Renewable and Sustainable Energy Reviews 78 (2017) 1410–1423

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A combined goal programming – AHP approach supported with TOPSIS for maintenance strategy selection in hydroelectric power plants

Evren Can Özcan[a,*], Sultan Ünlüsoy[b], Tamer Eren[b]

[a] *Maintenance Management Department, Electricity Generation Co., 06520 Ankara, Turkey*
[b] *Industrial Engineering Department, Kırıkkale University, 71451 Kırıkkale, Turkey*

A R T I C L E I N F O

Keywords:
Maintenance strategy selection
Hydroelectric power plant
Multi-criteria decision making (MCDM)
Goal programming (GP)
Analytic hierarchy process (AHP)
Technique for order of preference by similarity to ideal solution (TOPSIS)

A B S T R A C T

Sustainable energy supply defined as uninterrupted, reliable, efficient, economic and environmentally friendly electricity generation is the main goal of power plants. Carrying out the proper maintenance processes has critical importance in terms of prolonging the effective operational lifetime of power plants and thus improving the sustainable power generation of the system. Since it serves for such an important purpose, maintenance is a crucial process that must be managed and selection of the most appropriate maintenance strategy is the first and unignorably stage of maintenance management in power plants as in other manufacturing facilities. Within this scope, this study focuses on the maintenance strategy selection problem in hydroelectric power plants have great importance for world and Turkey energy mix. As hydroelectric power plants comprise thousands of equipment with different characteristics, nine equipment which have similar effects and the most important ones for power plant are determined by The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) under nine evaluation criteria weighted by the Analytic Hierarchy Process (AHP) for a big scale hydroelectric power plant in Turkey. Maintenance strategy combinations are obtained for each selected equipment via proposed goal programming (GP) model which uses the criteria weights and alternative priorities calculated with AHP and reflects the realities of power plant. Finally, it is determined that there is an improvement about 77% in downtimes arise from carrying out the improper maintenance strategy on selected critical equipment compared to the period when the model is not used.

1. Introduction

Energy is the most basic element for raising social welfare, playing a fascinating role in economic and social progress of the countries' and thus increasing the competitiveness of the countries in the globalizing world [1]. In addition to this, population growth, urbanization, industrialization and constantly developing technology increase the need and demand for this critical power slightly day by day. Countries take new measures to meet increasing energy demand and in this context, revise their existing policies within the scope of sustainability. Because, energy demand growth which has social, economic and environmental effects necessitates carrying out the sustainable energy policies based on relevant effects [2].

From this point of view, sustainable energy can be defined as the policies, technologies and implementations which enable continuous supply of the required energy by using minimum financial resources and minimizing the negative impacts on environment and society. As can be seen in this general definition, "renewable energy technologies" with positive impacts on environment and society and "energy efficiency" which enables performing the uninterrupted energy supply with the possible lowest cost are the twin pillars of sustainable energy. In this context, the maintenance activities to be carried out in power plants must be managed within a well-designed system for operating the power plants in environmentally friendly and uninterrupted way with minimum possible cost and maximum possible efficiency [3].

However, it is imperative to highlight that maintenance cost can even achieve 15–70% of the expenditure or even could exceed annual net profit in many cases [4–6]. Nevertheless, no matter how large the amount of expenditure is, it is impossible for manufacturing industries to abandon maintenance. Therefore, a suitable and optimized maintenance strategy/policy is required for maintenance management in accomplishing all maintenance activities to save a significant of money [6–8]. In other words, optimal maintenance policy is able to provide a deliberate plan of action that usually containing a set of rules used to provide guidance for maintenance management in conducting an effective maintenance [6,9,10].

In accordance with the above explanations, the first stage of maintenance management is the selection of the most appropriate

* Corresponding author.
E-mail addresses: evrencan.ozcan@euas.gov.tr (E.C. Özcan), sultanunlusoy@gmail.com (S. Ünlüsoy), teren@kku.edu.tr (T. Eren).

http://dx.doi.org/10.1016/j.rser.2017.04.039
Received 23 May 2016; Received in revised form 9 February 2017; Accepted 17 April 2017
Available online 06 June 2017
1364-0321/

maintenance strategy (corrective maintenance, preventive maintenance, predictive maintenance and revision maintenance) based on equipment for power plants. As maintenance is an extremely costly process in terms of the requirements for man work, material and time besides the generation losses, selection of the most appropriate maintenance strategy is a crucial optimization problem for power plants [3].

From the view of the necessities for operating the power plants with maximum possible efficiency and the lowest costs to implement the sustainable energy policies as well as the importance of maintenance and maintenance strategy selection in order to perform these policies, in this study, maintenance strategy is handled in hydroelectric power plants where 24.84% of electricity generation [11] is performed as of the end of 2016 in Turkey by considering the studies performed in the literature.

Following the second section which introduces the operation and maintenance of hydroelectric power plants, related works in the literature and multi-criteria decision making (MCDM) methods used in this study have been mentioned in the third and fourth sections respectively. In the scope of case study given in fifth section, nine equipment which are the most important ones for hydroelectric power plants have been determined by TOPSIS under nine evaluation criteria weighted by AHP. Followed by this main step, the maintenance strategy combinations have been obtained for each selected equipment through proposed GP model which uses the criteria weights and alternative priorities calculated with AHP and reflects the realities of power plant. This study is finalized by giving the results and recommendations in the sixth section.

2. Operation and maintenance fundamentals of hydroelectric power plants

Hydropower is the most mature and cost competitive renewable energy resource around the world. With approximately 16% of electricity generation worldwide and about 85% of electricity generation by renewables, it plays an important role in today's electricity mix. The fluctuations between energy demand and supply can be balanced by this important power [12]. Because, hydropower is the most consistent and the flexible renewable energy resource in terms of meeting peak and unexpected power demand as well as meeting base load electricity need [13]. These important characteristics of hydropower will become even more important in the coming decades, as the shares of variable renewable energy resources increase considerably [12].

According to the International Energy Agency (IEA), with the fastest growth rate, nuclear (3% annually) and renewable resources (2.3% annually for only hydro) will play an important role on electricity generation worldwide until 2040 [11]. Also, IEA reports that emerging economies have the potential to double hydroelectric generation by 2050, preventing up to 3 billion tons of CO_2 annually and fostering social and economic development [14]. In this context, as an emerging economy, Turkey is a rich country in terms of this crucial resource with 140 kW h of annual hydroelectricity potential and its position in the 7th rank around the world with regards to hydropower use [13]. As of the end of 2016, hydroelectric power plants are placed in the top with a rate of 34.02% of Turkey's installed capacity and these power plants have met 24.84% of Turkey's energy demand [11]. According to these data and information, hydroelectric power plants have great importance for Turkey energy mix and thus hydroelectric power plants have been selected as field of application in this study.

Water has the kinetic or potential energy varying by location. It is found as kinetic energy in rivers, flowing sea straits, the seas where tides occur, and as potential energy in high mountains and natural lakes in the plateaus and dams. Providing that the potential energy of water in the bodies of the dam or natural lakes is converted to kinetic energy in transmission tunnels such as penstocks, this energy is

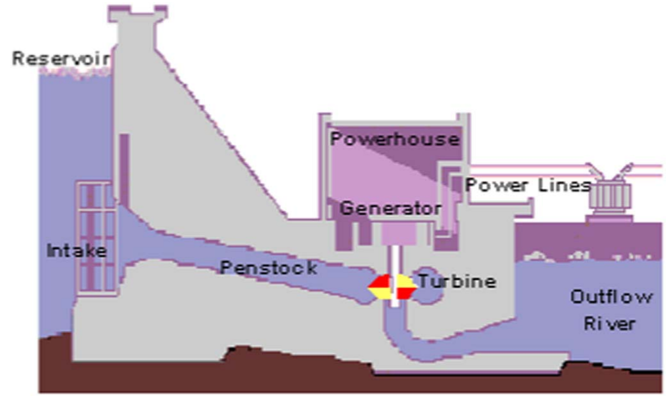

Fig. 1. A typical hydroelectric power plant with reservoir [16].

transformed into mechanical work by driving the water turbines. Turbine shaft is coupled to generator rotor directly or through a gear system. As a result of excitation of windings in generator rotor through a direct current power source, a magnetic field occurs around rotor and electricity is generated by inducing the stator windings. This energy is transferred to interconnected system by electrical equipment such as transformers, circuit breakers and disconnectors, and energy transmission lines [15] – Fig. 1.

All hydroelectric power plants worldwide have focused on the uninterrupted, reliable, efficient, economic and environmentally friendly power generation. The first step for realizing these goals named as sustainable energy supply, is conforming to the operational directives determined by the power plant producer and specified in operational guidelines. These rules are basically as follows: not to operate in cavitation limit, not to start-stop frequently, to clean the water intake grids continually, to consider the pressure differences for penstocks, to fix the clearance of inlet valve and wicket gates, to monitor the isolation values of rotor and stator windings, governor, current and voltage values of excitation generator, isolation of excitation transformer, vibration in generator rotor, coals in ring cell and oil temperature in main power transformer continuously [15].

To conform the operational directives outlined in above is not sufficient individually for sustainable power generation. Even if the power plant is operated properly, due to the pressure and temperature changes, metal fatigues in equipment etc., maintenance and repair needs emerge in every part of the power plant. Therefore, the second step for sustainable power generation in hydroelectric power plants is adopting to the maintenance schedules based on the suitable maintenance strategies determined by the equipment characteristics. Within this context, selection of the most appropriate maintenance strategy for each equipment has great importance for hydroelectric power plants. 4 maintenance strategies can be carry out in these plants. Brief descriptions of them are given below [3]:

Corrective maintenance strategy: The maintenance strategy which consists the repairment of equipment in malfunction situation.
Predictive maintenance strategy: The maintenance strategy which consists of taking required measures for preventing the failures with instrumentation and control (I & C) activities.
Preventive maintenance strategy: The maintenance strategy which is carried out periodically for uninterrupted running of equipment.
Revision maintenance strategy: The maintenance strategy which is performed for all the most important equipment of unit periodically (e.g. 8000 h or 5 years) and requires the long term (e.g. 2 months) shutdown of power plant unit.

