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Maintenance policy selection: a fuzzy-ANP approach

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Abstract

Purpose – The purpose of this paper is to develop a fuzzy analytic network process (FANP) model to select the maintenance policy of an acid manufacturing company.

Design/methodology/approach – Four maintenance strategies of Corrective Maintenance (CM), Time-Based Maintenance (TBM), Condition-Based Maintenance (CBM) and Shutdown Maintenance (SM) are investigated to be considered for seven equipment of the case study. These equipment are almost new and include boiler, molten sulfur ponds, cooling towers, absorption tower, converter, sulfur fuel furnace and heat exchanger. Chang's extended analysis has been employed to deal with fuzzy data and analyze the fuzzy decision matrices. The proposed approach is applied to a sulfuric acid production plant and the suitable maintenance policy is found for all seven equipment of the company.

Findings – Based on the obtained results, the CBM policy is appropriate for high-risk (cooling tower) and high added value equipment (absorption tower). In addition, TBM is selected for boiler and converters while SM is selected for molten sulfur ponds. Finally, high-cost, low-risk and low added value equipment (sulfur fuel furnace and heat exchanger) are more appropriate with CM policy.

Originality/value – This research presents a novel idea to consider cost, risk and added value in the context of maintenance policy selection. From the methodological and theoretical features, this research offers new insights in this area since, to the best of the authors' knowledge, no comparable study has been conducted before.

Keywords Decision making, Fuzzy logic, Manufacturing industry, Maintenance

Paper type Research paper

1. Introduction

With the advent of competitive markets, companies have acknowledged the crucial necessity of progressing the maintenance system of the companies. Diverse sections of industries face numerous strategic decisions to attain the best feasible and realistic answers in risky and competitive environments. These decisions are extremely significant regarding the technology development, diversity of customers in addition to public pressure. Maintenance is a significant task in any manufacturing system and has a critical role in attaining the organization's objectives (Seiti, Hafezalkotob and Fattahi, 2017). With the introduction of different maintenance systems, diverse maintenance strategies are

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applied to attain more added values. In this regard, numerous studies have been conducted on maintenance strategies (Alabdulkarim *et al.*, 2015; Shaaban and Awni, 2014; Graisa and Al-Habaibeh, 2011; Savsar, 2010). Choosing an appropriate maintenance policy is a critical activity in manufacturing systems as it affects the performance of companies' equipment. This practice is a common multi-criteria decision-making (MCDM) problem. An MCDM problem includes both perceptible and imperceptible factors (Galankashi *et al.*, 2013; Ziaei *et al.*, 2013; Dargi *et al.*, 2014). Although different studies have been conducted on maintenance policy selection, only a few attempts have been made to see the MCDM approaches in conjunction with the effect of cost, risk and added value. In this regard, recognizing, incorporating and selecting the right maintenance policy to efficiently screen and assess the current situation of the company are a challenge for many researchers. Cost, risk and added value are very influential in maintenance planning. However, their simultaneous consideration is less investigated in the previous studies. This is somewhat due to intrinsic difficulties connected with complex models of maintenance policy selection. Therefore, considering these factors in maintenance planning is useful and affects the performance of companies' equipment. The main justification to use a fuzzy-based method to tackle the problem of this research is the inherent struggle of comparing different policies using decision makers' comments. The decision makers are comfortable to compare these strategies in fuzzy environment instead of deterministic scales. In addition, Fuzzy Analytic Network Process (FANP) is a suitable method to study the relations between decision elements in hierarchical structures. Therefore, developing an FANP model to rank and select the best maintenance policy for different equipment of an acid manufacturing plant is the main objective of this study. As the main justification to apply this method, FANP considers the uncertainty of data and the relation of criteria and alternatives which are very unique compared to other MCDM approaches.

The scope of this study is limited to an acid manufacturing plant. Though, the study framework, approach and outcomes can be beneficial to practitioners and researchers who aim to select the proper maintenance policy by considering other different factors. This research contributes to provide an applicable model for selecting the proper maintenance policy for different equipment of an acid manufacturing company, along with considering the effect of cost, risk and added value in the proposed model. To prove the applicability of this study in real industrial environment, the method is applied by selecting the best maintenance policy for the equipment of a real-case study. Therefore, this research presents a novel idea to consider cost, risk and added value in the context of maintenance policy selection. From the methodological and theoretical features, this research offers new insights in this area since, to the best of our knowledge, no comparable study has been conducted before.

2. Literature review

Today, world-class competitiveness is a necessity for manufacturers (Ierace and Cavalieri, 2008; Galankashi and Helmi, 2016; Galankashi, Hisjam and Helmi, 2016a, b). Therefore, making correct decisions provide a significant contribution for companies. Choosing an operative policy, in addition to decision-making impartiality, relies on the investigated principles. With regard to growing complication in controlling and managing companies, incorporating experts' experiences and knowledge to make suitable judgments is a common approach (Lin *et al.*, 2008; Zavadskas *et al.*, 2017). Maintenance plays an important role in attaining such managerial goals. Maintenance policy can be defined from different perspectives. This is a concept including maintenance policies and actions integrated with a systematic decision-making approach to be used in different areas (Pintelon and Van Puyvelde, 1997). Maintenance systems play an important role as they help the companies to maintain their reliability and availability levels of products and services, safety and quality necessities (Mobley, 2002). Therefore, previous studies have highlighted the significance of the maintenance policy in improving system safety and availability in addition to product excellence (Muller *et al.*, 2008; Sadeghi and Manesh, 2012).

