z}_{1n} \\ \vdots & & \vdots & & \vdots \\ \mathbf{T}^{z}_{i1} & \cdots & \mathbf{T}^{z}_{ij} & \cdots & \mathbf{T}^{z}_{in} \\ \vdots & & \vdots & & \vdots \\ \mathbf{T}^{z}_{n1} & \cdots & \mathbf{T}^{z}_{nj} & \cdots & \mathbf{T}^{z}_{nn} \end{bmatrix}
$$

Furthermore, the weighted super-matrix W_w such as Eq. can be calculated by multiplying the unweighted supermatrix W and the normalized total-influence matrixT_z. That is W_w= $T_z \times$ W finally, we raise the weighted super-matrix to limiting powers l such as Eq. until the super-matrix converged to get the global priority vectors or weights. $\lim_{l\to\infty} W_w^l$ In addition, if the limiting super-matrix is not the only one, it would be calculated to get the final weighted limiting super-matrix W_f (i.e., the average priority weights) as In addition, if the limiting super-matrix is not the only one, it would be calculated to get the final weighted limiting super-matrix

W_f (i.e., the average priority weights) as $\lim_{k\to\infty}(\frac{1}{N})\sum_{j=1}^{N} W_j^k$ where W_j denoted the jth limiting super-matrix. The following figure shows the combined techniques of ANP and DEMATEL. Figure 3 presents a conceptual combined technique of ANP and DEMATEL.

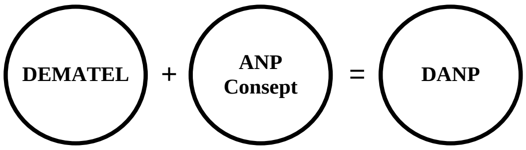

Fig. 3. DEMATEL and ANP, Tzeng (2011)

4. Optimum maintenance strategy selection with ANP-DEMATEL

In this paper by integrating ANP and DEMATEL methods a suitable method to select suitable maintenance strategies is proposed. At first a list of maintenance objectives which is derived from the research literature, is provided to the organization's experts and then was asked of them to choose the organization's most important demands from these objectives from the maintenance department in a way that objectives are proportional to the organization's needs. Table 1 below shows the goals and sub criteria in both strategic and tactical levels.

Table 1 maintenance objectives on the strategic and tactical levels

Strategic Level	Tactical Level
Maintenance budget	Maintenance cost – Maintenance Value
Functional and Technical aspect	Maintenance Quality – Availability – Reliability Maintainability – OEE – Productivity – Output Quality
Plant design life	Capital replacement decision – life-cycle Optimization
Support	Inventory of spare parts – Logistics
People and Environment	Environment impact – Safety/Risk/Health

Experts considered the Functional and Technical aspects of these objectives with the sub criteria of Maintenance Quality, Availability, Reliability, Maintainability, Overall Equipment Effectiveness (OEE), Productivity, and Output quality as the most important objectives for the maintenance department of the EXIR Pharmaceutical Factories. Also, the team of experts and decision makers of pharmaceutical factory after holding a number of meetings decided on four strategies based on Reliability Centered Maintenance (RCM), Total Productive Maintenance (TPM), Preventative Maintenance (PM), and Predictive Maintenance (Pdm) for competition phase. Research criteria are listed in Table 2 and named in a numeric index so that they can be easily be followed and studied throughout the research.

Table 2 Research criteria

Index	Selection criteria	Index	Maintenance strategies
C_1	Output quality	A_1	Reliability Centered Maintenance
C_2	Availability		
C_3	Reliability	A_2	Total Productive Maintenance
C_4	OEE		
C_5	Productivity	A_3	Preventive Maintenance
C_6	Maintenance quality		

C_7	Maintainability	A_4	Prediction Maintenance

The first step and perhaps the most important one in using ANP and DEMATEL methods is making the problem structure as a network, explaining the problem clearly and exact defining of the problem dimensions. In this step the problem structure was made with the aid of brain storming and previous studies (Figure 4).