Hydroelectric power plants have thousands of equipment under main titles of retention structure (dam, tunnel or open channel), intake structure, transmission line or penstocks, spiral casing, turbine, gen-

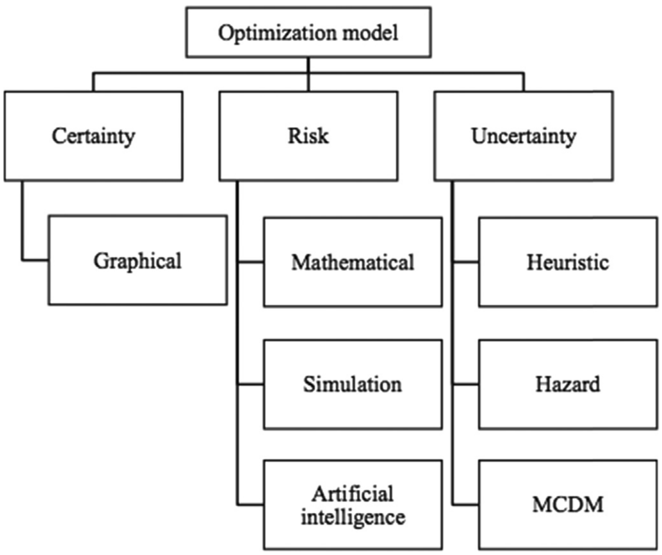

Fig. 2. Classification of maintenance policy optimization models [6].

erator, transformers and switchyard equipment. These equipment are classified as electrical, mechanical and I & C ones [15]. Though each equipment type has critical importance for electricity generation in hydroelectric power plants, the scope of this study is limited to electrical equipment as transmission of electricity energy is a problematic process.

3. Literature review

In the literature, there are so many academic studies regarding the maintenance strategy selection by using different methods carried out to reduce equipment breakdowns and maintenance costs in the manufacturing facilities. Ding and Kamaruddin [6] have explored these studies as detailed as never before and they brought in a valuable classification to the maintenance policy optimization literature by focusing on the used methods and application areas. The main classification of maintenance policy optimization models is shown in Fig. 2.

In graphical based models under certainty category, maintenance policy is simply pointed with the most desirable outcome through the detailed list of all policies. It is generally simple and does not require complicated optimization procedure [6]. A decision-making grid (DMG) is developed by Labib [17] by using a simple graphical model for optimal maintenance policy selection depending on the downtime and failure frequency of the system and implemented in automotive industry. This model is revised by Khalil et al. [18], Burhanuddin et al. [19] and Tahir et al. [20] to improve the effectiveness of DMG. The application areas of modified DMG are selected as aero industry, food processing industry, small and medium industries and failure-prone manufacturing system in these studies. Apart from DMG, another different graphical model using control chart is presented by Gupta et al. [21] to select the optimal maintenance strategy. Although the graphical based models have simple application procedures, the accuracy of the results produced by these models is low due to the limited criteria. Consideration of a limited number of criteria in the optimization process may also be lead to sub-optimization [6].

The states of nature influencing the system under optimization analysis, are known and can be described stochastically in mathematical, simulation based and artificial intelligence based models, which are developed/proposed by using different methods such as proportional hazard method [22], Markov method [23], non-linear programming [24], mixed integer linear programming [25], Monte Carlo simulation [26], agent-based simulation [27], genetic algorithm [28] and data envelopment analysis with Taguchi orthogonal array design [29], under risk category. Thus, these models able to predict future possible condition and determine the most suitable maintenance policy. But, these models are mostly involved considerably complex algebraic calculation. Because, these models are aimed to realize the theoretical research and therefore they neglect the application in real-life. However, maintenance management have not strong mathematical theoretical background hence, the models under risk category had to use various assumptions. When considering the inconsistencies between the assumptions and realities in maintenance management, it may be faced with the wrong maintenance policy decision-making [6].

A large amount of papers in the maintenance strategy selection literature have been used the models under uncertainty category in which this study is included. Future conditions and their regarding probabilities are not known in these models [30]. Therefore, the subjective judgements necessitate to be ascertained for the relevant information. This category is examined under three sub-categories including heuristically based, hazard based, and multi-criteria based models [6]. Heuristically based models which use the decision tree method, have given satisfactory solutions for selection of the most suitable maintenance strategy in cigar industry [30–32], thermal power plant [33] and drilling system [34]. Among these studies, Carazsa and Souza [33] determined the optimal maintenance policy in heavy-duty gas turbine in an open cycle thermal power plant with the objective of reducing the probability of failure besides reducing the maintenance costs and they demonstrated the viability and significance of the proposed method. In the second sub-category named as hazard based models, it is taken solving the failures effectively to forefront in comparison to the economic parameters. Improving maintenance quality in terms of safety and reliability without drastic increasing the cost by assigning maintenance policy is a main point of these models [6]. These models used the methods such as risk analysis [35], risk matrix [36], multi-criterion classification of critical equipment [37], failure mode effect analysis (FMEA) [38] and its fuzzy form [39] or integration with the other techniques like root case analysis [40] and integer linear programming [41]. Implementation areas are determined by the researchers in hazard based models as oil refinery industry, water treatment plant, gasification plant, petrochemical industry, process plant, paper mill, paper manufacturing plant and thermal power plants. For example, Dong et al. [42] used a combination of fuzzy criticality evaluation and FMEA for selection of the most suitable maintenance strategy of steam turbine in a fossil-fired power plant and the applicability of the proposed methodology is shown in their paper.

The last title under this category, MCDM based models are also one of the most popular and effective methods adopted in the maintenance strategy selection problem because of the advantages of the MCDM. This methodology considers the multiple and usually conflicting objectives in the decision-making process [43]. Conflicting objectives are commonly found in real-life like maximizing the system performance and minimizing the costs. Thus, it is useful in maintenance policy optimization that usually involve conflicting objectives such as maximizing system's availability with the lowest cost. In addition, by using MCDM in maintenance policy optimization, wider aspects such as safety (personnel, system, and environment), added value (spare parts inventories, production loss, and fault identification), and feasibility (acceptance by labors, method reliability) can be focused in order to obtain more accurate and precise results. In addition to these advantages of MCDM based models, Ding and Kamaruddin [6] have specified that these models give better measurement efficiency with less unrealistic assumptions. Meanwhile, MCDM can take a large amount of evaluation perspectives into the optimization process and this improves the overall reliability of the final outcome. Moreover, the MCDM approach gives a better view for maintenance management without limitation on using only the financial parameters as the maintenance policy performance measurement standard. Thus, providing a set of comprehensive measurements will be better and easier for maintenance policy performance indicator instead of converting all measures to financial measurement.

Among maintenance strategy selection studies in which MCDM methods are used, the following may be cited: Bevilacqua and Braglia [44] used AHP in an Italian oil refinery processing plant with referring to a group of systems which have similar failure criticality. Dey [45] determined the inspection and maintenance of oil pipelines that can maximize the availability with minimum cost by using AHP too. AHP also been used by Ratnayake and Markeset [46] to select the suitable maintenance strategy in oil and gas industry by considering the health, safety, environmentally awareness and cost criteria. Tan et al. [47] applied AHP to determine the most practicable maintenance policy for systems with different operational function in the oil refinery industry.

Although, AHP is a popular method for solution of the maintenance strategy selection problem, different MCDM methods such as TOPSIS, Analytic Network Process (ANP), Decision Making Trial and Evaluation Laboratory (DEMATEL), Elimination and Choice Expressing Reality (ELECTRE) and the combinations among themselves have also been used for maintenance policy optimization. While, Shyjith et al. [48], Ding et al. [49,50] and Momeni et al. [51] have adopted TOPSIS in selecting the optimal maintenance policy, ANP is used by Cheng and Tsao [52] for determining the optimal maintenance policy of rolling stock. ANP is integrated with the DEMATEL in order to convert the relations between cause and effect of criteria into a visual structural model and feasibility of the proposed methodology is tested in an automotive manufacturing plant [53]. Zaim et al. [54] used AHP and ANP methods when finding out the most appropriate strategies so as to protect printing machines and lower maintenance costs in a local newspaper printing facility in Turkey. Gonçalves et al. [55] used ELECTRE method in the selection of many key performance indications for assessing performance of maintenance services applied in the companies. Ahmadi et al. [56] assessed maintenance policies in aircraft and aviation systems using combined AHP-TOPSIS-VIKOR method. Moreover, Zeng et al. [57] used TOPSIS method combined with Grey Correlation Theory for smooth running of electrical equipment and condition based maintenance.

Recently, integration of fuzzy logic with MCDM methods is widely applied in maintenance policy optimization due to its flexibility in measuring uncertainty in the data [6]. Labib [58] proposed the fuzzy AHP method to determine the optimal maintenance policy that able to reduce downtime and failure frequency of system with better accuracy in an automotive company. Wang et al. [59] assessed ideal maintenance strategy with fuzzy AHP method for different vehicles in order to increase availability and reliability of the facilities in a thermal power plant in China. Nezami and Yıldırım [60] performed some applications in automotive industry using fuzzy VIKOR method to decrease the breakdowns causing generation losses. Furthermore, Ilangkumaran and Kumanan [61] introduced the integration of fuzzy AHP and TOPSIS to select the optimal maintenance strategy in a more efficient way in textile industry. Kumar and Maiti [62] preferred fuzzy ANP method as the most appropriate maintenance policy selection which will reduce breakdown risk and maintenance cost as there is relation between the criteria which they determined.