The old-style "Fail and Fix" method of the maintenance is expired and companies are seeking to an innovative "Predict and Prevent" approach aimed to anticipate the failure instead of fixing them (Lee *et al.*, 2006). There are diverse types of maintenance strategies. Reactive, preventive and Predictive Maintenance (PM) are three main categories of maintenance strategies. Predictive and preventive approaches signify two active policies where the companies can evade the breakdowns of equipment. In addition, Total Predictive Maintenance (TPM) is a policy which aims to progress the performance of equipment while continuing to evade their failure. Therefore, selecting the appropriate maintenance policy which is more suitable to the characteristics of the company's equipment is very important in industrial environments. According to Arunraj and Maiti (2010), availability of maintenance facilities should be considered in the process of selecting proper maintenance policy. Consequently, a proper maintenance policy should study different strategies for different types of machines (Wang *et al.*, 2007). Reliability-Centered Maintenance (RCM) is another approach which is discussed in previous studies. RCM was initiated in the aircraft industry and advanced in the military, oil, gas and nuclear industries. RCM provides a framework to use operating experience in a systemic way. The objective of RCM is to preserve the most significant equipment function with the required availability and reliability at the lowest maintenance cost. As it is shown, numerous studies have been done to select appropriate maintenance strategies. Following presents some related studies of this area.

Bevilacqua and Braglia (2000) defined a presentation of the Analytic Hierarchy Process (AHP) for choosing the preeminent maintenance policy of oil refinery process. Preventive, condition based, predictive, opportunistic and Corrective Maintenance (CM) are investigated in this research. Maintenance strategies have been investigated with other factors. For example, Swanson (2001) displayed robust and progressive relations among aggressive and proactive maintenance strategies. Developing appropriate maintenance policies for companies' equipment meaningfully decreases the overall cost and improves their functionality. Therefore, numerous studies have investigated different maintenance policies in different areas. As an example of renewable energies, Andrawus *et al.* (2006) applied Condition-Based Maintenance (CBM) actions to recognize and evaluate the wind turbines' life-cycle to take the full advantage of the wind farms. Wang *et al.* (2007) assessed diverse maintenance strategies comprising Time-Based Preventive Maintenance (TBPM), CM, PM and CBM for several equipment. Correspondingly, Sarkar *et al.* (2011) selected the preeminent maintenance policy for a power plant system. Five probable substitutes of predictive, preventive, corrective, opportunistic and CBM were focused in this research. Maintenance policy selection has been integrated with other perspectives. For instance, Ghazi Nezami and Bayram Yildirim (2013) developed a complete outline to use sustainability measures according to environmental, economic and social criteria. This study selected a suitable maintenance policy amongst a range of substitutes, including failure-based, preventive, condition-based, total productive and RCM strategies.

MCDM methods are regularly used to select the best maintenance policy. For instance, Shyjith *et al.* (2008) concentrated on the application of the AHP and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methods to choose the best maintenance policy of a textile company. In a similar study, Ilangkumaran and Kumanan (2009) applied fuzzy AHP and TOPSIS to choose a proper maintenance policy for a textile industry. In another similar study, Arunraj and Maiti (2010) concentrated on risk-based maintenance policy selection using AHP and goal programming. According to this study, CBM is a better maintenance policy compared to Time-Based Maintenance (TBM). This is mainly due to the fact that CBM can reduce the risk much better than TBM. Likewise, CM is still desired. Nevertheless, by concurrent seeing of both risk and cost, this study shows that CBM provides a better performance for high-risk equipment while CM is better for low-risk equipment. In another study, Pourjavad *et al.* (2013) focused on selecting the best maintenance policy in the mining industry by TOPSIS and ANP. Five maintenance strategies including TPM, design out maintenance, TBM, CBM and emergency maintenance were considered in this research. Azadeh and Abdolhossein Zadeh (2016) developed a joined AHP-fuzzy MCDM technique to make a complete comparison among different maintenance strategies.

Fouladgar *et al.* (2012) applied AHP and Complex Proportional Assessment (COPRAS) under fuzzy environment for maintenance policy selection. A new fuzzy technique was developed to assess feasible maintenance policy. In addition, application of the proposed model was tested using a real-world case study. Nezami and Yildirim (2013) proposed a new approach for maintenance policy selection. This study aimed to develop an inclusive framework to apply the environmental, economic and social criteria to choose a suitable maintenance policy. Ishizaka and Nemery (2014) assigned machines to incomparable maintenance strategies with ElectreSort. This research established a new sorting technique to consider an infinite amount of criteria to assign machines to incomparable strategies. A case study was used and showed that ElectreSort offers more flexible and precise maintenance strategies comparing the decision-making grid.

