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Studying the Factors Affecting Mainteneance Strategies & Computerised Maintenance

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Abstract
Manufacturing firms face great pressure to reduce their production 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 industry (Bevilacqua and Braglia, 2000). The amount of money spent on maintenance in a selected group of companies is estimated to be about 600 billion dollars in 1989 (Wireman, 1990, cited by Chan et al., 2005). On the other hand, maintenance plays an important role in keeping availability and reliability levels, product quality, and safety requirements. Unfortunately, unlike production and manufacturing problems which have received tremendous 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 is wasted as the result of unnecessary or improper 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 companies to achieve world-class competitiveness (Waeyenbergh and Pintelon, 2002). Therefore, research on maintenance represents an opportunity for making significant contribution by academics.

I. Introduction

In the literature, maintenance can be classified into two main types: corrective and preventive (Li et al., 2006 and Waeyenbergh and Pintelon, 2004). Corrective maintenance is the maintenance that occurs after systems failure, and it means all actions resulting from failure; preventive maintenance is the maintenance that is performed before systems failure in order to retain equipment in specified condition by providing systematic inspections, detection, and prevention of incipient failure (Wang, 2002). Based on the development of preventive maintenance techniques, three divisions of preventive maintenance are considered in this paper, i.e. time-based preventive maintenance, condition-based maintenance, and predictive maintenance. These maintenance strategies will be introduced in detail in the next section.

Most plants are equipped with various machines, which have different reliability requirements, safety levels, and failure effect. Therefore, it is clear that a proper maintenance program must define different maintenance strategies for different machines. Thus, the reliability and availability of production facilities can be kept in an acceptable level, and the unnecessary investment needed to implement an unsuitable maintenance strategy may be avoided. For example, for the pump with a standby, the corrective/time-based maintenance may be more cost-effective than the condition-based/predictive maintenance strategy in a production environment with a relatively low reliability requirement.

Although the selection of the suitable maintenance strategy for each piece of equipment is important for manufacturing companies, few studies have been done on this problem. Luce (1999), Okumura and Okino (2003) showed the methods to select the most effective maintenance strategy based on different production loss and maintenance costs incurred by different maintenance strategies. Although the calculation theories for the related costs presented by them are reasonable, the money spent on maintenance is only one of the factors that should be taken into account when choosing maintenance strategies in many cases. Azadivar and Shu (1999) presented the method to select a suitable maintenance strategy for each class of systems in a just-in-time environment, exploring 16 characteristic factors that could play a role in maintenance strategy selection. But this method is not applicable to process plants because of the difference between discrete manufacturing plants and process plants. In the report of Bevilacqua and Braglia (2000), the original method for the selection of maintenance strategies in an important Italian oil refinery was given, and the application of the analytic hierarchy process (AHP) for selecting the best maintenance strategy was described.

The criteria they considered seem sufficient, but a crisp decision-making method as the traditional AHP is not appropriate because many of the maintenance goals taken as criteria are non-monetary and difficult to be quantified. Al-Najjar and Alsyouf (2003), Sharma et al. (2005) assessed the most popular maintenance strategies using the fuzzy inference theory and fuzzy multiple criteria decision-making (MCDM) evaluation methodology. The application of the fuzzy theory for this problem is a good solution. However, only a few failure causes were considered as the criteria in their studies. In Mechefske and Wang (2003), the authors proposed to evaluate and select the optimum maintenance strategy and condition monitoring technique making use of fuzzy linguistics.

The fuzzy methodology based on qualitative verbal assessment inputs is more practical than the formers, because many of the overall maintenance objectives of the organization are intangible. However, the method of Mechefske and Wang (2003) is very subjective to directly assess the importance of each maintenance goal and the capability of each strategy to achieve each maintenance goal. Considering the shortcomings of the existing methods above, it is necessary to develop a new evaluation scheme for maintenance strategies. This scheme should include different aspects of maintenance goals, be able to model uncertainty and imprecise judgments of decision makers (i.e. maintenance managers and engineers), and be easy to use.