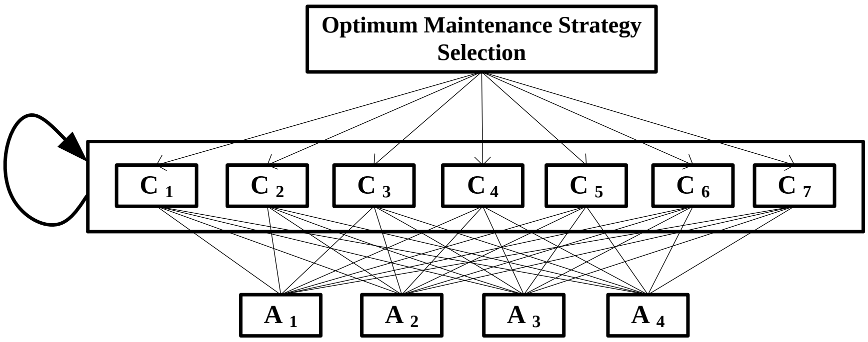

Fig. 4. structure of maintenance strategy selection

4.1. Review of main criteria relations with the aid of DEMATEL technique

To reflect the internal relations among the main criteria, the DEMATEL technique is utilized in such a way to enable the experts to express their opinions with more confidence in relation to the effects of (direction and intensity of effects) amongst the factored elements. It is necessary to mention that the resulting matrix from the DEMATEL technique (Internal Relation Matrix), shows casual and normal relation between the elements as well as showing responsiveness and effectiveness criteria.

4.2. Matrix Calculation of Direct Relation: M

Table 3 presents matrix of direct relation.

Table 3 Initial direct matrix M.

M	C_1	C_2	C_3	C_4	C_5	C_6	C_7
C_1	0.000	3.273	1.000	2.455	3.273	0.909	2.909
C_2	3.363	0.000	0.364	3.000	2.182	0.909	2.818
C_3	2.545	0.818	0.000	1.000	2.000	0.273	3.455
C_4	1.364	1.000	1.818	0.000	4.000	3.273	0.182
C_5	1.545	2.182	1.818	3.455	0.000	3.727	1.909
C_6	1.364	2.182	1.000	3.000	2.368	0.000	2.000
C_7	0.800	2.100	3.400	2.300	3.000	3.111	0.000

4.3. Matrix Calculation of Direct Normalized Relation: N

Table 4 presents Initial direct normalized matrix

$$k = \frac{1}{max \sum_{j=1}^{n} a_{ij}} = \frac{1}{16.818} = 0.055 \qquad (1\text{-}4)$$

N = 0.055*M

Table 4 Initial direct normalized matrix N.

N	C_1	C_2	C_3	C_4	C_5	C_6	C_7
C_1	0.000	0.195	0.059	0.146	0.195	0.054	0.173
C_2	0.216	0.000	0.022	0.178	0.130	0.054	0.168
C_3	0.151	0.049	0.000	0.059	0.119	0.016	0.205
C_4	0.081	0.059	0.108	0.000	0.238	0.195	0.011
C_5	0.092	0.130	0.108	0.205	0.000	0.222	0.114
C_6	0.081	0.130	0.059	0.178	0.141	0.000	0.119
C_7	0.048	0.125	0.202	0.137	0.178	0.185	0.000

4.4. Matrix Calculation of Total Relation: T

For the purposes of calculating the Matrix of Total Relation, at first the influence matrix (I) must be formed. Then subtract the Normal matrix from the Influence matrix, and then reverse the resulting matrix, and finally, multiplying the Normal matrix by reversed matrix.

$$T = N \times (I - N)^{-1} \qquad (2\text{-}4)$$

Table 5 Normalized the total influence matrix T

T	C_1	C_2	C_3	C_4	C_5	C_6	C_7
C_1	0.350	0.536	0.370	0.615	0.686	0.480	0.541
C_2	0.509	0.354	0.323	0.612	0.614	0.456	0.512
C_3	0.391	0.331	0.248	0.420	0.501	0.341	0.481
C_4	0.362	0.364	0.350	0.408	0.629	0.522	0.344
C_5	0.435	0.484	0.410	0.666	0.530	0.617	0.495
C_6	0.372	0.428	0.325	0.571	0.573	0.367	0.437
C_7	0.403	0.477	0.491	0.608	0.675	0.583	0.403