Van Horenbeek and Pintelon (2014) developed a maintenance performance measurement framework. This study applied an ANP to select the performance indicators of maintenance. The developed methodology of this research was used in numerous case studies including companies from different industries. The outcomes demonstrate the capability and applicability of the proposed model to help maintenance engineers and managers. The ANP methodology allows a better understanding of the compound interactions. Azadeh and Abdolhossein Zadeh (2016) suggested a joined AHP-fuzzy MCDM methodology to make a complete evaluation among diverse maintenance strategies. The AHP is applied to define the importance of the criteria. Successively, a fuzzy MCDM approach is used to rank numerous maintenance strategies and choose the best one. Ibraheem and Atia (2017) applied AHP for maintenance policy selection of flexible pavement. This research developed tools and methods to support maintenance management system of transportation.

Seiti, Tagipour, Hafezalkotob and Asgari (2017) developed a Fuzzy Axiomatic Design (FAD) model for decision making in evaluation and assortment of appropriate maintenance policy in risky circumstances. Each assessment has both pessimistic and optimistic fuzzy scores. To improve the model accuracy, a new concept named "acceptable risk" is recommended. Also, to measure the effectiveness of the proposed model, a rolling mill company is considered and the attained results are analyzed with other FAD concepts. Yang *et al.* (2017) focused on a short-term maintenance policy. For facilities operating in improper situation, its active maintenance and operation risk costs are assessed, correspondingly. Next, the newest maintenance time is considered assuming that its operation risk costs are not bigger than active maintenance costs. Considering the maintenance time, the best time is computed by setting the extreme relative earnings of postponing maintenance as the aim, which offers a complete maintenance-decision support.

With the growth of prediction methodology, according to Ji *et al.* (2017), numerous studies have developed a PM model. Though, previous literature has focused on providing the predictive model and assessing its performance instead of choosing the suitable elements for PM. However, choosing the PM policy and target components are as significant as the choice of the model and performance measurement. Ji *et al.* (2017) suggested a component selection technique for ranked PM. In this research, a selection approach is developed to progress component selection by considering both industry expert knowledge and current literature. The outcomes of this study can be served as a basis for supplementary research in this area. Choosing an appropriate maintenance policy is a complex process. Seiti, Tagipour, Hafezalkotob and Asgari (2017) aimed to develop a risk-based model, namely, RAHP, to address the maintenance policy issues. A steel rolling company was considered to assess the model effectiveness. An approach to select the maintenance policy is suggested in this study. In the suggested model, AHP is applied as a tool to determine the weight of decision-making criteria and RAHP is used to rank maintenance policies. Also, the obtained results of RAHP and AHP are compared.

Subsequently, the highlights of the literature indicate that numerous maintenance strategies have been established and are effectively used in numerous areas. Nevertheless, selecting the best maintenance policy is still a big challenge due to the involvement of numerous alternatives and attributes which are linked to this MCDM problem. In this paper, four maintenance strategies of CM, TBM, CBM and Shutdown Maintenance (SM) are investigated to be considered for seven equipment of the case study. These equipment include boiler, molten sulfur ponds, cooling towers, absorption tower, converter, sulfur fuel furnace and heat exchanger. Chang's extended analysis has been employed to deal with fuzzy data and analyze the fuzzy decision matrices. The proposed approach is applied to a sulfuric acid production plant and the suitable maintenance policy is found for the equipment of this company.

3. Research methodology

In this section, the research methodology of this study is illustrated by discussing each step. The procedure of this research is shown in Figure 1. This figure shows how the cost, risk and added value can be integrated with FANP technique in the maintenance policy selection problem to improve the availability of equipment. Different steps of the research methodology are discussed as follows.