While selecting the suitable maintenance strategies for different machines in manufacturing firms, many maintenance goals or comparing criteria must be taken into consideration, e.g. safety and cost. Therefore, the MCDM theory should be used for the maintenance strategy selection. Several MCDM methods have been developed, such as the weighted-sum model (WSM), the weighted-product model (WPM), the TOPSIS method, and the AHP (Triantaphyllou and Lin, 1996). The AHP is one of the most popular MCDM methods. It has the following advantages (Triantaphyllou et al., 1997 and Bevilacqua and Braglia, 2000): (1) it is the only known MCDM model that can measure the consistency in the decision makers' judgments; (2) the AHP can help the decision makers to organize the critical aspects of a problem into a hierarchical structure similar to a family tree, making the decision process easy to handle; (3) pairwise comparisons in the AHP are often preferred by the decision makers, allowing them to derive weights of criteria and scores of alternatives from comparison matrices rather than quantify weights/scores directly.

Despite its popularity, this MCDM method is often criticized for its inability to adequately deal with the uncertainty and imprecision associated with the mapping of the decision-makers' perception to crisp numbers (Deng, 1999). For example, when constructing comparison judgment matrices, it is difficult for maintenance managers to exactly quantify the statements such as "what is the relative importance of safety in terms of cost, considering the selection of the suitable maintenance strategy for a boiler in a power plant". The answer may be "between three and five times more important", not "three times more important exactly". Consequently, it is desirable to evaluate maintenance strategies based on the fuzzy AHP methods which use fuzzy data.

The aim of this paper is twofold. One is to evaluate maintenance strategies with the application of the fuzzy AHP method, allowing better modeling of the uncertain judgments with the help of triangular fuzzy numbers. The other is to propose a new fuzzy prioritization method, which can derive exact priorities from fuzzy judgment matrices of pairwise comparisons, in order to avoid the fuzzy priorities calculation and fuzzy ranking procedures as in traditional fuzzy AHP methods. The presented modification of the fuzzy AHP might be beneficial for plant managers to select maintenance strategies as well as other MCDM problems.

II. Alternative maintenance strategies

Four alternative maintenance strategies considered in this paper are introduced as following:

(1) *Corrective maintenance*: This alternative maintenance strategy is also named as fire-fighting maintenance, failure based maintenance or breakdown maintenance. When the corrective maintenance strategy is applied, maintenance is not implemented until failure occurs (Swanson, 2001). Corrective maintenance is the original maintenance strategy appeared in industry (Waeyenbergh and Pintelon, 2002 and Mechefske and Wang, 2003). It is considered as a feasible strategy in the cases where profit margins are large (Sharma et al., 2005). However, such a fire-fighting mode of maintenance often causes serious damage of related facilities, personnel and environment. Furthermore, increasing global competition and small profit margins have forced maintenance managers to apply more effective and reliable maintenance strategies.

(2) *Time-based preventive maintenance*: According to reliability characteristics of equipment, maintenance is planned and performed periodically to reduce frequent and sudden failure. This maintenance strategy is called time-based preventive maintenance, where the term "time" may refer to calendar time, operating time or age. Time-based preventive maintenance is applied widely in industry. For performing time-based preventive maintenance, a decision support system is needed, and it is often difficult to define the most effective maintenance intervals because of lacking sufficient historical data (Mann et al., 1995). In many cases when time-based maintenance strategies are used, most machines are maintained with a significant amount of useful life remaining (Mechefske and Wang, 2003). This often

leads to unnecessary maintenance, even deterioration of machines if incorrect maintenance is implemented.

(3) *Condition-based maintenance*: Maintenance decision is made depending on the measured data from a set of sensors system when using the condition-based maintenance strategy. To date a number of monitoring techniques are already available, such as vibration monitoring, lubricating analysis, and ultrasonic testing. The monitored data of equipment parameters could tell engineers whether the situation is normal, allowing the maintenance staff to implement necessary maintenance before failure occurs. This maintenance strategy is often designed for rotating and reciprocating machines, e.g. turbines, centrifugal pumps and compressors. But limitations and deficiency in data coverage and quality reduce the effectiveness and accuracy of the condition-based maintenance strategy (Al-Najjar and Alsyouf, 2003).

(4) *Predictive maintenance*: In the literature, predictive maintenance often refers to the same maintenance strategy with condition-based maintenance (Sharma et al., 2005 and Mobley, 2002). In this paper, considering the recent development of fault prognosis techniques (Bengtsson, 2004), predictive maintenance is used to represent the maintenance strategy that is able to forecast the temporary trend of performance degradation and predict faults of machines by analyzing the monitored parameters data. Fault prognostics is a young technique employed by maintenance management, which gives maintenance engineers the possibility to plan maintenance based on the time of future failure and coincidence maintenance activities with production plans, customers' orders and personnel availability. Recently, the intelligent maintenance system was described by Djurdjanovic et al. (2003), focusing on fault prognostic techniques and aiming to achieve near-zero-downtime performance of equipment.