As stated before, multiple and conflicting objectives are taken into account in the decision-making process by MCDM methods [43]. One of these methods, GP is effective technique in terms of considering the multiple and conflicting objectives such as maximizing system's availability with the lowest cost in the decision-making processes like maintenance strategy selection problem. In this context, some studies like this study, which integrates AHP with GP are performed in the maintenance strategy selection literature. Bertolini and Bevilacqua [63] used AHP and GP methods integratedly for 10 critical centrifugal pumps they determined considering maintenance periods and maintenance costs in Italian oil refinery facilities. Arunraj and Maiti [64] also developed a similar integration to identify an optimal maintenance policy in a benzene extraction unit of a chemical plant in terms of cost and risk. Moreover, a combination of AHP, GP and fuzzy logic is presented by Ghosh and Roy [65] to determine the optimal maintenance policy. The application of proposed model is performed by using data obtained from Wang et al. [59].

4. Multi criteria decision making methods

In our daily or professional lives, conflicting/related multiple criteria need to be considered while making decisions. The decision-making processes are related to energy, which are included in the crucial optimization problems group when considering the indispensability of energy in terms of world politics and humanity, and they have also intrinsically multiple criteria structures and therefore, analytical approaches for effective solutions for these problems are needed. In this context and within the frame of the advantages of MCDM stated in previous section, in this study, MCDM, which is a subdiscipline of operations research that explicitly considers multiple criteria in decision-making environments [66] is based and a mathematical model that combines AHP and GP, and supported with TOPSIS, is suggested to select the most suitable maintenance strategies for a hydroelectric power plant in Turkey.

There are so many improved MCDM methods such as AHP [67], ANP [68], Case-Based Reasoning (CBR) [69], GP [70], TOPSIS [71], ELECTRE [72] and The Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) [73] in the literature, and their relative advantages and disadvantages are discussed according to their applicability in different situations. AHP is "a theory of measurement through pairwise comparisons and relies on the judgments of experts to derive priority scales" [74]. One of its advantages is its ease of use. AHP uses the pairwise comparisons and this allows to weight criteria or coefficients and compare alternatives. It is scalable, and can easily adjust in size to accommodate decision-making problems due to its hierarchical structure [75]. TOPSIS is the other MCDM method used in this study, and "an approach to identify an alternative which is closest to the ideal solution and farthest to the negative ideal solution in a multi-dimensional computing space" [76]. It has more simple process than the other outranking algorithms such as ELECTRE and PROMETHEE. Furthermore, the number of steps remains the same regardless of the number of attributes [77]. Finally, GP is a pragmatic MCDM method that can choose from an infinite number of alternatives. One of its advantages is that it has the capacity to handle large-scale problems [75]. GP is frequently used in the literature such as energy planning [78], supplier selection [79], scheduling [80] and production planning [81], and generally it is combined with other MCDM techniques such as AHP [82], TOPSIS [83], PROMETHEE [84] and ANP [85] to accommodate proper weighting. By doing so, it eliminates one of its weaknesses while still being able to choose from infinite alternatives.

Besides the basic specifications and the advantages of the methods are used in this study which are given above, in consideration of the structure of maintenance strategy selection problem for hydroelectric power plants in terms of complexity and the number of equipment, in this study a combined AHP-GP model supported with TOPSIS is suggested to select the most suitable maintenance strategies for a hydroelectric power plant in Turkey. In the following sub-sections, TOPSIS, AHP and GP approach will be explained in detail.

4.1. TOPSIS

TOPSIS method was developed by Hwang and Yoon [71] in 1981 and it is a useful technique in dealing with MCDM problems in the real-life. It helps to decision makers for comparing and ranking the alternatives. Hwang and Yoon propose that the ranking of alternatives will be based on the shortest distance from the ideal solution and the farthest from the negative ideal solution. It makes ranking among alternatives and chooses the nearest alternative to the ideal solution. Application steps are given below [71]:

Step 1: Construct the decision matrix.

The established matrix consists of m alternatives and n criteria with the intersection of each alternative and criteria given as x_{ij}, and therefore have a matrix $(x_{ij})_{mxn}$.

Step 2: Construct a normalized decision matrix.

Normalization is made to obtain comparable scales. The vector normalization is defined below.

$$Rij = aij/\sqrt{\sum_{k=1}^{m} aij^2} \quad i = 1, 2, \ldots, m \quad ve\ j = 1, 2, \ldots, n \tag{1}$$

Step 3: Calculate the weighted decision matrix.

After forming the normalized decision matrix, calculate the weighted normalized decision matrix V;

$$V_{ij} = w_j \times r_{ij}\ \forall_i\ , j,\ w_j \text{ is the weight of criterion } j. \tag{2}$$

Step 4: Identify the ideal and negative ideal solution.

$$A^+ = (max_i\ vij\,|j€J),\ (min_i\ vij\,|j€J) \tag{3}$$

$$A^- = (min_i\ vij\,|j€J),\ (max_i\ vij\,|j€J) \tag{4}$$

The ideal solution which maximizes the benefit criteria (or attributes) and minimizes the cost criteria, whereas the negative ideal solution (also called anti-ideal solution) maximizes the cost criteria/attributes and minimizes the benefit criteria/attributes [59]. The negative ideal solution consists of the worst performance values whereas the best alternative is the one that is nearest to the ideal solution [86].

Step 5: Calculate the separation distance of each competitive alternative from the ideal and negative ideal solution

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (vij - vj^+)^2} \qquad i = 1, 2, 3, \ldots, m \tag{5}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (vij - vj^-)^2} \qquad i = 1, 2, 3, \ldots, m \tag{6}$$

Step 6: By comparing C^+ values, the ranking of alternatives is determined.

$$C_i^+ = S_i^-/(S_i^- + S_i^+) \qquad i = 1, 2, 3, \ldots, m \tag{7}$$

where $0 \le C_i^+ \le 1$.

4.2. AHP

AHP is applied to support many types of multi-criteria decision problems. It has particular application in group decision-making, and it has recently become increasingly popular around the world in a wide variety of decision situations, in fields such as public policy, business, industry, healthcare, shipbuilding and education. This method helps people to set priorities between alternatives, sub-criteria and criteria in the decision-making process. Also, it helps making better decisions by taking into account the qualitative and quantitative aspects of the decision [75].

AHP application steps are as follows [67]:

Step 1: Determine the objective, main-criteria, sub-criteria, alternatives and structure of the hierarchy.

This step contains aim of decision-maker, criteria according to aim, and hierarchical structure of criteria (Fig. 3).

Step 2: Make pairwise comparisons of criteria and comparisons of alternatives for each criterion.

The pairwise comparison is conducted by asking a decision-maker or an expert questions, such as which criterion is more important with regard to the decision goal and comparison is made according to 1–9 scale, which was generated by Saaty, as shown in Table 1.

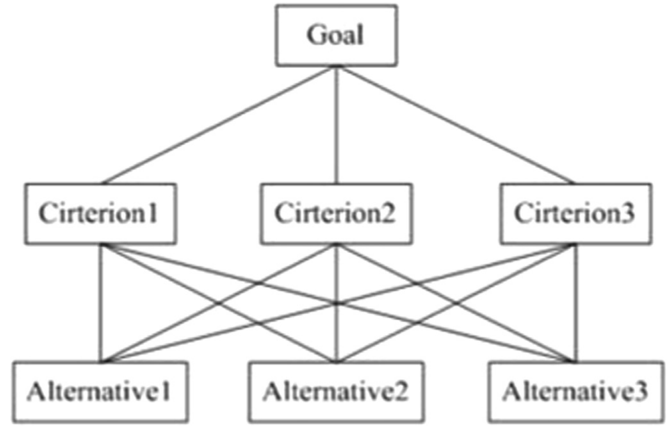

Fig. 3. Sample hierarchy structure [67].

Step 4: Calculation of priority vectors.

By using the comparison matrixes the vector of weights (w) is computed in two steps. First, the pairwise comparison matrix, $A.w = \lambda_{max}\ .w$ is normalized, then the weights are computed.

Normalization process is conducted simply by dividing each element of a_{ij} by the column totals.

Weight calculation is made as follows:

$$wi = \sum_{i=1}^{n} aij^*/n \tag{8}$$

Step 5: Calculate and check the consistency ratio (CR).

In the AHP, the pairwise comparisons in a judgement matrix are considered to be adequately consistent, if the corresponding *CR* is less than 10%. The *CR* coefficient is calculated after Consistency Index (*CI*). *CI* is defined and numerical calculation is made as follows:

$$(CI) = (\lambda_{max} - n)/(n-1) \tag{9}$$

Next the *CR* is obtained by dividing the *CI* value by the Random Consistency Index (*RCI*). *RCI* values are shown in Table 2.

Then, the *CR* value is calculated by using the formula:

$$(CR) = CI/RI \tag{10}$$

The test of consistency is completed when the *CR* is numerically calculated.

If *CR < 10%*, achieved data is consistent.

If *CR≥10%*, achieved data is inconsistent, the original values in the pairwise comparison matrix should be reconsidered and revised.

Step 6: Analysis of the AHP scores.

After all 5 steps, if the model is consistent, the best alternative by AHP score is chosen.

4.3. GP method

GP is an extension or generalization of linear programming (LP) to handle multiple and conflicting objective measures. It developed in the early 1960s owing to the study of Charnes and Cooper [87]. LP deals with only one single objective to be minimized or maximized, and subject to some constraint. Therefore, it has limitations in solving a problem with multiple objectives. However, GP can be used as an effective approach to handle a decision concerning multiple and conflicting goals [63].

GP is frequently used in the literature as stated before. Most of all, multi-criteria decision problems, such as selection ones in different topics and areas constitute the main field of application of GP. The different types of GP models include the non-linear and linear ones are used for analyzing the multi-criteria decision problems. These are classified as Archimedean Weights (i.e. weighted GP), the Interactive Weighted Tchebycheff Procedure (IWT), the MINMAX (Chebyshev)

Table 1
The Saaty rating scale [67].

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective.
3	Somewhat more important	Experience and judgement slightly favour one over the other.
5	Much more important	Experience and judgement strongly favour one over the other.
7	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favouring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed.