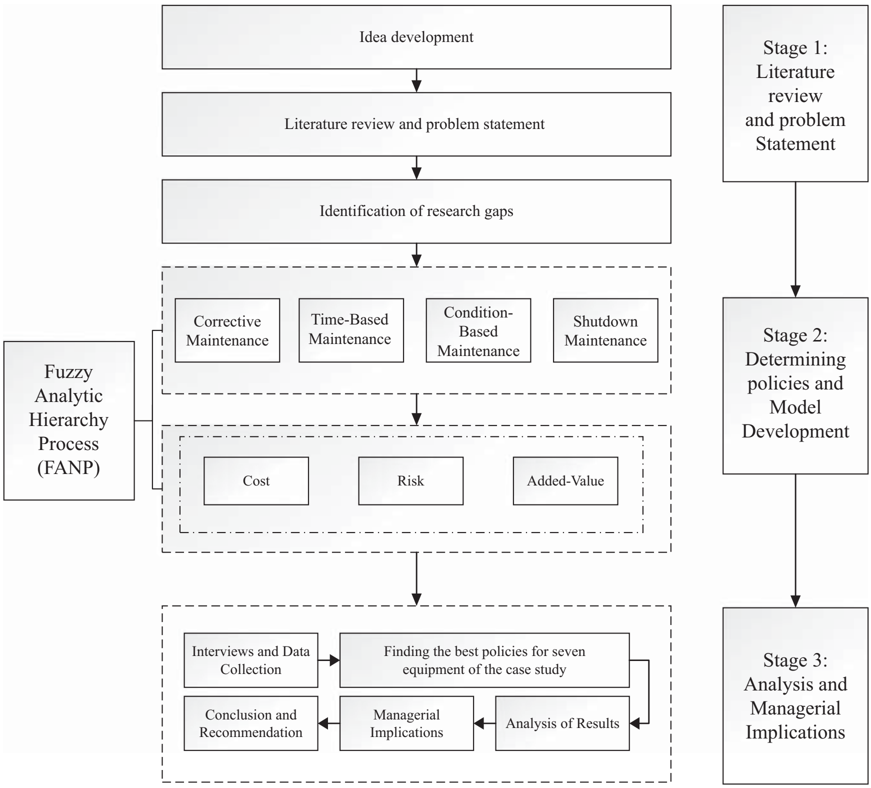

Figure 1.
Research procedure

Step 1: idea development, literature review and identification of research gap

As mentioned before, the main aim of this study is to develop an FANP model to select the best maintenance policy for different equipment of an acid manufacturing plant. According to the conducted literature review provided in Section 2, in spite of the vast quantity of studies on maintenance policy selection, the capability of these strategies to decrease the cost, decrease the risk and increase the added value is not studied. Therefore, to fill this gap, four maintenance policies of CM, TBM, CBM and SM are investigated to be considered for seven equipment of the case study. In other words, this step is involved with selecting all criteria and their network relations to find the best maintenance policy from CM, TBM, CBM and SM for different equipment of the case study. These criteria and their network relation are chosen according to the previous literature and the approval of the case study's experts. Figure 2 shows the hierarchy of the FANP model. As shown in this figure, three main criteria of cost, added value and risk are used to find the best maintenance policy for each equipment. In other words, seven different FANP models are proposed and solved to find the best maintenance policy of each equipment. The arrows in the second box of Figure 2 show the network relation of the criteria. Based on these networks, all relations between three criteria of selecting the best maintenance policy are considered.

Step 2: development of the FANP model

To define the degree of interdependence and relationship, the ANP method, as a developed version of AHP, is applied to investigate the criteria's comparative ranking (Galankashi and Helmi, 2016; Galankashi, Hisjam and Helmi, 2016a, b; Dargi *et al.*, 2014). Basically, ANP is established to create ranking for alternatives without having assumptions on a unidirectional hierarchy relationship among the different levels of decision (Saaty, 1996, 2008). The relative importance on a specified component is measured on a ratio scale that is comparable to AHP. According to Saaty (1996), this concept is based on the process of Markov chain. Similarly, according to Saati, the final weight of the relative ranking of a given factor is computed using a ratio scale that is same as AHP method. ANP considers the explicit interactions in its process which increases the accuracy of decision making (Shyur, 2003). Deprived of supposing the interdependency of criteria, decision makers were requested to make the pairwise comparisons or evaluate all suggested criteria. Although the decision makers employ their practical and academic capabilities to compare the alternatives, both AHP and ANP cannot reflect the human thinking clearly (Galankashi *et al.*, 2013). To overcome this weakness, fuzzy sets are applied to deal with ambiguities and linguistic terms used by decision makers (Zadeh, 1965). Therefore, it is recommended to use fuzzy values in order to make real-world judgments. The mean is commonly used for the experts' consensus and is applied by numerous researchers in the literature (Galankashi and Helmi, 2016; Galankashi, Hisjam and Helmi, 2016a, b;

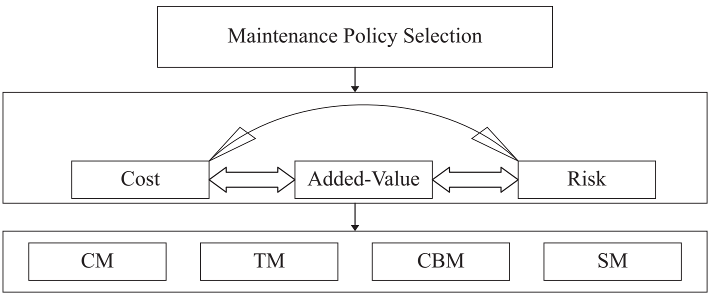

Figure 2.
FANP hierarchy

Saaty, 2008). Each value of the pairwise comparison matrix displays the individual view of experts which is an ambiguous perception. Consequently, applying fuzzy values is the best method to unite experts' comments. As mentioned before, The Chang's extended analysis (Chang, 1996) has been applied in this study. The phases of Chang's extended analysis are as follows. In addition, a comprehensive discussion of each phase is discussed for all equations.

Phase 1: construct the pairwise matrix. By using Triangular Fuzzy Numbers (TFNs), using pairwise comparison, the fuzzy evaluation matrix is constructed.

Phase 2: define the value of fuzzy synthetic extent. The value of fuzzy synthetic extent is defined in this phase.

Phase 3: define the possibility degrees. Defining the possibility degrees is the third phase of Chang's extended analysis which is discussed in Equations (9)-(11).