4.5. Presenting Network Relations Map

To determine the Network Relations Map (NRM) the threshold values must be calculated. With this method minor relations can be ignored and draw a notable relations network. In this study the threshold is calculated to be 0.469. Therefore, the model of significant relationships is determined as follows:

Table 6 Model of significant relations amongst set criteria

T	C_1	C_2	C_3	C_4	C_5	C_6	C_7
C_1	-	0.536	-	0.615	0.686	0.480	0.541
C_2	0.509	-	-	0.612	0.614	-	0.512
C_3	-	-	-	-	0.501	-	0.481
C_4	-	-	-	-	0.629	0.522	-
C_5	-	0.484	-	0.666	0.530	0.617	0.495
C_6	-	-	-	0.571	0.573	-	-
C_7	-	0.477	0.491	0.608	0.675	0.583	-

In considering the model of relations a casual chart can be drawn:

Table 7 Sum of influences given and received on each criterion

N	D	R	D+R	D-R
C_1	3.579	2.822	6.401	0.757
C_2	3.379	2.974	6.354	0.405
C_3	2.713	2.517	5.230	0.196
C_4	2.979	3.900	6.879	-0.922
C_5	3.637	4.208	7.745	-0.571
C_6	3.073	3.366	6.439	-0.292
C_7	3.640	2.886	6.526	0.754

Figure 5 shows the Cartesian graph of relation between the research measures

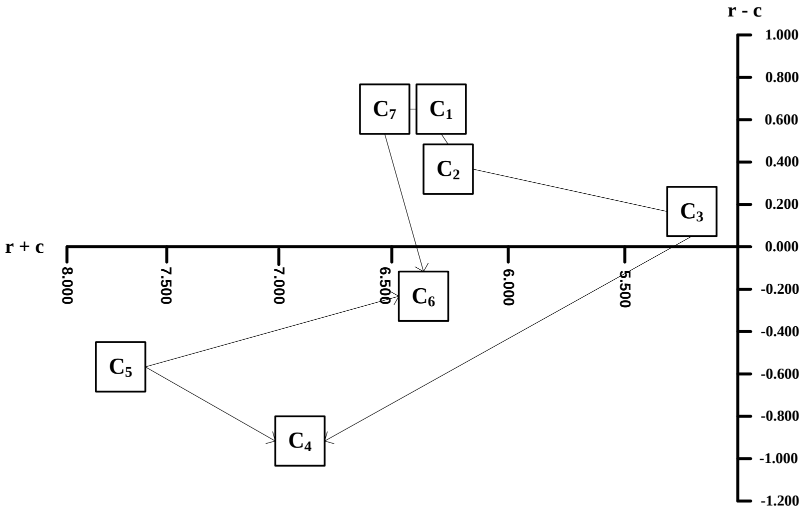

Fig. 5. The impact-direction map

5. Compare and Prioritize Maintenance Strategies

In this step, with the ANP technique of existing strategies based on each criterion, comparisons are made in pairs, which sufficiently are mentioned in the two following situations:

5.1. Paired comparison of criteria considering the goal

The weight of each criterion is evaluated. Table 8 presents group matrix of paired comparisons related to the goal.

Table 8 Comparison of criteria considering the goal

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	W
C_1	0.350	0.536	0.370	0.615	0.686	0.480	0.541	0.218
C_2	0.509	0.354	0.323	0.612	0.614	0.456	0.512	0.212
C_3	0.391	0.331	0.248	0.420	0.501	0.341	0.481	0.156
C_4	0.362	0.364	0.350	0.408	0.629	0.522	0.344	0.126
C_5	0.435	0.484	0.410	0.666	0.530	0.617	0.495	0.120
C_6	0.372	0.428	0.325	0.571	0.573	0.367	0.437	0.098
C_7	0.403	0.477	0.491	0.608	0.675	0.583	0.403	0.070

5.2. Paired comparison of criteria considering criteria

In this step the priority of criteria considering interdependence of criteria is identified. Results are shown in Table 9.