Table 2
RCI values for different values of *n* [67].

n	1	2	3	4	5	6	7	8	9
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

GP, the Reference Point Method (RPM), the Compromise Programming (CP), and the Lexicographic Linear GP (LGP). LGP is actually one of the most significant devices in tackling multi-criteria decision problems: the different goals can be ranked according to different priority levels that reflect the target allocated to them by the decision maker. The lexicographic approach defines different priority

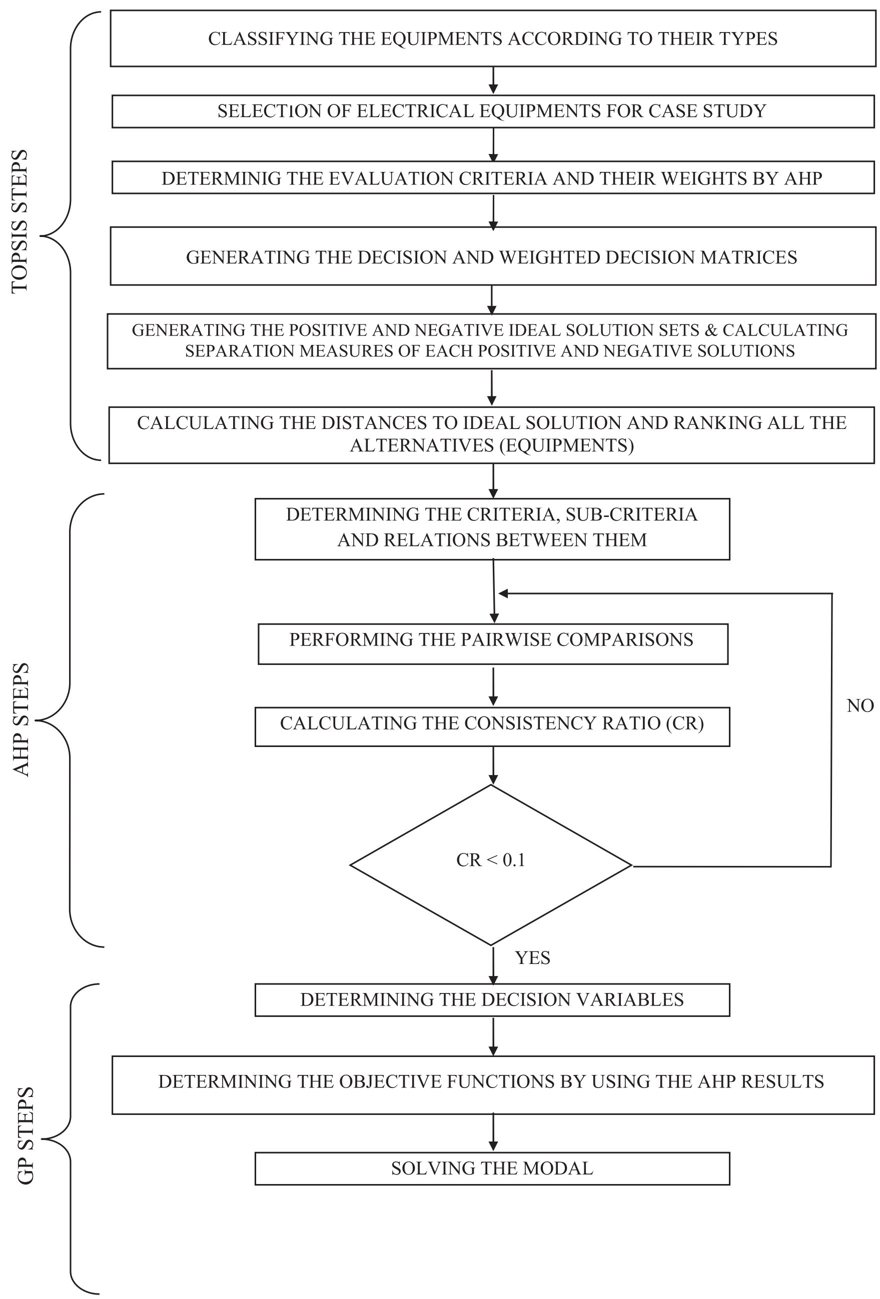

Fig. 4. The flowchart of case study.

Renewable and Sustainable Energy Reviews 78 (2017) 1410–1423

levels P_j for the goals of the analysis. The different priority levels reflect the hierarchical relationship between the targets in the objective function where they are arranged in order of decreasing priority. To identify the solution to the problem, the highest priority goals and constraints are considered first; if more than one solution is found in the first step, another GP problem is formulated which takes into account the second priority level targets. The procedure is repeated until a unique solution is found, gradually considering decreasing priority levels [63].

In this paper, the LGP model is applied defining a binary structural variable (zero-one programming), and the objective function given in Eq. (11) shows that the goal of the problem consists in the minimization of the unwanted deviations from the target.

The mathematical formulation of the standard GP is as follows [70]:

Considering the m objectives we have,

$$\text{MinZ} = \sum_{i=1}^{m} (d_i^+ + d_i^-) \tag{11}$$

$$\sum_{j=1}^{n} a_{ij}x_j - d_i^+ + d_i^- = b_i, \qquad i = 1, ..., m, j = 1, ..., n \tag{12}$$

d_i^+, d_i^- and $x_j \geq 0$

The variables d_i^+ and d_i^- are positive and negative deviations from the target value of the ith goal (b_i).

5. Case study

Especially, as a result of population increase, industrialization and ever growing technology, energy demand has increased by average 5.6% over the past decade in Turkey. Electricity consumption per capita has also increased from 2052 kW h to 3373 kW h with the rate of 64.4% in Turkey at the same period and hydroelectric power plants met about one quarter of this significant increased demand [11]. Therefore, uninterrupted power generation in these power plants has great importance with regards to energy supply security in Turkey. In this context, the maintenance activities to be carried out in hydroelectric power plants must be managed within a well designed system for economic, efficient and green electricity generation within the scope of sustainability as well as this necessity.

When it is taken into account the first and unignorably stage of maintenance management is the selection of the most appropriate maintenance strategy, in this study, the maintenance strategy combinations have been obtained for nine electrical equipment respectively which have similar effects to power plants in a big scale hydroelectric power plant via combined GP – AHP approach supported with TOPSIS. The steps of the case study is presented in Fig. 4.

5.1. Selection of equipment

As stated before, however all equipment types (electrical, mechanical and I & C) have critical importance for electricity generation, due to the transmission of electricity energy is a problematic process, electrical equipment are specified for the application.

After limiting the scope of the study by electrical equipment, it has been initiated to determine the criticality levels of the equipment for power plant. This step has been performed with TOPSIS methodology and first, evaluation criteria have been determined (Table 3). Evaluation criteria related with all equipment in power plant have been created by the specialists and within this period all factors which effect the importance of the equipment for power plant have been taken into account.

There are 1404 electrical equipment in selected hydroelectric power plant. Linguistic values have been set to each equipment according to each criterion by using criterion parameters given in Table 3. The numerical equivalents of the parameters of evaluation criteria have been generated by power plant specialists as all parameters must be numerical for running the TOPSIS algorithm. A scale comprises of the numbers between 0 and 10 is used for this procedure and the highest score has been assigned to the parameter (unit shutdown) which effects to uninterrupted electricity generation directly. Scores of the other parameters have been determined by considering the highest scores given among all criteria. By finalizing this step, initial decision matrix with dimension of 1404×9 is obtained and it is started to TOPSIS methodology.

Weights of nine evaluation criteria given in Table 3 have been calculated with AHP for determining the priorities of all electrical equipment by TOPSIS. *CR* of the criteria pairwise comparison matrix has been computed as 0.051 and the weights of nine criteria which are calculated through this consistent matrix are shown in Table 4.

By using the criteria weights and Eq. (2), weighted decision matrix is composed and positive and negative ideal solution sets have been obtained according to the Eq. (3) and Eq. (4). After calculating the separation distances of each competitive alternative (equipment) from the ideal and non-ideal solutions respectively by using Eq. (6) and Eq. (5), each equipment priority (C_i^+) is obtained by Eq. (7). In this

Table 3
Evaluation criteria.

Criteria		Criteria parameters	Numerical equivalents of the parameters
C1	Warehouse backup	Never	3
		Sometimes	2
		All the time	1
C2	Maintenance pre-conditions	Unit shutdown	7
		Shutdown by situation	6
		Shutdown by time	5
		Maintenance without back up	2
		Shutdown does not require	1
C3	Failure period	Monthly	8
		Quarterly	5
		Semi-annually	3
		Annually	2
		Long term	1
		Unknown	1
C4	Possible consequences	Unit shutdown	10
		Problem in emergency situation	9
		Load reduction	8
		Running without back up	7
		Equipment shutdown	6
		Security problem	6
		Deficient function	2
		Damage in associated equipment	2
		Problem in start	1
		Fluid consumption increase	1
C5	Availability of measuring equipment	Yes	3
		No	1
C6	Static, dynamic or electrical property of equipment	Mechanical-dynamic	2
		Mechanical-static	1
		Electrical	1
		I & C	1
C7	Trouble shooting time	One week	9
		More than one day	3
		Unknown	3
		2–8 h	2
		Less than 2 h	1
C8	Detectability of failure	Difficult	3
		Easy	1
C9	Additional work requirement	Required	5
		Not required	1

Table 4
Criteria weights.

Criteria		Weights
C1	Warehouse backup	0.051044486
C2	Maintenance pre-conditions	0.241414796
C3	Failure period	0.070515831
C4	Possible consequences	0.400571433
C5	Availability of measuring equipment	0.061857822
C6	Static, dynamic or electrical property of equipment	0.054580192
C7	Trouble shooting time	0.029078809
C8	Detectability of failure	0.061857822
C9	Additional work requirement	0.029078809

Table 5
Selected equipment and their priorities.