Phase 4: combine the weights derived in phase 4 to obtain overall rate. Finally, overall composite weight of each factor is computed. Following shows the related equations:

$$M_{ij} = \left(l_{ij}, m_{ij}, u_{ij}\right) \tag{1}$$

$$l_{ij} = \min\left(B_{ijk}\right) \tag{2}$$

$$m_{ij} = \sqrt[n]{\prod_{k=1}^{n} B_{ijk}} \tag{3}$$

$$u_{ij} = \max\left(B_{ijk}\right) \tag{4}$$

In which L, M and K show the triangular fuzzy values. B_{ijk} represents Kth decision makers' scores for comparing the importance of two criteria $C_i - C_j$. So, $C_i - C_j$ shows different considered criteria of the model. The numerical computation for each two triangular fuzzy values M_1 and M_2 can be definite as follow:

$$M_1 + M_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{5}$$

$$M_1 \times M_2 = (l_1 \times l_2,\ m_1 \times m_2,\ u_1 \times u_2) \tag{6}$$

$$M_1^{-1} = \left(\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1}\right), M_2^{-1} = \left(\frac{1}{u_2}, \frac{1}{m_2}, \frac{1}{l_2}\right) \tag{7}$$

where M_1^{-1} and M_2^{-1} are the inverse functions of M_1 and M_2, respectively. It should be noted that the output of multiplying two convex triangular fuzzy number or TFNs is not a triangular fuzzy value. These equations show an approximation for the convex TFNs or real two TFNs multiplication. Following equation is used for each column of the pairwise matrix to recognize triangular number (S_k) in addition to the fuzzy joint value for the ith object:

$$S_k = \sum_{j=1}^{n} M_{kj} \times \left[\sum_{i=1}^{m} \sum_{j=1}^{n} M_{ij}\right]^{-1} \tag{8}$$

Once S_k is computed, possibility degree of each two S_k must be computed. Consequently, if M_1 and M_2 are triangular fuzzy values, their possibility degree is computed as follows:

$$\left\{\begin{array}{ll} V(M_1 \geqslant M_2) = 1 & \text{if } M_1 \geqslant M_2 \\ V(M_1 \geqslant M_2) = 0 & \text{if } L_1 \geqslant U_2 \\ V(M_1 \geqslant M_2) = hgt\ (M_1 \cap M_2) & \text{otherwise} \end{array}\right\} \tag{9}$$

$$hgt(M1 \cap M2) = \frac{u_{1-}l_2}{(u_1 - l_2) + (m_2 - m_1)} \tag{10}$$

The ANP encounters a big scale of triangular values from the residual k number of the triangular values which are attained from Equation (9):

$$V(M_1 \geqslant M_2, \ldots, M_k) = V(M_1 \geqslant M_2), \ldots, V(M_1 \geqslant M_k) \tag{11}$$

Following equation is considered to compute the indices' weights in pairwise comparison matrix. Therefore, $W(x_i)$ provides this value as follows:

$$W(x_i) = \min\{V(S_i \geqslant S_k)\}, \quad k = 1, 2, 3, \ldots, n\ k \neq i \tag{12}$$

Consequently, the weight vectors $(w'(X)_i)$ are as follows:

$$w'(X_i) = \left[W'(C_1), W'(C_2), W'(C_n)\right]^T \tag{13}$$

Equation (12) consequences to normal values of attained outcomes of Equation (11). The normal values are called as W_i:

$$W_i = \frac{w'_i}{\sum w'_i} \tag{14}$$

Subsequently, the effect of correlations between criteria is calculated. Pairwise comparisons are used to measure the mutual influence of criteria in contradiction of each other by the decision makers. As these matrices are available for each criterion, the relative influences of interdependent criteria relationships are necessary. To do so, Equation (15) is applied to compute the relative correlation of the criteria. Therefore, W_c provides the relative correlation of the criteria as follows:

$$W_c = B.W \tag{15}$$

Step 3: questionnaire design

A questionnaire including four different sections of questions (Section A to Section D) was designed and sent to a set of experts to be filled by them. Section A of the questionnaire includes three different questions, which aim to make the pairwise comparison of cost, risk and added value. With regard to the complete relations between cost, risk and added value, section B of the questionnaire makes the pairwise comparison matrix of two criteria based on the remaining criteria. In other words, it compares cost and risk based on the added value;

cost and added value based on the risk and, risk and added value based on the cost. Section C of the questionnaire includes three different questions to compare the different maintenance policies based on the cost, added value and risk criteria. Finally, section D includes 12 different questions, which aims to focus on two criteria in each four questions separately. The developed questionnaire and data collection method were verified and validated using some pilot tests and interviews before the final data collection.

Step 4: data collection

As sending questionnaire and waiting for response could be timely and ends in imprecise data, the authors decided to distribute it manually and provide some explanations to respondents. In other words, after designing the questionnaire, the authors collected data using filled questionnaires. These data were in the form of pairwise comparison matrices to be used in FANP. The details of data collection are as follows. After a comprehensive explanation of the questionnaire to respondents, the interpretation of the respondents might be different from researchers, all of them were first asked to fill the questionnaire and submit it to the authors. This step lasted one month as it was very hard to ask them to fill it earlier. In addition, some interviews and meetings were conducted to improve the consistency of respondents. The filled questionnaires were rechecked and some minor improvements were conducted to make the contents more clear and consistent. Therefore, the initial questionnaire was revised and resubmitted to respondents to make it more usable and reliable.