It is worth mentioning that equipment failure and corrective actions of maintenance cannot be avoided completely when the preventive maintenance strategies (including the time-based, condition-based, and predictive maintenance) are applied. This is due to the stochastic nature of equipment failure. However, generally speaking, the amount of equipment failure can be reduced if the preventive maintenance strategies are correctly selected, especially the condition-based/predictive maintenance.

III. Comparing criteria

When different maintenance strategies are evaluated for different machines, the manufacturing firms must set maintenance goals taken as comparing criteria first. Different manufacturing companies may have different maintenance goals. But in most cases, these goals can be divided into four aspects analyzed as follows:

(1) *Safety*: Safety levels required are often high in many manufacturing factories, especially in chemical industry and power plants. The relevant factors describing the Safety are:

(a) *Personnel*: The failure of many machines can lead to serious damage of personnel on site, such as high pressure vessels in chemical plants.
(b) *Facilities*: For example, the sudden breakdown of a water-feeding pump can result in serious damage of the corresponding boiler in a power plant.
(c) *Environment*: The failure of equipment with poisonous liquid or gas can damage the environment.

(2) *Cost*: Different maintenance strategies have different expenditure of hardware, software, and personnel training.
(a) *Hardware*: For condition-based maintenance and predictive maintenance, a number of sensors and some computers are indispensable.
(b) *Software*: Software is needed for analyzing measured parameters data when using condition-based maintenance and predictive maintenance strategies.
(c) *Personnel training*: Only after sufficient training can maintenance staff make full use of the related tools and techniques, and reach the maintenance goals.

(3) *Added-value*: A good maintenance program can induce added-value, including low inventories of spare parts, small production loss, and quick fault identification.
(a) *Spare parts inventories*: Generally, corrective maintenance need more spare parts than other maintenance strategies. Spare parts for some machines are really expensive.
(b) *Production loss*: The failure of more important machines in the production line often leads to higher production loss cost. Selecting a suitable maintenance strategy for such machines may reduce production loss.
(c) *Fault identification*: Fault diagnostic and prognostic techniques involved in the condition-based and predictive maintenance strategies aim to quickly tell maintenance engineers where and why fault occurs. As a result, the maintenance time can be reduced, and the availability of the production system may be improved.

(4) *Feasibility*: The feasibility of maintenance strategies is divided into acceptance by labors and technique reliability.

(a) *Acceptance by labors*: Managers and maintenance staff prefer the maintenance strategies that are easy to implement and understand.
(b) *Technique reliability*: Still under development, condition-based maintenance and predictive maintenance may be inapplicable for some complicated production facilities.

IV. Fuzzy AHP

The AHP was developed first by Satty (Zuo, 1991). It is a popular tool for MCDM by structuring a complicated decision problem hierarchically at several different levels. Its main steps include:

(1) *Organizing problem hierarchically*: The problem is structured as a family tree in this step. At the highest level is the overall goal of this decision-making problem, and the alternatives are at the lowest level. Between them are criteria and sub-criteria.

(2) *Development of judgment matrices by pairwise comparisons*: The judgment matrices of criteria or alternatives can be defined from the reciprocal comparisons of criteria at the same level or all possible alternatives. Pairwise comparisons are based on a standardized evaluation schemes (1=equal importance; 3=weak importance; 5=strong importance; 7=demonstrated importance; 9=absolute importance).

(3) *Calculating local priorities from judgment matrices*: Several methods for deriving local priorities (i.e. the local weights of criteria and the local scores of alternatives) from judgment matrices have been developed, such as the eigenvector method (EVM), the logarithmic least squares method (LLSM), the weighted least squares method (WLSM), the goal programming method (GPM) and the fuzzy programming method (FPM), as summarized by Mikhailov (2000). Consistency check should be implemented for each judgment matrix.

(4) *Alternatives ranking*: The final step is to obtain global priorities (including global weights and global scores) by aggregating all local priorities with the application of a simple weighted sum. Then the final ranking of the alternatives are determined on the basis of these global priorities.