Equipment title		Priority score
E1	Generator rotor	100
E2	Generator stator	100
E3	Excitation transformer	98
E4	Main power transformer	100
E5	380 kV switchyard circuit breaker	94
E6	380 kV switchyard bus bar disconnector	94
E7	380 kV switchyard current transformer	92
E8	380 kV switchyard voltage transformer	92
E9	Slipring and carbon brushes	90

context, generator rotor and generator stator are determined as the most important equipment with the highest C_i^+ score. 0.8370501 is the highest priority value has considered as 100 to identify the equipment' priorities in easier way. According to this, priorities of all 1404 equipment have been recalculated and nine equipment with the scores of 90 and above have been determined for solution of proposed model. Selected nine equipment and their priorities showing the criticality levels of relevant equipment for power plant are given in Table 5.

As stated before, one of the main goals of power plants is uninterrupted electricity generation and the equipment in Table 5 are the determinants for this target. Because, power plant units must be stopped for carrying out the maintenance operations of these equipment. Furthermore, units of power plants shutdown in the event that outage of relevant equipment. These realities about power plant operations prove the correctness of the analysis for executing to determine the importance levels of equipment in power plant.

Schematic representation of relationships between the selected equipment and their functions are shown in Fig. 5.

5.2. Determining the criteria priorities

As stated before, 4 maintenance strategies (preventive, corrective, predictive and revision) can be carry out in hydroelectric power plants. Furthermore, occurrence, severity and detectability are determined as criteria which effect the goal of the most appropriate maintenance strategy selection for 4 alternatives. In this context, hierarchical representation for selection of the most appropriate maintenance strategy problem is shown in Fig. 6.

Pairwise comparison matrices for these criteria and alternatives (for each criterion respectively) have been prepared by taking power plant specialists' opinions and the consistency ratios of the matrices have been calculated as less than 0.1. In consequence of performing the calculations on these consistent matrices, the global priority ($SCORE_{AHP,i}$) of the different ith alternatives (4 possible maintenance strategies), the local priority ($SCORE_{k,i}$) of the ith alternative with respect to each criterion, and the weights (w_k) of the kth criteria (occurrence, severity and detectability) have been obtained. These values are given in Tables 6–8.

Maintenance is an extremely costly process because of man work, material and time requirements as well as generation losses. Therefore, selection of the most appropriate maintenance strategy is a crucial optimization problem in a power plant. In this context, direct and indirect maintenance costs and durations of maintenance operations must be reflected to mathematical models for determining the maintenance strategy combinations.

Costs and operation durations vary from each maintenance strategy in hydroelectric power plants in common with the other production facilities. Hence, these data have been collected for each selected equipment by taking into account the real-life power plant operation rules. In this context, maintenance costs are classified as man work, material and generation losses for each maintenance strategy. Furthermore, frequently occurred failures for each selected equipment are determined and all actual duration and cost data are given in Tables 9–12.

Costs arising from generation losses are the most notably ones within these data. These are significantly greater than the others. Because, big scale power plants generate thousands kWh of energy in a few hours and if a power plant stops for any reason such as maintenance or malfunction, this vast amount of energy cannot be generated. When considered the importance of generation shutdown in power plants in terms of energy supply security as well as its cost effects, importance of the models – like a combined GP – AHP model which is proposed for determining the most appropriate maintenance strategy combinations for critical equipment in a hydroelectric power plant in the context of this study -increase.

5.3. Model formulation

In this study, a combined GP – AHP model is proposed to select the most appropriate combination among 4 maintenance strategies for the most critical equipment determined by using TOPSIS methodology and effects the uninterrupted electricity generation directly in selected hydroelectric power plant by taking as a reference the studies of Bertolini and Bevilacqua [63], and Badri [88]. Model formulation is given below with notations and decision variables.

Notations.

P_i	factors reflect the problem hierarchy ($P_1 >>> P_4$), i=1,...,4.
T_C	available budget for maintenance.
T_{MT}	available time capacity for maintenance.
w_k	the weights of the kth criteria (e.g. w_O is the weights of occurrence criteria).
C_{PREV}	maintenance cost for preventive strategy.
C_{CORR}	maintenance cost for corrective strategy.
C_{PRED}	maintenance cost for predictive strategy.
C_{REV}	maintenance cost for revision strategy.
MT_{PREV}	required duration for preventive maintenance.
MT_{CORR}	required duration for corrective maintenance.
MT_{PRED}	required duration for the predictive maintenance.
MT_{REV}	required duration for the revision maintenance.
$SCORE_{AHP,\ i}$	the global priority of the different ith alternative.
$SCORE_{k,l}$	the local priority of the kth alternative with respect to each criterion.
$T_{k,SCORE}$	the targets defined for the constraint equations linked to the local score maximization score.
d_i^-	the negative deviation from the value designated, of the ith objective.
d_i^+	the positive deviation from the value designated, of the ith objective.
d_k^-	the negative deviation from the target for criterion, k=o(occurrence), s(severity), d(detectability).
d_k^+	the positive deviation from the target for criterion, k=o(occurrence), s(severity), d(detectability).
M	A large number.

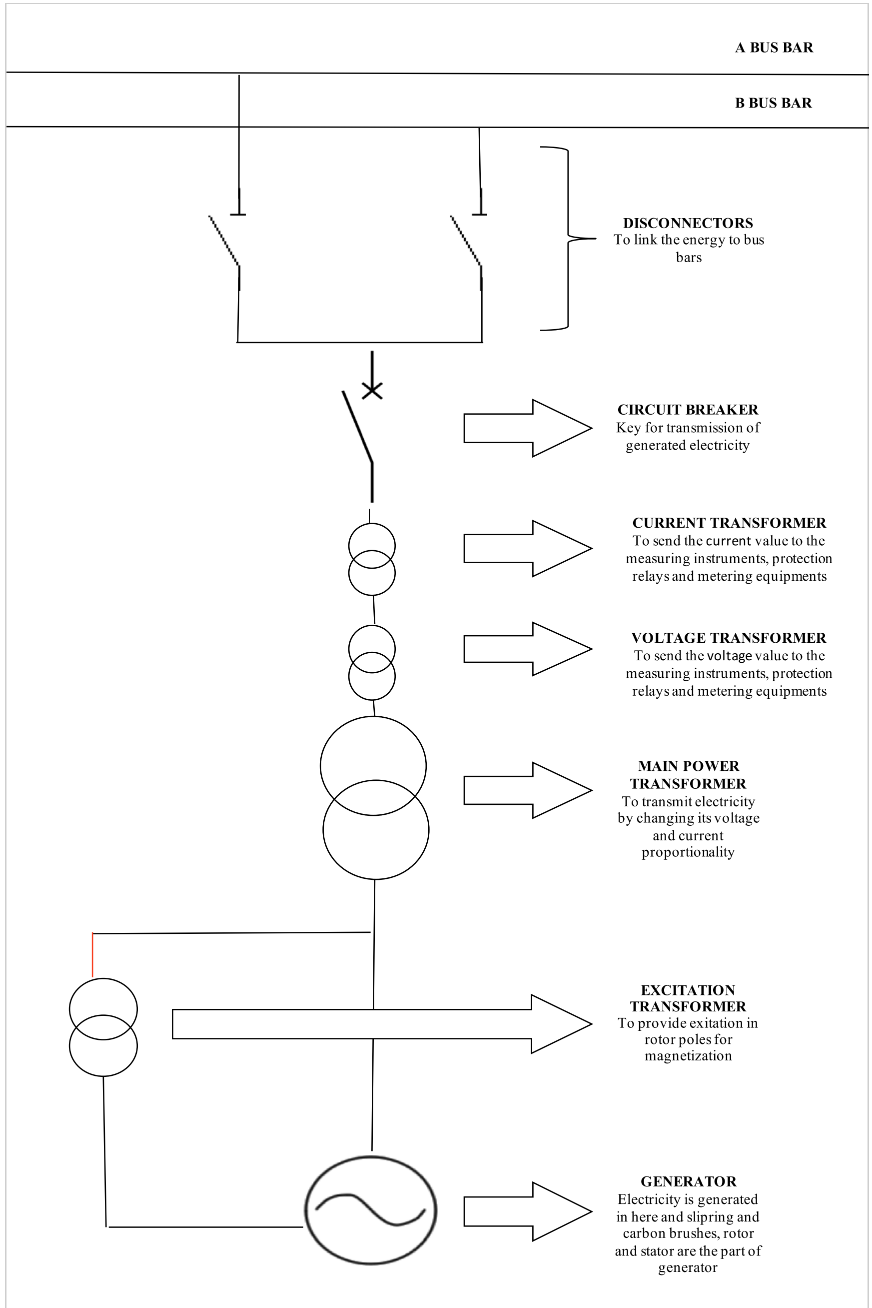

Fig. 5. Schematic representation of relationships between the selected equipment.

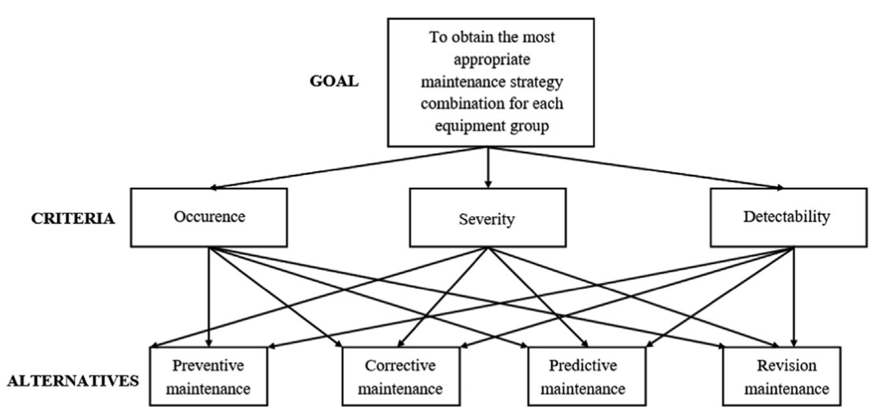

Fig. 6. Hierarchical representation of the most appropriate maintenance strategy selection problem.