4. Case study

Chemical manufacturing companies are a part of the oil industry. The consumption rate of chemical products is increasing annually as they are used in different industries including electrical, automotive, aerospace, military, etc. Among several chemical products, sulfuric acid is consumed in a big diversity of products regarding its chemical and physical specifications. It is an oily liquid without any detectable color which is corrosive to tissue and metals. With regard to the extraordinary usage ratio of sulfuric acid in chemical and oil industries, considering appropriate maintenance strategies for different equipment of its manufacturers improve the availability of these equipment through their production plan. Consequently, sulfuric acid manufacturing companies need to select and execute systematic approaches for their maintenance system. Furthermore, as sulfuric acid is produced by different equipment of manufacturing companies, considering different maintenance strategies for different equipment can result in very efficient maintenance plans.

To show the practicality and the proficiency of the research design, a sulfuric acid manufacturer has been used as the case study. The case study is a large and reputable sulfuric acid manufacturer located in a developing country. The case study's production managers aimed to focus and consider different maintenance strategies for different equipment of this company to improve the performance of the company. Originally, the executives and production managers of the case study decided on different maintenance strategies which were focused in the previous literature. Furthermore, they were interested in determining the best maintenance strategies for seven different equipment of the case study while cost, risk and added value are taken into account. In this case study, seven types of equipment are used to produce the sulfuric acid. These equipment are different with regard to size, functions and their failure as they are used in different steps of producing sulfuric acid. Different equipment of this case study include boiler, molten sulfur ponds, cooling towers, absorption tower, converter, sulfur fuel furnace and heat exchanger.

5. Results and discussion

This section discusses the results of the proposed FANP model to select the best maintenance policy for all equipment of an acid manufacturing plant. As mentioned before, the capability of these strategies to decrease the cost, decrease the risk and increase the added value is considered in the proposed model. Therefore, four maintenance strategies of CM, TBM, CBM and SM are investigated to be considered for seven equipment of the case study. In other words, this section suggests the best maintenance policy for different equipment of the case study including boiler, molten sulfur ponds, cooling towers, absorption tower, converter, sulfur fuel furnace and heat exchanger.

According to what discussed in the research methodology section, Chang's extended analysis is applied to analyze the fuzzy decision matrices and deal with fuzzy data. The inputs of FANP model are pairwise comparison matrices as shown in Tables I-IV. The research is conducted for seven equipment operating in a sulfuric acid plant. The data used in pairwise comparison matrices are separately gathered for risk, cost and added value.

Table I. Pairwise comparison matrix of criteria with regard to objective (without seeing the relation among criteria)

Criteria	Risk	Added value	Cost	Weight of criteria
Risk	(1,1,1)	(1/2,2/3,1)	(1,3/2,2)	0.37
Added value	(1,3/2,2)	(1,1,1)	(1,3/2,2)	0.49
Cost	(1/2,2/3,1)	(1/2,2/3,1)	(1,1,1)	0.12

Table II. Pairwise comparison matrix of criteria (with seeing the relation among criteria)

Weights with regard to risk

	Added value	Cost	Weight
Added value	(1,1,1)	(1/2,1,3/2)	0.5
Cost	(2/3,1,2)	(1,1,1)	0.5

Weights with regard to added value

	Risk	Cost	Weight
Risk	(1,1,1)	(1,3/2,2)	0.68
Cost	(1/2,2/3,1)	(1,1,1)	0.31

Weights with regard to cost

	Risk	Added value	Weight
Risk	(1,1,1)	(2/3,1,2)	0.5
Added value	(1/2,1,3/2)	(1,1,1)	0.5

Table III. Pairwise comparison matrices of policies with regard to objective

	CM	TBM	CBM	SM	Weight
Pairwise comparison matrix with regard to risk					
CM	(1,1,1)	(1/2,2/3,1/3)	(2/5,1/2,2/3)	(1/2,1,3/2)	0.06
TBM	(1,3/2,2)	(1,1,1)	(2/5,1/2,2/3)	(3/2,2,5/2)	0.31
CBM	(3/2,2,5/2)	(3/2,2,5/2)	(1,1,1)	(2,5/2,3)	0.56
SM	(2/3,1,2)	(2/5,1/2,2/3)	(1/3,2/5,1/2)	(1,1,1)	0.05
Pairwise comparison matrix with regard to added value					
CM	(1,1,1)	(1/2,2/3,1/3)	(2/5,1/2,2/3)	(1/2,1,3/2)	0.06
TBM	(1,3/2,2)	(1,1,1)	(2/5,1/2,2/3)	(3/2,2,5/2)	0.31
CBM	(3/2,2,5/2)	(3/2,2,5/2)	(1,1,1)	(2,5/2,3)	0.56
SM	(2/3,1,2)	(2/5,1/2,2/3)	(1/3,2/5,1/2)	(1,1,1)	0.05
Pairwise comparison matrix with regard to cost					
CM	(1,1,1)	(1,3/2,2)	(1,3/2,2)	(1,3/2,2)	0.32
TBM	(1/2,2/3,1)	(1,1,1)	(1,3/2,2)	(1/2,1,3/2)	0.25
CBM	(1/2,2/3,1)	(1/2,2/3,1)	(1,1,1)	(1/2,2/3,1)	0.16
SM	(1/2,2/3,1)	(2/3,1,2)	(1,3/2,2)	(1,1,1)	0.25