The above process of the AHP method is similar to the process of human thinking, and turns the complex decision-making process into simple comparisons and rankings. However, decision makers often face uncertain and fuzzy cases when considering the relative importance of one criterion or alternative in terms of another. Therefore, it is difficult to determine the ratios based on the standard scheme in the second step above. For this reason, the fuzzy AHP was proposed, in which the uncertain comparisons ratios are expressed as fuzzy sets or fuzzy numbers, such as “between three and five times less important” and “about three times more important”. The triangular fuzzy number, because of its popularity, is used to represent the fuzzy relative importance in this paper. The membership function of triangular fuzzy numbers can be described as:

$$\mu_{\tilde{N}}(x) = \begin{cases} \dfrac{x-l}{m-l}, & l \leqslant x \leqslant m \\ \dfrac{u-x}{u-m}, & m < x \leqslant u, \\ 0 & \text{otherwise}, \end{cases} \quad (1)$$

where l, m, and u are also considered as the lower bound, the mean bound, and the upper bound, respectively. The triangular fuzzy number $\tilde{N}$ is often represented as (l,m,u).
After pairwise comparisons are finished at a level, a fuzzy reciprocal judgment matrix $\tilde{A}$ can be established as

$$\tilde{A} = \{\tilde{a}_{ij}\} = \begin{pmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & \tilde{a}_{nn} \end{pmatrix}, \quad (2)$$

where n is the number of the related elements at this level, and $\tilde{a}_{ij} = 1/\tilde{a}_{ji}$.

After constructing $\tilde{A}$, fuzzy priorities $\tilde{w}_i$, $i = 1, 2, \ldots, n$, should be calculated in the traditional fuzzy AHP methods. Many fuzzy prioritization approaches have been developed, such as the method based on the fuzzy modification of the LLSM (Boender et al., 1989), the fuzzy geometry mean method (Buckley, 1985), the direct fuzzification of the λ_{max} method of Satty (Csutora and Buckley, 2001), and the fuzzy least square method (Xu, 2000). In these methods, global priorities expressed as fuzzy numbers can be determined by aggregating fuzzy local priorities. However, as pointed out by Mikhailov (2003), the global fuzzy priorities often have large supports and overlap a wide range. After the normalization procedure of the fuzzy global scores, the unreasonable conditions where the normalized upper value < the normalized mean value < the normalized lower value may occur. Furthermore, to compare the global fuzzy scores, a fuzzy ranking procedure must be included in the traditional fuzzy AHP methods. But different ranking procedures for fuzzy numbers often give different ranking conclusions (Li, 2002).

Proper maintenance of plant equipment can significantly reduce the overall operating cost, while boosting the productivity of the plant. Although many management personnel often view plant maintenance as an expense, a more positive approach in looking at it is to view maintenance works as a profit center. The key to this approach lies in a new perspective of proactive maintenance approach.

Reviewing the most likely ways that equipment will fail has been a major concern in reliability-centered maintenance (RCM) to ensure that proactive, predictive and preventive maintenance activities during turnaround could be planned and carried out. So often that maintenance department will adopt a more cautious approach of playing safe and relying on the conventional or usual method of equipment maintenance rather than trying a proven method which has been tested to be efficient just to avoid any complicated matter arising from the method.

To overcome the shortcomings of the fuzzy prioritization methods above, two new approaches that can derive crisp priorities from fuzzy pairwise comparison judgments are proposed (Mikhailov, 2003 and Mikhailov and Tsvetinov, 2004). One is based on α-cut decomposition of the fuzzy numbers into interval comparisons. In this method, the fuzzy preference programming (FPP) method (Mikhailov, 2000) transforming the prioritization procedure into a fuzzy linear programming problem is used to derive optimized exact priorities, and eventually an aggregation of the optimal priorities derived at the different α-levels is needed for obtaining overall crisp scores of the prioritization elements. These steps make this method a little complicated. The other is a non-linear modification of the FPP strategy without applying α-cut transformations. This idea, deriving crisp priorities from fuzzy judgment matrices, shows a new way to deal with the prioritization problem from fuzzy reciprocal comparisons in the fuzzy AHP. A new and simple prioritization method, which can also derive exact priorities from fuzzy pairwise comparisons, is described in the next section.