Table 6
Criteria weights.

Criteria	Weight
Occurence	0.083307883
Severity	0.723506057
Detectability	0.193186060

Table 7
Global priority scores of each alternative ($SCORE_{AHP,i}$).

Alternative strategy	Priority score
Preventive maintenance	0.252372367
Corrective maintenance	0.039045987
Predictive maintenance	0.413479883
Revision maintenance	0.295101763

Table 8
Local priority scores of each alternative by criteria ($SCORE_{k,i}$).

Alternative strategy	Priority score		
	Occurence	Severity	Detectability
Preventive maintenance	0.239437377	0.287949766	0.124708509
Corrective maintenance	0.047361745	0.037634346	0.040746745
Predictive maintenance	0.122329784	0.503849299	0.200588117
Revision maintenance	0.590871094	0.170566589	0.633956629

Decision variables

$$x_{i,j} = \begin{cases} 1, & \text{if } jth \text{ maintenance strategy is chosen for } ith \text{ equipment} \\ 0, & otherwise \end{cases}$$

j values of 1, 3 and 4 represent the preventive, predictive and revision maintenance strategies respectively. Because of the second strategy is corrective one, the number of 2 has been passed not to cause any confusion and a_j value has been set to each failure type given in Table 8 under the corrective maintenance strategy. In this context, j values of 5–27 represent the corrective maintenance strategy for each failure type.

$$y_{i,f} = \begin{cases} 1, & \text{if } fth \text{ failure occurs for } ith \text{ equipment} \\ 0, & otherwise \end{cases} \quad i = 1, \ldots, 9, f = 1, \ldots, 23$$

Four goals which are determined in this study and their priorities (P_i) are given below.

1. Minimize the costs,
2. Minimize the maintenance durations,
3. Maximize the global AHP scores,
4. Maximize the local AHP scores.

Model formulation

$$MinZ = P_1(d_C^+) + P_2(d_{MT}^+) + P_3(d_{SCORE,AHP}^-) + P_4(w_O d_O^- + w_S d_S^- + w_D d_D^-) \tag{13}$$

subject to

$$C_{PREV}x_{i,PREV} + C_{CORR}x_{i,CORR} + C_{PRED}x_{i,PRED} + C_{REV}x_{i,REV} + d_C^- - d_C^+ = T_C \tag{14}$$

$$MT_{PREV}x_{i,PREV} + MT_{CORR}x_{i,CORR} + MT_{PRED}x_{i,PRED} + MT_{REV}x_{i,REV} + d_{MT}^- - d_{MT}^+ = T_{MT} \tag{15}$$

$$x_{i,CORR} - My_{i,f} \le 0 \tag{16}$$

$$SCORE_{AHP,PREV}x_{i,PREV} + SCORE_{AHP,CORR}x_{i,CORR} + SCORE_{AHP,PRED}x_{i,PRED} + SCORE_{AHP,REV}x_{i,REV} + d_{SCORE,AHP}^- - d_{SCORE,AHP}^+ = 1 \tag{17}$$

$$SCORE_{O,PREV}x_{i,PREV} + SCORE_{O,CORR}x_{i,CORR} + SCORE_{O,PRED}x_{i,PRED} + SCORE_{O,REV}x_{i,REV} + d_O^- - d_O^+ = T_{O,SCORE} \tag{18}$$

$$SCORE_{S,PREV}x_{i,PREV} + SCORE_{S,CORR}x_{i,CORR} + SCORE_{S,PRED}x_{i,PRED} + SCORE_{S,REV}x_{i,REV} + d_S^- - d_S^+ = T_{S,SCORE} \tag{19}$$

$$SCORE_{D,PREV}x_{D,PREV} + SCORE_{D,CORR}x_{i,CORR} + SCORE_{D,PRED}x_{i,PRED} + SCORE_{D,REV}x_{i,REV} + d_D^- - d_D^+ = T_{D,SCORE} \tag{20}$$

$$x_{i,j} = 1 \quad \left\{ \begin{array}{l|l} i = 1 & j = 4 \\ i = 2 & j = 2,3,4 \\ i = 3 & j = 3,4 \\ i = 4 & j = 3,4 \\ i = 5 & j = 2,3,4 \\ i = 6 & j = 3,4 \\ i = 7 & j = 3,4 \\ i = 8 & j = 2,4 \\ i = 9 & j = 3,4 \end{array} \right\} \tag{21}$$

The objective is the minimization of unwanted deviations by taking into account the AHP scores. While Eq. (14) (1st goal constraint) states the costs of maintenance carried out for all selected equipment within the limited budget, Eq. (15) (2nd goal constraint) restricts the maintenance durations within total available time capacity. Available budget (T_C) and available time capacity (T_{MT}) for maintenance are determined as the highest values among all maintenance strategies given in Tables 9–12.

Table 9
Cost and duration data for preventive maintenance strategy.

Equipment title	Preventive maintenance strategy				
	Duration (Minute)	Material cost (₺)	Man work cost (₺)	Generation loss cost (₺)	Total cost (₺)
380 kV switchyard bus bar disconnector	120	50	50	29,740	29,840
380 kV switchyard circuit breaker	60	100	25	14,870	14,995
380 kV switchyard current transformer	30	50	12.5	7435	7498
380 kV switchyard voltage transformer	30	50	12.5	7435	7498
Main power transformer	60	150	25	14,870	15,045
Generator rotor	60	150	25	0	175
Generator stator	60	150	25	0	175
Slipring and carbon brushes					
Excitation transformer	60	150	25	14,870	15,045

Table 10
Cost and duration data for corrective maintenance strategy.

Equipment title	Failure title	Corrective maintenance strategy				
		Duration (Minute)	Material cost (₺)	Man work cost (₺)	Generation loss cost (₺)	Total cost (₺)
380 kV switchyard bus bar disconnector						
	Melting the disconnector contacts based on overcurrent	480	500	400	118,960	119,860
	Depleting disconnector engine coals	240	50	100	59,480	59,630
	Breaking the gears in disconnector gear case	2400	1000	2000	594,800	597,800
	Position switch failure	60	60	25	14,870	14,955
380 kV switchyard circuit breaker						
	SF6 leakage in unions	60	100	25	14,870	14,995
	Failure in on-off coils	120	400	50	29,740	30,190
	Position switch failure	30	200	12,5	7435	7648
	Failure in spring setting engine	960	1000	800	237,920	239,720
	Failure in cabin heater	30	50	12,5	7435	7498
	Failure in SF6 indicator	60	250	25	14,870	15,145
380 kV switchyard current transformer		480	1000	400	118,960	120,360
380 kV switchyard voltage transformer		480	1000	400	118,960	120,360
Main power transformer						
	Failure in air-oil heat serpentines	240	1000	200	59,480	60,680
	Cooling fan failure	120	500	50	29,740	30,290
	Pump failure	240	2000	200	59,480	61,680
	Expansion tank failure	240	3000	100	59,480	62,580
	High voltage bushing failure	120	7000	400	44,610	52,010
	Buccholz relay fault	120	7000	400	44,610	52,010
	Failure in fire fighting system of main power transformer	30	250	12.5	7435	7698
Generator rotor		960		800	237,920	238,720
Generator stator		960		800	237,920	238,720
Slipring and carbon brushes		60	300	25	14,870	15,195
Excitation transformer		480	2000	400	118,960	121,360

Table 11
Cost and duration data for predictive maintenance strategy.

Equipment title	Predictive maintenance strategy				
	Duration (Minute)	Material cost (₺)	Man work cost (₺)	Generation loss cost (₺)	Total cost (₺)
380 kV switchyard bus bar disconnector	60	50	25	44,610	44,685
380 kV switchyard circuit breaker	120	120	100	44,610	44,810
380 kV switchyard current transformer		0			
380 kV switchyard voltage transformer		0			
Main power transformer	240	50	150	66,915	67,115
Generator rotor	240	0	200	59,480	59,680
Generator stator	240	0	200	59,480	59,680
Slipring and carbon brushes	30	0	13	7435	7448
Excitation transformer	120	0	100	29,740	29,840

Table 12
Cost and duration data for revision maintenance strategy.

Equipment title	Revision maintenance strategy				
	Duration (Minute)	Material cost (₺)	Man work cost (₺)	Generation loss cost (₺)	Total cost (₺)
380 kV switchyard bus bar disconnector	480	2000	300	118,960	121,260
380 kV switchyard circuit breaker	480	500	400	118,960	119,860
380 kV switchyard current transformer	120	200	50	29,740	29,990
380 kV switchyard voltage transformer	120	200	50	29,740	29,990
Main power transformer	2400	1200	4000	594,800	600,000
Generator rotor	1440	500	1800	356,880	359,180
Generator stator	1440	500	1800	356,880	359,180
Slipring and carbon brushes	480	150	300	118,960	119,410
Excitation transformer	480	150	300	118,960	119,410

Table 13
Selected maintenance strategies for each equipment.

Equipment title	Maintenance strategies			
	Preventive	Corrective	Predictive	Revision
380 kV switchyard bus bar disconnector	✓	✓	✓	✓
380 kV switchyard circuit breaker	✓	✓	✓	✓
380 kV switchyard current transformer	✓		✓	✓
380 kV switchyard voltage transformer	✓		✓	✓
Main power transformer	✓	✓	✓	✓
Generator rotor	✓		✓	✓
Generator stator	✓		✓	✓
Slipring and carbon brushes	✓			✓
Excitation transformer	✓		✓	✓

Eq. (16) effects all the other constraints. Because, any failure must occur to assign the corrective maintenance to the relevant equipment.

In this model, global ($SCORE_{AHP,i}$) and local scores ($SCORE_{k,l}$) of alternative strategies are considered to assign the maintenance strategies to each equipment. Therefore, Eq. (17) (3rd goal constraint) and Eqs. (18)–(20) (4th goal constraints) have been added to the model.