	Risk	Added value	Cost	Weight
Pairwise comparison matrix with regard to CM				
Risk	(1,1,1)	(1/2,1,3/2)	(2/5,1/2,2/3)	0.23
Added value	(1/2,1,2)	(1,1,1)	(1/2,1,3/2)	0.33
Cost	(3/2,2,5/2)	(1/2,1,2)	(1,1,1)	0.42
Pairwise comparison matrix with regard to TBM				
Risk	(1,1,1)	(1/2,1,3/2)	(1/2,1,3/2)	0.33
Added value	(1/2,1,2)	(1,1,1)	(1/2,1,3/2)	0.33
Cost	(1/2,1,2)	(1/2,1,2)	(1,1,1)	0.33
Pairwise comparison matrix with regard to CBM				
Risk	(1,1,1)	(1/2,1,3/2)	(1/2,1,3/2)	0.33
Added value	(1/2,1,2)	(1,1,1)	(1/2,1,3/2)	0.33
Cost	(1/2,1,2)	(1/2,1,2)	(1,1,1)	0.33
Pairwise comparison matrix with regard to SM				
Risk	(1,1,1)	(1/2,2/3,1)	(2/5,1/2,2/3)	0.09
Added value	(1,3/2,2)	(1,1,1)	(1/2,2/3,1)	0.34
Cost	(3/2,2,5/2)	(1,3/2,2)	(1,1,1)	0.55

Table IV. Pairwise comparison matrices with regard to alternatives

The collected data are in the form of fuzzy intervals instead of crisp values for the linguistic terms stated by the decision makers. In addition, related data which are used for the internal relationship of alternative and criteria should be considered in FANP calculations. The applied data are collected from ten experts of the case study company. The ratings of all ten experts are combined using the average of their pairwise comparison values. According to FANP, obtaining priority weights of the criteria is the first step which should be calculated. Table I shows the pairwise comparison matrix of the criteria with regard to the objective. In other words, each criterion is compared with others to find the relative weigh as shown in the last column of Table I.

The next step is to compare each set of criteria together. In other words, two criteria are compared to each other to find their relative priority. These values are shown in Table II. The priority weight vector of this table is displayed using Chang's extended analysis. Therefore, comparable to Table I, Chang's priority weights and fuzzy intervals of cost, risk and added value are obtained for all criteria. Consequently, Table II compares each pair of criteria in the presence of the third criterion. Table III shows the fuzzy intervals and Chang's priority weights for pairwise comparison matrices of each policy with regard to the objective. Finally, using fuzzy intervals and Chang's priority weights, the pairwise comparison matrices of alternatives are shown in Table IV.

The next step is to construct the super matrix of FANP. To do so, the obtained priority vectors of previous steps are positioned in the proper columns to shape the super matrix. Similar to previous steps, as pairwise comparison matrices are displayed in the fuzzy form, the super matrix is shaped using the crisp values achieved by Chang's input. According to Table V, the first three columns including risk, cost and added value are the criteria. These columns are then followed by the four alternatives of CM, TBM, CBM and SM to be assigned to the seven equipment of the case study. The next step is to construct the limiting matrix. This matrix offers the rankings of all the components in the cluster and other preferences. The process of constructing this matrix is as follows. First, the super matrix should be stochastic to attain the weighted matrix. This matrix is shown in Table VI. Next, the values are found and shown in Table VII which is the limiting matrix.

The ultimate rankings of the alternatives for all seven equipment of the company are displayed in Table VIII. According to FANP result, the alternative with the best ranking is

Table V. Super matrix of the best maintenance policy for absorption tower

Cluster node level	Goal	Risk	Criteria Added value	Cost	CM	Alternatives TBM	CBM	SM
Goal	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Criteria								
Risk	0.970	0.000	0.684	0.500	0.237	0.333	0.333	0.097
Added value	0.345	0.500	0.000	0.500	0.335	0.333	0.333	0.345
Cost	0.559	0.500	0.316	0.000	0.428	0.333	0.333	0.556
Alternative								
CM	0.000	0.061	0.061	0.330	0.000	0.000	0.000	0.000
TBM	0.000	0.312	0.312	0.252	0.000	0.000	0.000	0.000
CBM	0.000	0.569	0.569	0.159	0.000	0.000	0.000	0.000
SM	0.000	0.058	0.058	0.260	0.000	0.000	0.00	0.000

Table VI. Weighted super matrix of best maintenance policy for absorption tower

Cluster node level	Goal	Risk	Criteria Added value	Cost	CM	Alternative TBM	CBM	SM
Goal	0.000000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Criteria								
Risk	0.096988	0.0000	0.3421	0.2500	0.2374	0.3333	0.3333	0.0970
Added value	0.344646	0.2500	0.0000	0.2500	0.3350	0.3333	0.3333	0.3446
Cost	0.558366	0.2500	0.1579	0.0000	0.4275	0.3333	0.3333	0.5584
Alternative								
CM	0.000000	0.0306	0.0306	0.1648	0.0000	0.0000	0.0000	0.0000
TBM	0.000000	0.1562	0.1562	0.1259	0.0000	0.0000	0.0000	0.0000
CBM	0.000000	0.2843	0.2843	0.0794	0.0000	0.0000	0.0000	0.0000
SM	0.000000	0.0290	0.0290	0.1300	0.0000	0.0000	0.0000	0.0000