V. Fuzzy prioritization method

Suppose that a fuzzy judgment matrix is constructed as Eq. (2) in a prioritization problem, where n elements are taken into account. Among this judgment matrix $\tilde{A}$, the triangular fuzzy number $\tilde{a}_{ij}$ is expressed as (l_{ij},m_{ij},u_{ij}), i and j=1,2,…,n, where l_{ij}, m_{ij}, and u_{ij} are the lower bound, the mean bound, and the upper bound of this fuzzy triangular set, respectively. Furthermore, we assume that $l_{ij}<m_{ij}<u_{ij}$ when $i\neq j$. If $i=j$, then $\tilde{a}_{ij} = \tilde{a}_{ii} = (1, 1, 1)$. Therefore, an exact priority vector $w=(w_1,w_2,\ldots,w_n)^T$ derived from $\tilde{A}$ must satisfy the fuzzy inequalities:

$$l_{ij} \mathrel{\tilde{\leqslant}} \frac{w_i}{w_j} \mathrel{\tilde{\leqslant}} m_{ij}. \quad (3)$$

where $w_i>0$, $w_j>0$, $i\neq j$, and the symbol $\tilde{\leqslant}$ means "fuzzy less or equal to".

To measure the degree of satisfaction for different crisp ratios w_i/w_j with regard to the double side inequality (3), a function can be defined as:

$$\mu_{ij}\left(\frac{w_i}{w_j}\right) = \begin{cases} \dfrac{m_{ij} - (w_i/w_j)}{m_{ij} - l_{ij}}, & 0 < \dfrac{w_i}{w_j} \leqslant m_{ij} \\ \dfrac{(w_i/w_j) - m_{ij}}{u_{ij} - m_{ij}}, & \dfrac{w_i}{w_j} > m_{ij}, \end{cases} \quad (4)$$

where $i\neq j$. Being different from the membership function (1) of triangular fuzzy numbers, the function value of $\mu_{ij}(w_i/w_j)$ may be larger than one, and is linearly decreasing over the interval $(0,m_{ij}]$ and linearly increasing over the interval $[m_{ij},\infty)$, as shown in Fig. 1. The less value of $\mu_{ij}(w_i/w_j)$ indicates that the exact ratio w_i/w_j is more acceptable.

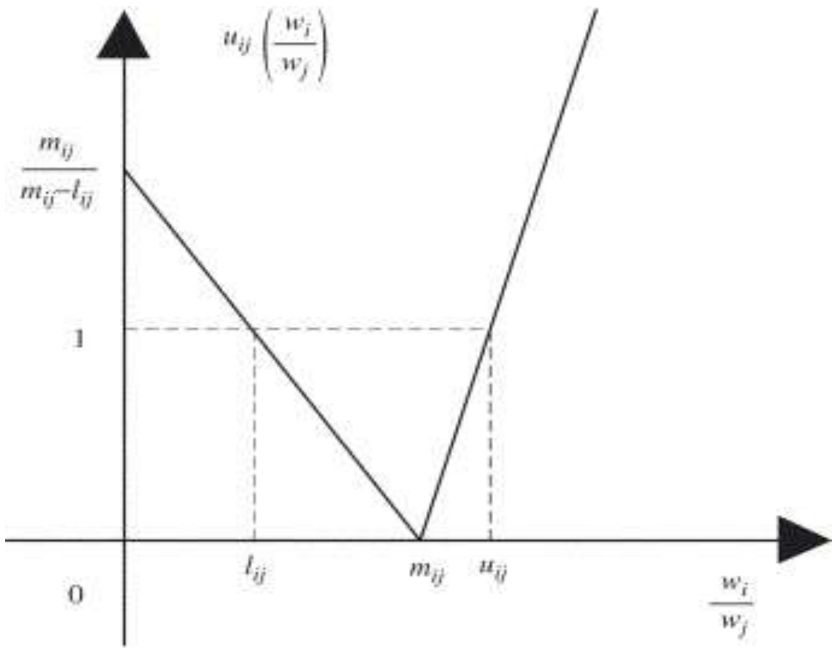

Fig. 1. Function for measuring the satisfaction degree of w_i/w_j.