Considering the hydroelectric power plant operational rules in terms of maintenance is the key feature which differentiates the model from referenced two models and Eq. (21) specifies these realities. Some maintenance strategies must be carry out in equipment (e.g. revision maintenance for generator rotor, predictive maintenance for main power transformer or preventive maintenance for 380 kV switchyard current breaker) in hydroelectric power plant because of the operational rules.

The proposed GP-AHP model is solved by Hyper Lindo 6.01 and results are shown in Table 13.

The obtained results given in Table 13 is consistent with the power plant operational realities. Corrective maintenance strategy is assigned to only 380 kV switchyard bus bar disconnector, 380 kV switchyard circuit breaker and main power transformer. No matter how carrying out the maintenance for these equipment, failures occur as a result of the effects of especially high pressure, temperature, voltage and current in real-life power plant operation. Furthermore, assigned failures for each equipment is consistent with reality too. These matches are given below.

- Assigned failures to 380 kV switchyard bus bar disconnector
  1. Melting the disconnector contacts based on overcurrent
  2. Position switch failure
- Assigned failures to 380 kV switchyard circuit breaker
  1. Position switch failure
  2. Failure in SF6 indicator
- Assigned failures to main power transformer
  1. Expansion tank failure
  2. Buccholz relay fault

The rest of strategies has been assigned to all equipment (except for slipring and carbon brushes – preventive maintenance) in the consequence of solution of the model. Slipring and carbon brushes are the part of generator and preventive maintenance cannot be carried out technically. This result is also consistent with real-life applications. In other words, all maintenance strategies must be carried out for these equipment for preventing the equipment and unit shutdowns.

6. Conclusion

Uninterrupted, efficient, reliable, economic and environmentally friendly electricity generation are the most important 5 components of the main goal of power plants. Efficient management of the maintenance process by considering the necessities about power plant operation as well as all relevant parameters such as limited budget and time capacity is the main topic for reaching this goal. Therefore in this study, maintenance management in hydroelectric power plants has been handled by regarding the importance of these plants in Turkey's energy mix with the rate of 24,84% generation performance and it has been focused to the most appropriate maintenance strategy selection which is the first stage of this crucial process.

In this context within the scope of the study, a combined AHP-GP model is proposed to determine the most appropriate maintenance strategy combinations for the most critical electrical equipment in a big scale hydroelectric power plant in Turkey by considering the operational rules of this plant besides the maintenance strategies priorities as globally and locally, costs and durations. A combined AHP-TOPSIS methodology has been used for the selection of the most critical equipment and thus the proposed model is supported with this verified powerful analysis.

According to the long-term operational data of hydroelectric power plant where the application implemented, it is determined that the maximum power generation took place in August of each year. This means that power plant works more in these month and hence, it may be lead to the frequency of failures increase. Only corrective and revision maintenance strategies are adopted in this power plant in the past years and each power plant unit has been disabled for an average of 23.6 h in August of each year due to the malfunctions in the selected equipment. As a result of applying the proposed model, this duration per unit has been decreased to 5.4 h and this corresponds to a significant improvement of 77.1%.

Ding and Kamaruddin [6] have stated that there is still a big gap occurs between academic and industrial applications; it is very difficult for industrial companies to adapt maintenance policy optimization models to their specific business context. Utne [89] has also specified that maintenance strategy selection models are limited to very specific problems, and few are applied to solve real-life problems. Therefore, developing/proposing the applied based models is very important when considering the criticality of this problem for manufacturing industry. In this context, it can be said that the proposed model is applicable and contributes the necessity stated in previous sentence, when the application results and above-mentioned improvement are based.

Although, the proposed AHP-GP model shows similarity to the models proposed by Bertolini and Bevilacqua [63] and Badri [88], this model consists of the hydroelectric power plant operational rules in terms of maintenance activities as a main distinctness. Furthermore, proposed model is supported with TOPSIS to select the important equipment properly and this selection procedure is designed according to not only electrical equipment but also mechanical and I & C ones. Moreover, all types of power plants consist of the electrical equipment such as selected ones in the scope of this study. At the same time, Ding and Kamaruddin [6] have stated that most of the maintenance policy optimization models focused on a sole system or a single sub-system. When these three sentences are handled together, this model can also be used for determining the maintenance strategy combination for all equipment types in any power plant, provided that adding the required specific constraints to the model.

Finally, the maintenance strategy selection problem has never been handled for hydroelectric power plants in the literature. Most of the researches except for some studies performed by Özcan and Eren [1], Carazsa and Souza [33], Bevilacqua and Braglia [38], Dong et al. [42] and Utne [89] have not already applied in electricity generation sector. In this context, with application field selection as well as the other additive effects, it is thought that this study can shed light on future researches.

References

[1] Özcan EC, Eren T. Application of TOPSIS method for maintenance planning: natural gas combined cycle power plant case study. Int J Eng Res Dev 2014;6(2):1–13, [Turkish].