Table VII. Limiting super matrix of the best maintenance policy for absorption tower

Cluster node level	Goal	Risk	Criteria Added value	Cost	CM	Alternative TBM	CBM	SM
Goal	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Criteria								
Risk	0.2270	0.2270	0.2270	0.2270	0.2270	0.2270	0.2270	0.2270
Added value	0.2227	0.2227	0.2227	0.2227	0.2227	0.2227	0.2227	0.2227
Cost	0.2170	0.2170	0.2170	0.2170	0.2170	0.2170	0.2170	0.2170
Alternative								
CM	0.0495	0.0495	0.0495	0.0495	0.0495	0.0495	0.0495	0.0495
TBM	0.0975	0.0975	0.0975	0.0975	0.0975	0.0975	0.0975	0.0975
CBM	0.1451	0.1451	0.1451	0.1451	0.1451	0.1451	0.1451	0.1451
SM	0.0412	0.0412	0.0412	0.0412	0.0412	0.0412	0.0412	0.0412

the ideal maintenance policy with regard to decreased cost, decreased risk and increased added value. Therefore, the CBM policy is appropriate for high-risk (cooling tower) and high added value equipment (absorption tower). In addition, TBM is selected for boiler, molten sulfur ponds and converters. Finally, high-cost, low-risk and low added value equipment (sulfur fuel furnace and heat exchanger) are more appropriate with CM policy.

The italic values of Table VIII show the best maintenance policy for each equipment of the company. Additionally, it can be concluded that TBM is the most common maintenance policy comparing to others as it has been selected for different equipment. Alternatively, it can be seen that CBM and CM have attained a same attention unlike the SM which is only assigned to one equipment.

The proposed approach of this study was applied in a sulfuric acid production plant and the suitable maintenance policy was found for all seven equipment of this company. These equipment included boiler, molten sulfur ponds, cooling towers, absorption tower, converter, sulfur fuel furnace and heat exchanger. Chang's extended analysis is employed to deal with fuzzy data and analyze the fuzzy decision matrices. The main justification to apply a fuzzy-based technique to address the problem of this study is the inherent complexity of comparing the strategies. The decision makers feel more comfortable to compare the maintenance strategies in fuzzy environment rather than deterministic scales. In addition, FANP is an appropriate technique to consider the relations among decision elements in the hierarchical structures. Regarding the contextualization, it is worthy to note that translating decision makers opinion using mathematical approaches make a valuable contribution in the maintenance area. This is mainly due to the fact that manages prefer to see the quantitative values instead of descriptions which might be confusing. As an implication of the research, this study provides essential empirical data on the maintenance policy selection. The applied methodology of this research can be used to determine the best maintenance policy of other case studies. There are numerous interdependence relationships among different factors of real-world problem. To define the interdependence degree and relationship, the ANP method, as a developed version of AHP, can be applied. As another implication of this study, as the decision making of real-world problems occurs in fuzzy environments, the applied FANP of this research can be implemented to select the best maintenance policy of equipment. As an implication for the case study, the proposed methodology and research framework of this research help maintenance managers of the company to apply appropriate maintenance policies for specific equipment.

6. Conclusion and future research directions

The major objective of this research was to propose an FANP technique to choose the best maintenance policy of an acid manufacturing company. In this research, four maintenance strategies of CM, TBM, CBM and SM were investigated to be considered for seven equipment of a real-case study. The next considered factor was the real nature of decision makers who prefer fuzzy numbers instead of exact values. Therefore, Chang's extended analysis was used to deal with fuzzy data and analyze the fuzzy decision matrices. The developed technique was used to a sulfuric acid production plant and the proper maintenance policy was found for all seven equipment of this company. According to the results, the CBM policy is suitable for high-risk (cooling tower) and high added value equipment (absorption tower). Furthermore, TBM is selected for boiler and converters while

No.	Equipment	CBM	CM	SM	TBM
1	Absorption tower	*0.43*	0.14	0.12	0.29
2	Cooling tower	*0.29*	0.21	0.20	0.27
3	Boiler	0.25	0.22	0.17	*0.34*
4	Molten sulfur ponds	0.33	0.13	*0.37*	0.15
5	Converters	0.26	0.21	0.14	*0.37*
6	Sulfur fuel furnace	0.25	*0.38*	0.18	0.17
7	Heat exchanger	0.27	*0.33*	0.12	0.26

Table VIII. Priority score of the four alternatives for seven equipment of company

SM is selected for molten sulfur ponds. Finally, high-cost, low-risk and low added value equipment (sulfur fuel furnace and heat exchanger) are more appropriate to use CM policy. However, although the proposed approach was applied in a sulfuric acid production plant, it should be noted that the statement of "one particular maintenance policy is best suited to a specific industry" might not be a correct and general rule. In other words, the best fit policy is a function of many factors including the condition of equipment, regulations, operators and decision-makers' comments. As a direction for future research, one may investigate more maintenance policies with more criteria to be fit with different equipment of companies. In addition, the maintenance policy can be investigated with regard to desired functionality and consequence of failures.

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