Table 9 Paired comparison of criterions considering criterion

	C_1	C_2	C_3	C_4	C_5	C_6	C_7
C_1	0.152	0.185	0.204	0.173	0.165	0.185	0.169
C_2	0.187	0.160	0.164	0.157	0.160	0.172	0.156
C_3	0.142	0.163	0.142	0.162	0.156	0.158	0.160
C_4	0.142	0.158	0.139	0.156	0.151	0.133	0.152
C_5	0.137	0.119	0.141	0.154	0.138	0.126	0.147
C_6	0.127	0.108	0.120	0.097	0.112	0.113	0.115
C_7	0.113	0.106	0.090	0.102	0.117	0.112	0.100

5.3. Paired comparisons of criteria related to strategies

In this step after calculating the interdependency between the criteria, the importance of each criterion considering the mentioned four strategies is identified. The weights of criteria against the maintenance strategies are shown in Table 10.

Table 10 Paired comparisons of criteria related to strategies

	A_1	**A_2**	**A_3**	**A_4**
C_1	0.184	0.171	0.180	0.165
C_2	0.150	0.161	0.173	0.158
C_3	0.146	0.156	0.133	0.162
C_4	0.139	0.160	0.118	0.142
C_5	0.140	0.150	0.125	0.141
C_6	0.130	0.099	0.125	0.115
C_7	0.115	0.104	0.121	0.110

5.4. Paired comparisons of strategies related to criteria

In the previous step, the importance of the criteria regarding to the strategies is measured, in this step the importance of the strategies than the criteria will be measured.

5.4.1. Determining Strategic Priorities Based on Availability Criteria

Here, also in terms of groups; experts have been used. The geometric mean of expert opinion is calculated, and to determine the strategic priorities based availability, the results are presented in Table 11.

Table 11 Determining Strategy Priorities based availability Criteria

	A_1	**A_2**	**A_3**	**A_4**	**W**
A_1	0.461	0.056	0.492	0.331	0.451
A_2	0.217	0.238	0.274	0.255	0.250
A_3	0.157	0.146	0.168	0.296	0.188
A_4	0.164	0.110	0.067	0.118	0.112

Based on the obtained special vector, the most priorities are related to reliability maintenance strategies weighing 0.451, while predictable maintenance and repair strategies with normal weight of 0.112 are considered as the least of priorities.

5.4.2. Determining Strategy Priorities based on Output Quality Criteria

Table 12 Determining Strategy Priorities based Output quality Criteria

OQ	**A_1**	**A_2**	**A_3**	**A_4**	**W**
A_1	0.219	0.371	0.268	0.565	0.364
A_2	0.250	0.254	0.407	0.068	0.223

A3	0.416	0.173	0.213	0.171	0.248
A4	0.115	0.202	0.112	0.195	0.164

Based on the obtained special vector, the most priorities are related to reliability maintenance strategies weighing 0.364, while predictable maintenance strategies with normal weight of 0.164 are considered as the least of priorities.

5.4.3. Paired comparisons of strategies related to criteria

In the previous step, the importance of the criteria regarding to the strategies is measured, in this step the importance of the strategies than the criteria will be measured. The weights of each strategy against each criterion are shown in Table 13.

Table 13 Paired comparisons of strategies related to criteria

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
A1	0.451	0.392	0.220	0.409	0.447	0.248	0.284
A2	0.250	0.239	0.233	0.226	0.234	0.164	0.249
A3	0.188	0.236	0.300	0.219	0.148	0.364	0.263
A4	0.112	0.133	0.248	0.147	0.171	0.223	0.205

5.5. Determining the Final Weight of Criteria and Strategies using Super-matrix

For the purposes of determining the final weight, the output of comparisons of main criteria based on objectives and internal relations between the criteria are entered in a super-matrix. This super-matrix is called the Preliminary Super Matrix or unweighted.

Given the Normal definition, the unweighted super-matrix can be converted to a weighted Super-matrix (Normalized) and ultimately the Limited Super-matrix can be calculated.