[2] Özcan EC. Multiobjective optimization approach for electricity generation planning: case of Turkey [doctoral dissertation]. Ankara: Gazi University; 2013, [Turkish].
[3] Özcan EC. Maintenance management system: fundamentals of installation and operation. Ankara: Electricity Generation Co; 2016, [Turkish].
[4] Madu CN. Competing through maintenance strategies. Int J Qual Reliab 2000;17(9):937–48.
[5] Mobley RK. An introduction to predictive maintenance. Woburn: Buttherworth-Heinemann; 2002.
[6] Ding SH, Kamaruddin S. Maintenance policy optimization—literature review and directions. Int J Adv Manuf Technol 2015;76:1263–83.
[7] Tan MT, Raghavan N. Root cause analysis based maintenance policy. Int J Qual Reliab Manag 2007;24(2):203–28.
[8] Lu KY, Sy CC. A real-time decision-making of maintenance using fuzzy agent. Expert Syst Appl 2009;36(2):2691–8.
[9] Gupta S, Maiti J, Kumar R, Kumar U. A control chart guided maintenance policy selection. Int J Min Reclam Environ 2009;23(3):216–26.
[10] Xia T, Xi L, Lee J, Zhou X. Optimal CBPM policy considering maintenance effects and environmental condition. Int J Adv Manuf Technol 2011;56:1181–93.
[11] Albayrak B Budget presentation for 2017. Republic of Turkey Minister of Energy and Natural Resources; 2017. [In Turkish].
[12] Medium-term renewable energy market report 2015, market analysis and forecasts to 2020. International Energy Agency (IEA); 2016. ISSN: 2307-0293ISBN: 978-92-64-24367-5.
[13] Renewables 2015 global status report. Renewable Energy Policy Network for the 21st Century (REN 21); 2016. ISBN: 978-3-9815934-6-4.
[14] The 2012 technology roadmap for hydropower. International Energy Agency (IEA); 2012.
[15] Başeşme H. Hydroelectric power plants and facilities. Ankara: Electricity Generation Co; 2003, [Turkish].
[16] United States Geological Surveys [Internet]. Wisconsin [cited May 11 2016]. Hydroelectric power: How it works. Available from: ⟨https://water.usgs.gov/edu/hyhowworks.html⟩.
[17] Labib AW. World-class maintenance using a computerized maintenance management system. J Qual Maint Eng 1998;4(1):66–75.
[18] Khalil J, Saad SM, Gindy N, MacKechnie K. A maintenance policy selection tool for industrial machine parts. Int Fed Inf Process Emerg Sol Future Manuf 2005;159:431–40.
[19] Burhanuddin MA, Ahmad AR, Desa MI. An application of decision making grid to improve maintenance strategies in small and medium industries. In: Proceedings of the IEEE international industrial electronics and application conference. Harbin; 2007. p. 455–60.
[20] Tahir Z, Burhanuddin MA, Ahmad AR, Halawani SM, Arif F. Improvement of decision making grid model for maintenance management in small and medium industries. In: Proceedings of the industrial and information systems international conference. Sri Lanka; 2009. p. 598–603.
[21] Gupta S, Maiti J, Kumar R, Kumar U. A control chart guided maintenance policy selection. Int J Min Reclam Environ 2009;23(3):216–26.
[22] Martorell S, Sanchez A, Serradell V. Age-dependent reliability model considering effects of maintenance and working conditions. Reliab Eng Syst Safe 1999;64(1):19–31.
[23] Nourelfath M, Ait-Kadi D. Optimization of series–parallel multi-state systems under maintenance policies. Reliab Eng Syst Safe 2007;92(12):1620–6.
[24] Lofsten H. Management of industrial maintenance-economic evaluation of maintenance policies. Int J Opera Prod Manag 1999;19(7):716–37.
[25] Goel HD, Grievink J, Weijnen MPC. Integrated optimal reliable design, production and maintenance planning for multipurpose process plants. Comput Chem Eng 2003;27(11):1543–55.
[26] Hilber P, Miranda V, Matos MA, Bertling L. Multiobjective optimization applied to maintenance policy for electrical networks. IEEE Trans Pow Syst 2007;22(4):1675–82.
[27] Lu KY, Sy CC. A real-time decision-making of maintenance using fuzzy agent. Expert Syst Appl 2009;36(2):2691–8.
[28] Heo JH, Park GP, Yoon YT, Park JK, Lee SS. Optimal maintenance strategies for transmission systems using the genetic algorithm. In: Proceedings of the transmission and distribution conference. New Orleans; 2010. p. 1–6.
[29] Azadeh A, Sheikhalishahi M, Firoozi M, Khalili SM. An integrated multi-criteria Taguchi computer simulation-DEA approach for optimum maintenance policy and planning by incorporating learning effects. Int J Prod Res 2013;51(18):5374–85.
[30] Waeyenbergh G, Pintelon L. A framework for maintenance concept development. Int J Prod Econ 2002;77(3):299–313.
[31] Waeyenbergh G, Pintelon L. Maintenance concept development: a case study. Int J Prod Econ 2004;89(3):398–405.
[32] Waeyenbergh G, Pintelon L. CIBOCOF: a framework for industrial maintenance concept development. Int J Prod Econ 2009;121(2):633–40.
[33] Carazsa FG, Souza GFM. Risk-based decision making method for maintenance policy selection of thermal power plant equipment. Energy 2000;35:964–75.
[34] Ding SH, Goh TT, Tan PS, Wee SC, Kamaruddin S. Implementation of decision tree for maintenance policy decision making—a case study in semiconductor industry. Adv Mater Res 2012;591–593:704–7.
[35] Qingfeng W, Wenbin L, Xin Z, Jianfeng Y, Qingbin Y. Development and application of equipment maintenance and safety integrity management system. J Loss Prev Process Ind 2011;24(4):321–32.
[36] Rosqvist T, Laakso K, Reunnanen M. Value-driven maintenance planning for a production plant. Reliab Eng Syst Saf 2009;94(1):97–110.
[37] Leon Hijes FCG, Cartagena JJR. Maintenance strategy based on a multicriterion classification of equipments. Reliab Eng Syst Saf 2006;91(4):444–51.
[38] Bevilacqua M, Braglia M, Gabbrielli R. Monte Carlo simulation approach for a modified FMECA in a power plant. Qual Reliab Eng Int 2000;16:313–24.
[39] Braglia M, Frosolini M, Montanari R. Fuzzy criticality assessment model for failure modes and effects analysis. Int J Qual Reliab Manag 2003;20(4):503–24.
[40] Sharma RK, Sharma P. System failure behavior and maintenance decision making using RCA, FMEA and FM. J Qual Maint Eng 2010;16(1):64–88.
[41] Braglia M, Frosolini M, Montanari R. Fuzzy criticality assessment model for failure modes and effects analysis. Int J Qual Reliab Manag 2003;20(4):503–24.
[42] Dong YL, Gu YJ, Dong XF. Selection of optimum maintenance strategy for power plant equipment based on evidential reasoning and FMEA. In: Proceedings of the IEEE international industrial engineering and engineering management conference. Singapore; 2008. p. 862–6.
[43] Vinodh S, Varadharajan AR. Application of fuzzy VIKOR for concept selection in agile environment. Int J Adv Manuf Technol 2012;42:1025–33.
[44] Bevilacqua B, Braglia M. The analytic process applied to maintenance strategy selection. Reliab Eng Syst Safe 2000;70(1):71–83.
[45] Dey PK. Decision support system for inspection and maintenance: a case study of oil pipelines. IEEE Trans Eng Manag 2004;51(1):47–56.
[46] Ratnayake RMC, Markeset T. Technical integrity management: measuring HSE awareness using AHP in selecting a maintenance strategy. J Qual Maint Eng 2010;16(1):44–63.
[47] Tan Z, Li J, Wu Z, Zheng J, He W. An evaluation of maintenance strategy using risk based inspection. Saf Sci 2011;49(6):852–60.
[48] Shyjith K, Ilangkumaran M, Kumanan S. Multi-criteria decision-making approach to evaluate optimum maintenance strategy in textile industry. J Qual Maint Eng 2008;14(4):375–86.
[49] Ding SH, Kamaruddin S, Azid IA. Development of a model for optimal maintenance policy selection. Eur J Indust Eng 2014;8(1):50–68.
[50] Ding SH, Kamaruddin S, Azid IA. Maintenance policy selection model—a case study in the palm oil industry. J Manuf Technol Manag 2014;25(3):415–35.
[51] Momeni M, Fathi MR, Zarchi MK, Azizollahi S. A fuzzy TOPSIS-based approach to maintenance strategy selection: a case study. Middle East J Sci Res 2011;8(3):699–706.
[52] Cheng YH, Tsao HL. Rolling stock maintenance strategy selection, spares parts' estimation and replacement interval calculation. Int J Prod Econ 2010;128(1):404–12.
[53] Aghaie M, Fazli S. An improved MCDM method for maintenance approach selection: a case study of auto industry. Manag Sci Lett 2012;2(1):137–46.
[54] Zaim S, Türkyılmaz A, Acar MF, Al-Turki U, Demirel OF. Maintenance strategy selection using AHP and ANP algorithms: a case study. J Qual Maint Eng 2012;18(1):16–29.
[55] Gonçalves CDF, Dias JAM, Machado VAC. Multi-criteria decision methodology for selecting maintenance key performance indicators. Int J Manag Sci Eng Manag 2015;10(3):215–23.
[56] Ahmadi A, Gupta S, Karim R, Kumar U. Selection of maintenance strategy for aircraft systems using multi-criteria decision making methodologies. Int J Reliab Qual Saf Eng 2010;17(3):223–43.
[57] Zeng W, Jiang F, Zeng QS, Ye Y, Fan R. Decision-making method for electrical equipment condition-based maintenance. Int J Emerg Electr Power Syst 2015;16(4):349–55.
[58] Labib AW. A decision analysis model for maintenance policy selection using a CMMS. J Qual Maint Eng 2004;10(3):191–202.
[59] Wang L, Chu J, Wu J. Selection of optimum maintenance strategies based on a fuzzy analytical hierarchy process. Int J Prod Econ 2007;107(1):151–63.
[60] Nezami FG, Yıldırım MB. A sustainability approach for selecting maintenance strategy. Int J Sustain Eng 2013;6(4):332–43.
[61] Ilangkumaran M, Kumanan S. Selection of maintenance policy for textile industry using hybrid multi-criteria decision making approach. J Manuf Technol Manag 2009;20(7):1009–22.
[62] Kumar G, Maiti J. Modeling risk based maintenance using fuzzy analytic network process. Expert Syst Appl 2012;39(11):9946–54.
[63] Bertolini M, Bevilacqua M. A combined goal programming-AHP approach to maintenance selection problem. Reliab Eng Syst Saf 2006;91(7):839–48.
[64] Arunraj NS, Maiti J. Risk-based maintenance policy selection using AHP and goal programming. Saf Sci 2010;48(2):238–47.
[65] Ghosh D, Roy S. A decision-making framework for process plant maintenance. Eur J Ind Eng 2010;4(1):78–98.
[66] Özcan EC, Küçükyarar U. Assessment of potential southern gas corridor projects with a combined methodology. In: Proceedings of the 23rd world energy congress. İstanbul; 2016. p. 105–21.
[67] Saaty T. The analytic hierarchy process: planning, priority setting, resource allocation. New York: McGraw-Hill; 1980.
[68] Saaty T. Rank from comparisons and from ratings in the analytic hierarchy/network processes. Eur J Opera Res 2006;168:557–70.
[69] Daengdej J, Lukose D, Murison R. Using statistical models and case-based reasoning in claims prediction: experience from a real-world problem. Knowl Based Syst 1999;12(5–6):239–45.
[70] Ignizio JP. Goal programming and extensions. Lexington: Lexington Books; 1976.
[71] Hwang CL, Yoon K. Multiple attribute decision making: methods and applications. New York: Springer-Verlag; 1981.
[72] Roy B. Classement et choix en présence de points de vue multiples (la méthode ELECTRE). La Revue d'Informatique et de Recherche Opérationelle (RIRO). 8; 1968. p. 57–75.
[73] Brans JP, Mareschal B, Vincke PH. PROMETHEE – a new family of outranking methods in multicriteria analysis. Opera Res 1984;84:477–90.
[74] Saaty T. Decision making with the analytic hierarchy process. Int J Serv Sci

2008;1(1):83–98.
[75] Velasquez M, Hester PT. An analysis of multi-criteria decision making methods. Int J Opera Res 2013;10(2):56–66.
[76] Qin X, Huang G, Chakma A, Nie X, Lin Q. A MCDM-based expert system for climate-change impact assessment and adaptation planning – a case study for the Georgia Basin, Canada. Expert Syst Appl 2008;34(3):2164–79.
[77] Ic Y. An experimental design approach using TOPSIS method for the selection of computer-integrated manufacturing technologies. Robot Comput Integr Manuf 2012;28(2):245–56.
[78] Chang CT. Multi-choice goal programming model for the optimal location of renewable energy facilities. Renew Sustain Energy Rev 2015;41:379–89.
[79] Özder E, Eren T. Supplier selection with MCDM and goal programming methods. Selçuk Univ J Eng Sci Technol 2016;4(3):196–207.
[80] Özcan EC, Varlı E, Eren T. Goal programming approach for shift scheduling problems in hydroelectric power plants. Int J Inf Technol 2017.
[81] Aalaei A, Davoudpou H. Revised multi-choice goal programming for incorporated dynamic virtual cellular manufacturing into supply chain management: a case study. Eng Appl Artif Intell 2016;47:3–15.
[82] Trivedi A, Singh A. A hybrid multi-objective decision model for emergency shelter location-relocation projects using fuzzy analytic hierarchy process and goal programming approach. Int J Proj Manag 2017;35(5):827–40.
[83] Özder E, Eren T, Çetin Özel S. Supplier selection with TOPSIS and goal programming methods: a case study. J Trends Dev Mach Assoc Technol 2015;19(1):109–12.
[84] Yılmaz B, Dağdeviren M. A combined approach for equipment selection: F-PROMETHEE method and zero–one goal programming. Expert Syst Appl 2011;38(9):11641–50.
[85] Gür Ş, Hamurcu M, Eren T. Using analytic network process and goal programming methods for project selection in the public institution. Les Cahiers du MECAS 2016;13:36–51.
[86] Ertuğrul I, Karakaşoğlu N. Performance evaluation of Turkish cement firms with fuzzy analytic hierarchy process and TOPSIS methods. Expert Syst Appl 2009;36(1):702–15.
[87] Charnes A, Coopper WW. Management models and industrial applications of linear programming. New York: Wiley; 1961.
[88] Badri MA. A combined AHP-GP model for quality control system. Int J Prod Econ 2001;72:27–40.
[89] Utne IB. Maintenance strategies for deep-sea offshore wind turbine. J Qual Maint Eng 2010;16(4):367–81.