A hybrid model to optimize the maintenance policies in the hydroelectric power plants

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Highlights

❖ *The obtained results are consistent with the real-life power plant operational rules.*

❖ *Proposed approach has been determined that there has been no malfunction caused by the main power transformer. This is a means of 100% improvement.*

❖ *Three methods in MCDM are combined for increasing the analyticalness level of evaluations.*

❖ *Proposed methodology is applicable for all equipment groups such as mechanical, electrical and instrumentation and control equipment in the power plants.*

Graphical Abstract

In this study, maintenance policy optimization in a hydroelectric power plant is discussed. In order to increase the analytical level of the evaluation, AHP, TOPSIS and PROMETHEE methods were used.
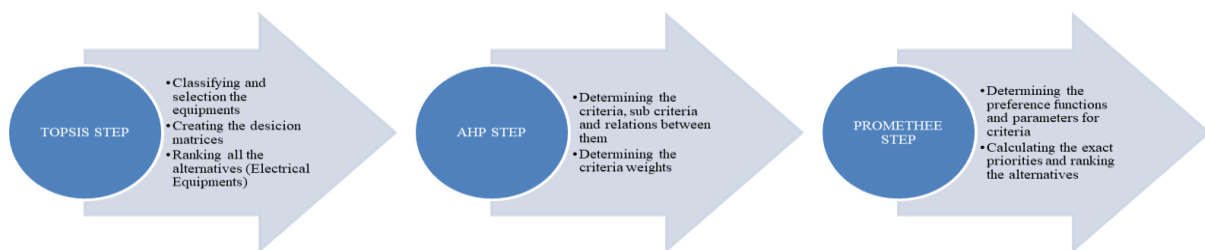

Figure. Application steps of study

Aim

The main goal of power plants is to generate the electricity in sustainability perspective consisting of the principles of environmental awareness, reliability, efficiency, economy and uninterruptedness. Complying with the operational directives and maintenance are twin pillars for achieving this comprehensive goal. Within this scope, this study handles the maintenance strategy selection problem which is the first step of the effective maintenance management for one of the most important equipment groups among thousands of equipment in one of the large-scale hydroelectric power plants which have great importance for Turkey energy mix with approximately a fifth share in the total generation.

Design & Methodology

Determining the most critical equipment group AHP-TOPSIS combination is used. For the selected equipment group, the most appropriate of all applicable 4 maintenance strategies are determined via PROMETHEE, which has been limited used for the maintenance strategy selection problem in the literature despite its advantages.

Originality

This study is the first in the literature with its method configuration and its application in hydroelectric power plants

Findings

As a result of this study, revision maintenance, predictive maintenance, preventive maintenance, corrective maintenance were found as the most appropriate maintenance policy for the hydroelectric power plant, respectively.

Conclusion

As a result of this study, a 1-year observation is conducted to confirm the proposed approach, and a 100% improvement is achieved in the unit shutdowns resulting from the selected equipment.

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Araştırma Makalesi / Research Article

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ABSTRACT

The main goal of power plants is to generate the electricity in sustainability perspective consisting of the principles of environmental awareness, reliability, efficiency, economy and uninterruptedness. Complying with the operational directives and maintenance are twin pillars for achieving this comprehensive goal. Within this scope, this study handles the maintenance strategy selection problem which is the first step of the effective maintenance management for one of the most important equipment groups among thousands of equipment in one of the large-scale hydroelectric power plants which have great importance for Turkey energy mix with approximately a fifth share in the total generation. So as to determine the most critical equipment group AHP-TOPSIS combination is used. For the selected equipment group, the most appropriate of all applicable 4 maintenance strategies are determined via PROMETHEE, which has been limited used for the maintenance strategy selection problem in the literature despite its advantages. As a result of this study which is the first in the literature with its method configuration and its application in hydroelectric power plants, a 1-year observation is conducted to confirm the proposed approach, and a 100% improvement is achieved in the unit shutdowns resulting from the selected equipment.

Keywords: Maintenance strategy selection, hydroelectric power plant, AHP, TOPSIS, PROMETHEE.

1. INTRODUCTION

As a result of economic developments and increasing levels of prosperity, there is a rapid increase in demand in every aspect of the energy sector in Turkey as in all the world [1]. In this context, Turkey has started to give more importance to local and renewable energy resources to meet this ever-increasing demand and to increase the competitive power in the world for the last years. Because, Turkey is a rich country especially in terms of renewable resources and her annual economic total renewable energy resource potential is reached to 770 billion kWh [2].

In addition to these, hydroelectric power is the most important renewable energy resource for Turkey. Turkey is ranked 5th in the world in hydroelectric power energy with the potential of 140 billion kWh annual for 2017 [3]. Turkey's installed capacity is 87,138.7 MW as of the end of June 2018 and hydroelectric power plants are at the top with rate of 32%. Furthermore, 21.05% of the energy generated during the period January 2017 to August 2018 is met from these plants in Turkey [4]. All of these data and explanations show clearly the importance of hydroelectric power plants for Turkey, and hence these big-scale generation facilities are selected as application area in this study.

The main purpose of hydroelectric power plants is to generate electricity in a continuous, high quality, reliable, efficient and environmentally sensitive manner (called as sustainable energy generation) as in all other power plants. The power plants are operated under extreme conditions such as high pressure, high temperature, metal fatigue, failure to comply with the operational and maintenance directives and operator errors during years. Therefore, the maintenance necessity of especially the main systems and equipment emerges at this point. In this context, for achieving the sustainable energy generation goal in hydroelectric power plants is complying with the maintenance schedules producing from the equipment characteristics and criticality levels for the power plant. Thus, equipment-based maintenance strategy optimization in hydroelectric power plants which is the first step of the maintenance planning has great importance. Moreover, maintenance costs can reach to 70% of the different manufacturing costs depending on the types of products and sectors [5-8]. In this direction, it would not be wrong to say that systematic planning of maintenance processes and carrying out the maintenance applications according to these planning outputs are even more important for complex, critical and continuous production facilities such as hydroelectric power plants.