Table 14 The limit super-matrix

	Goal	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**A1**	**A2**	**A3**	**A4**
Goal	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C1	0.079	0.079	0.079	0.079	0.079	0.079	0.079	0.079	0.079	0.079	0.079	0.079
C2	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078
C3	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076
C4	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073
C5	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072
C6	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064
C7	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059

A_1	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177
A_2	0.114	0.114	0.114	0.114	0.114	0.114	0.114	0.114	0.114	0.114	0.114	0.114
A_3	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122
A_4	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088

5.6. Selection of the best strategy

In the last steps by solving the super-matrix which was arranged in last step with the aid of Super Decision software, the strategies will be ranked. In fact the final superiority of each strategy will be obtained. According to the calculations, the priorities of strategies are:

$W_{Strategies} = (W_{A_1}, W_{A_2}, W_{A_3}, W_{A_4}) = (0.177, 0.114, 0.122, 0.088)$

The final result indicates the RCM strategies have higher ranking.

6. Discussion

In this paper, by integrating DEMATEL, ANP methods a new method to determine a suitable maintenance strategy is proposed. The presented methodology in this research determines the optimal maintenance strategy used for the equipment manufacturing sector of the EXIR Pharmaceutical Factories of Boroujerd city. In this research four strategies of maintenance named RCM, TPM, PM, and Pdm based on seven quality criteria of maintenance and repair of; Maintenance Quality, Availability, Reliability, Maintainability, Overall Equipment Effectiveness OEE, Productivity, and Output Quality are compared with one another. Based on the obtained results, the strategy of Reliability Centered Maintenance was determined to be ranked as number one. Table 15 shows the comparison of the result of this research with a number of other similar researches.

Table 15 comparison of the result of this research with a number of other similar researches

Authors	Strategies	Criteria	Method	Result
Wang et al. (2007)	CBM , TBM CM , Pdm	Feasibility, added value cost and safety	AHP Fuzzy	Pdm
Arunranj and Maiti (2010)	EM , CBM, TBM , CM	Cost and risk	AHP and GP	CBM
Shahin et al. (2012)	EM , TBM , CBM TPM , DOM	Reliability, Availability Maintainability, Cost	ANP	TPM
Pourjavad et al. (2013)	EM , TBM , CBM TPM , DOM	Reliability, Availability Maintainability, Cost	ANP and TOPSIS	TPM
Nakhjavani et al (2014)	RCM ,TPM PM , Pdm	Output quality, Availability Reliability, OEE Productivity, Maintainability Maintenance quality	ANP And DEMATEL	RCM

7. Conclusions

Applying any of the approaches for selecting the suitable maintenance strategy might have limitations. It is worth to mention that the results of this approach depend on experts' conceptual opinions. Therefore, it is critically significance that experts who make the comparisons be familiar with the strategies and criteria of maintenance. In a company with various equipments and machinery it is necessary to categorise them considering their performance and facilities and then selecting maintenance strategies for each category. Since the number of decision criteria might be enormous in action, it is important to select those criteria which are more important than others for further analysis. For example, in addition to the seven addressed criteria of this study, safety is an important criterion in the oil refinery industry. It should be noted that this study was limited to transformer equipments of Exir Pharmaceutical Company of Boroujerd and in one plant and therefore, the findings could not be generalised to other types of equipments and plants. Prior to the comparison of maintenance strategies for an industrial unit, it is necessary to study the feasibility of their application. In fact the application of the maintenance strategies is dependent on hardware and software requirements.

7.1. Research limitations and managerial implications

Applying any of the approaches for selecting the suitable maintenance strategy might have limitations. One of the limitations of ANP and DEMATEL is its wide range of calculations. While in this paper, only four maintenance strategies and seven criteria were considered, increase in the numbers of strategies and criteria will result in an increase in calculations. Another important subject is that the results of this approach are dependent upon experts' conceptual opinions. Therefore, it is critically important that experts who make the comparisons be familiar with the strategies and criteria of maintenance. Since the number of decision criteria might be enormous in action, it is important to select those criteria which are more important than others for further analysis.

7.2. Future study

In this paper by integrating ANP and DEMATEL methods a suitable method to select suitable maintenance strategies is proposed while its considerable calculations its integration with other multi-criteria decision-making approaches such as TOPSIS. In this paper, the maintenance strategies were compared according to only seven criteria; therefore, the use of more criteria and studying its impact on the approach and it findings is recommended.