To find the solution of the priority vector $(w_1,w_2,\ldots,w_n)^T$, the idea is that all exact ratios w_i/w_j should satisfy $n(n-1)$ fuzzy comparison judgments (l_{ij},m_{ij},u_{ij}) as possible as they can, i and $j=1,2,\ldots,n$, $i\neq j$. Therefore, in this study, the crisp priorities assessment is formulated as a constrained optimization problem:

(5)

$$\min J(w_1,w_2,\ldots,w_n) = \min\sum_{i=1}^{n}\sum_{j=1}^{n}\left[\mu_{ij}^{p}\left(\frac{w_i}{w_j}\right)\right] = \min\sum_{i=1}^{n}\sum_{j=1}^{n}\left[\delta\left(m_{ij}-\frac{w_i}{w_j}\right)\left(\frac{m_{ij}-(w_i/w_j)}{m_{ij}-l_{ij}}\right)^{p} +\delta\left(\frac{w_i}{w_j}-m_{ij}\right)\left(\frac{(w_i/w_j)-m_{ij}}{u_{ij}-m_{ij}}\right)^{p}\right].$$

subject to

$$\sum_{k=1}^{n} w_k = 1,\quad w_k>0,\ k=1,2,\ldots,n.$$

where $i\neq j$, $p\in\mathbb{N}$, and

$$\delta(x)=\begin{cases}0, & x<0,\\ 1, & x\geqslant 0.\end{cases}$$

The function $J(w_1,w_2,\ldots,w_n)$ is non-differentiable. General algorithms for function optimization, limited to convex regular functions, cannot be applied to this optimization problem. Therefore, genetic algorithms, which have great ability to solve difficult optimization problems with discontinuous, multi-modal or non-differentiable objective functions, are chosen in this paper. A toolbox GOAT of genetic algorithms provided by Houck et al. (1995) is utilized in the next section. Because the optimization problem above has non-linear constraints, the penalty techniques (Gen and Cheng, 1996) are combined when employing genetic algorithms for the optimal solution.

In some cases, decision-makers are unable or unwilling to give all pairwise comparison judgments of n elements. However, provided that the known fuzzy set of pairwise comparisons involves n elements, such as $F=\{\widetilde{a}_{ij}\}=\{\widetilde{a}_{12},\widetilde{a}_{13},\ldots,\widetilde{a}_{1n}\}$ or $\{\widetilde{a}_{21},\widetilde{a}_{31},\ldots,\widetilde{a}_{n1}\}$, the solution of priority vector $(w_1,w_2,\ldots,w_n)^T$ will be still able to be derived based on the optimization problem above. Thus, the proposed method can obtain priorities from an incomplete comparison judgment set, which is an interesting advantage comparing with the traditional fuzzy AHP methods. In order to measure the consistency degree of the fuzzy comparison judgment matrix $\widetilde{A}$ as Eq. (2), an index γ can be defined after the optimal crisp priority vector $(w_1^*,w_2^*,\ldots,w_n^*)^T$ is obtained:

(6)

$$\gamma=\exp\left\{-\max_{ij}\left\{\mu_{ij}\left(\frac{w_i^*}{w_j^*}\right)\middle|\, i,\ j=1,2,\ldots,n,\ i\neq j\right\}\right\},$$

where $\mu_{ij}(w_i^*/w_j^*)$ is the function of (4). The value of γ satisfies $0<\gamma\leqslant 1$ always. If it is larger than $e^{-1}=0.3679$, all exact ratios satisfy the crisp inequalities $l_{ij}\leqslant w_i^*/w_j^*\leqslant m_{ij}$, i and $j=1,2,\ldots,n$, $i\neq j$, and the corresponding fuzzy judgment matrix has good consistency. γ=1 indicates that the fuzzy judgment matrix is completely consistent. In conclusion, the fuzzy judgment matrix with a larger γ value is more consistent.

VI. Conclusion

In this paper, the selection of maintenance strategies in manufacturing firms is studied. An optimal maintenance strategy mix can improve availability and reliability levels of plants equipment, and reduce unnecessary investment in maintenance. The evaluation of maintenance strategies for each piece of equipment is a multiple criteria decision-making (MCDM) problem. Considering the imprecise judgments of decision makers, the fuzzy AHP is used for the evaluation of different maintenance strategies. The fuzzy AHP models the uncertainty with triangular fuzzy numbers. A new and simple fuzzy prioritization method is proposed to derive crisp priorities from fuzzy comparison judgment matrices, based on an optimization problem with non-linear constraints.

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