8. References

Almeida, A.T. and Bohoris, G.A. (1995), "Decision theory in maintenance decision making", *Journal of Quality in Maintenance Engineering*, Vol. 1 No. 1, pp. 39-45.

Al-Najjar, B. and Alsyouf, I. (2003), "Selecting the most efficient maintenance approach using fuzzy multiple criteria decision making", *International Journal of Production Economics*, Vol. 84, pp. 85-100.

Arunraj, N.S. and Maiti, J. (2010), "Risk-based maintenance policy selection using AHP and goal programming", *Journal of Safety Science*, Vol. 48, pp. 238-47.

Azadivar, F. and Shu, V. (1999), “Maintenance policy selection for JIT production systems”, *International Journal of Production Research*, Vol. 37 No. 16, pp. 3725-3738.

Bertolini, M. and Bevilacqua, M. (2006), “A combined goal programming-AHP approach to maintenance selection problem”, *Journal of Reliability Engineering and System Safety*, Vol. 91, pp. 839-48.

Bevilacqua, M. and Braglia, M. (2000) ‘The analytic hierarchy process applied to maintenance strategy selection’, *Reliability Engineering and System Safety*, Vol. 70, No. 1, pp. 71–83.

Chan, F.T.S., Lau, H.C.W., Ip, R.W.L., Chan, H.K. and Kong, S. (2005) ‘Implementation of total productive maintenance: a case study’, *International Journal of Production Economics*, Vol. 95, No. 1, pp.71–94.

Chiu, Y. J., Chen, H. C., Tzeng, G. H., And Shyu, J. Z. (2006). Marketing strategy based on customer behavior for the LCD-TV. *International Journal of Management and Decision Making*,Vol 7. No 2, pp. 143–165.

Hadidi, L.A., Al-Turki, U.M. and Rahim, A. (2012) ‘Integrated models in production planning and scheduling, maintenance and quality: a review’, *International Journal of Industrial and Systems Engineering*, Vol. 10, No. 1, pp.21–50.

HajShirmohammadi, A. and Wedley, W.C. (2004), “Maintenance management – an AHP application for centralization/decentralization”, *Journal of Quality in Maintenance Engineering*, Vol. 10 No. 1, pp. 16-25.

Hong Ding, S., Kamaruddin, S, And Abdul Azid, I. (2014). Development of model for optimal maintenance policy selection. *European Journal of Industrial Engineering* ,Vol. 8 No. 1, pp. 55-68.

Hori, S., & Shimizu, Y. (1999). Designing methods of human interface for supervisory control systems. *Journal of Control Engineering Practice*, Vol. 7 No. 11, pp. 1413–1419.

Huang, C. Y., & Tzeng, G. H. (2007). Reconfiguring the innovation policy portfolios for Taiwan’s SIP mall industry. Technovation, Vol. 27 No. 12, pp. 744–765.

Ilangkumaran, M. and Kumanan, S. (2009), “Selection of maintenance policy for textile industry using hybrid multi-criteria decision making approach*”, Journal of Manufacturing Technology Management*, Vol. 20 No. 7, pp. 1009-22.

Labib, A.W., O’Connor, R.F. and Williams, G.B. (1998), “An effective maintenance system using the analytic hierarchy process”, *Journal of Integrated Manufacturing Systems*, Vol. 2 No. 9, pp. 87-98.

Labib, A.W. (2004), “A decision analysis model for maintenance policy selection using a CMMS”, *Journal of Quality in Maintenance Engineering*, Vol. 10 No. 3, pp. 191-202.

Li, J.R., Khoo, L.P. and Tor, S.B. (2006), “Generation of possible multiple components disassembly sequence for maintenance using a disassembly constraint graph”, International Journal of Production Economics, Vol. 102, pp. 51-65.

Liou, J. J. H., Tzeng, G. H., And Chang, H. C. (2007). Airline safety measurement using a hybrid model. *Journal of Air Transport Management*, Vol. 13 No. 1, pp. 243–249.

Luce, S. (1999), “Choice criteria in conditional preventive maintenance*”, Journal of Mechanical Systems and Signal Processing*, Vol. 13 No. 1, pp. 163-8.

Mechefske, C.K. and Wang, Z. (2003) ‘Using fuzzy linguistics to select optimum maintenance and condition monitoring strategies’, *Journal of Mechanical Systems and Signal Processing*, Vol. 17, No. 2, pp.305–316.

Mobley, R.K. (2002) *An Introduction to Predictive Maintenance*, 2nd ed., Elsevier Science, New York, NY.

Okumura, S. and Okino, N. (2003), “A maintenance policy selection method for a critical single-unit item in each workstation composing a FMS with CBM optimization”, *International Journal of COMADEM*, Vol. 6 No. 2, pp. 3-9.

Pourjavad, E., Shirouyehzad, H. And Shahin, A. (2013) , “Selecting maintenance strategy in mining industry by analytic network process and TOPSIS*” International Journal of Industrial and Systems Engineering*, Vol. 15, No. 2, pp .171-192.

Sawhney, R., Kannan, S. and Li, X. (2009) ‘Developing a value stream map to evaluate breakdown maintenance operations’, *International Journal of Industrial and Systems Engineering*, Vol. 4, No. 3, pp. 229–240.

Shahin, A., Shirouyehzad, H. And Pourjavad, E. (2012), “Optimum maintenance strategy: a case study in the mining industry*” International Journal of Services and Operations Management*, Vol. 12, No. 3, pp .368-386.

Shahin, A. Ghofrani, I. N., Tbatabaei, N. A. (2013). Determining appropriate maintenance strategy based on decision making grid, Sigma level, and process capability index - with a case study in a steel company. *International Journal of Applied Management Science*, Vol. 5 No. 3, pp. 265-280.

Sharma, R.K., Kumar, D. and Kumar, P. (2005) ‘FLM to select suitable maintenance strategy in process industries using MISO model’, *Journal of Quality in Maintenance Engineering*, Vol. 11, No. 4, pp. 359–374.

Shorrocks, P. (2000), “Selection of the most appropriate maintenance model using a decision support framework”, unpublished report, UMIST, Manchester.

Shorrocks, P. and Labib, A.W. (2000), “Towards a multimedia based decision support system for word class maintenance”, Proceedings of the 14th ARTS (Advances in Reliability Technology Symposium), IMechE, University of Manchester, Manchester.

Shyjith, K., Ilangkumaran, M. and Kumanan, S. (2008), “Multi-criteria decision-making approach to evaluate optimum maintenance strategy in textile industry”, *Journal of Quality in Maintenance Engineering*, Vol. 14 No. 4, pp. 375-86.

Tamura, M., Nagata, H., And Akazawa, K. (2002). Extraction and systems analysis of factors that prevent safety and security by structural models. In 41st SICE annual conference, Osaka, Japan.

Triantaphyllou, E., Kovalerchuk, B., Mann, L. and Knapp, G.M. (1997), “Determining the most important criteria in maintenance decision making”, *Journal of Quality in Maintenance Engineering*, Vol. 3 No. 1, pp. 16-28.

Tzeng, G. H., Chiang, C. H., And Li, C. W. (2007). Evaluating intertwined effects in elearning programs: A novel hybrid MCDM model based on factor analysis and DEMATEL. *Journal of Expert Systems with Applications*, Vol. 32 No. 4, pp. 1028–1044.

Waeyenbergh, G. and Pintelon, L. (2002) 'A framework for maintenance concept development', *International Journal of Production Economics*, Vol. 77, No. 3, pp. 299–313.

Wang, H. (2002), "A survey of maintenance policies of deteriorating systems", *European Journalof Operational Research*, Vol. 139, pp. 469-89.

Wang, L., Chua, J. and Wu, J. (2007) 'Selection of optimum maintenance strategies based on a fuzzy analytic hierarchy process', *International Journal Production Economics*, Vol. 107, No. 1, pp.151–163.

Wongmongkolrit, S. and Rassameethes, B. (2011) 'The heuristics of effective maintenance policy under the given availability', *International Journal of Collaborative Enterprise*, Vol. 2, No. 4, pp.251–262.