Ding and Kamaruddin [7] have stated that the implementation of corrective maintenance is insufficient without considering the requirements in the system and the special conditions in their study which is the most comprehensive review for maintenance policy optimization/strategy selection in the literature. They have also pointed out that sustainability in production can be ensured through effective maintenance planning starts with the maintenance policy optimization. Corrective (repairs/restores the system back when failure occurs), preventive (performing fixed periods maintenance activities for reducing the failure frequency of the system or preventing it from the possible failures), predictive (carried out according to the actual condition of the system by utilizing the advanced technologies),

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autonomous (new maintenance concept where maintenance and production departments corporate to accomplish the maintenance activities) and design out (improves the system design to make the maintenance easier) maintenance are defined as maintenance policies (Fig.1) by them into three categories. With the addition of integrated maintenance to these five known maintenance policies, Hajej et al. [9] and Guiras et al. [10] have talked about the contribution of different systems in enterprises to maintenance processes and their contribution to profit margins. In these studies, maintenance concept in maintenance management is taken into consideration by integrating with different systems. Bouslikhane et al. [11] and Hafidi et al. [12] have aimed at increasing the level of service and reducing the costs in their studies related with integrated maintenance management.
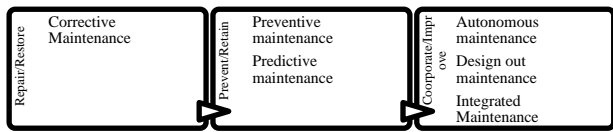

Figure 1. Maintenance policies [7, 9-12]

In this context, one of the first and most critical stages of maintenance planning is to determine the appropriate maintenance strategy for each equipment. Thus, only necessary and adequate maintenance activities can be performed, and the number and duration of possible stoppages which occurs as a result of breakdowns and/or necessity for some maintenance applications may be reduced with the planning studies to be carried out accordingly in the hydroelectric power plants that adopts the sustainable generation as its most important goal.

Selection of the appropriate maintenance strategy for each system or equipment is a very complex problem in the hydroelectric power plants for some reasons such as differences in the numbers and functions of system components, many qualitative and quantitative criteria that need to be considered and difficulty in obtaining data. For this reason, it is necessary to decide on appropriate maintenance strategies for equipment from possible options such as corrective, preventive, predictive and revision (comprehensive and long-term periodical/preventive maintenance) maintenance, which are the applied strategies in the hydroelectric power plants, in planning stage [13]. System or equipment-based maintenance strategy optimization is of extra importance, especially since unnecessary or inadequate maintenance practices are likely to cost approximately one-third of the entire maintenance budget [6].

When considering the above-mentioned multi-objective and multi-criteria structure of the maintenance policy optimization problem in the hydroelectric power plants, it can be said that multi-criteria decision-making (MCDM) methods are useful for solution of the problem. Because, MCDM algorithms consider the conflicting/related parameters, criteria and/or objectives in their solution processes and structure of the problem

coincides with the MCDM philosophy. Furthermore, while the solution stages of these approaches are easier than the other methods such as mathematical based, heuristically based or simulation-based models, they produce results consistent with real life. [7]. Therefore, in this study one of the MCDM approaches, Analytical Hierarchy Process (AHP), Technique for Order-Preference by Similarity to Ideal Solution (TOPSIS) and Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) are selected for solving the problem. In MCDM methods, the objectives should be clearly defined as the first step. Then, the stage of creating the criteria affecting the purpose is passed. After the creation of these criteria, which are inclusive and measurable, the alternatives to be decided are determined and evaluated according to the criteria. Thus, the alternative priority sequence is obtained [14].

As mentioned above, in this study, maintenance policy optimization problem in power plants is discussed in order to implement sustainable energy policies. Maintenance strategy is selected for the main power transformers of great importance among all electrical equipment in one of the hydroelectric power plants. As a result of extensive investigation in literature, despite its advantages, very few scientific studies about maintenance strategy selection or maintenance policy optimization problem that use the PROMETHEE have been found in the literature. However, the maintenance strategy selection problem has never been solved for energy generation facilities by using these combined MCDM approach (AHP-TOPSIS-PROMETHEE) in the literature. Other prominent features of the study include the managerial contributions that it provides, a methodology that can be applied to all types of power plants, and the consistent results produced by this methodology.

Literature review given in the second section. Then, MCDM methods are given in third sections. Within the scope of case study given in the fourth section, based on the multi-criteria structure of maintenance strategy selection and the risks of equipment in the power plant in terms of operation of the power plants in maximum efficiency, importance level of equipment groups are determined by using TOPSIS methodology among MCDM methods based on 9 criteria weighted by AHP, and main power transformers are selected as the equipment group which is the top priority. Following this stage, the most appropriate policy among corrective, preventive, predictive and revision maintenance strategies has been determined via PROMETHE method, which has been used as limited for the maintenance strategy selection problem in the literature despite its advantages, using the same criteria weights. And finally, the specific findings of this research and recommendations are emphasized in the fifth section.

2. LITERATURE FRAMEWORK

While many studies have been carried out for the selection of maintenance strategies in the literature, the most comprehensive of them have been done by Shafiee [13], Wang [15], Garg and Deshmukh [16], Ding and Kamaruddin [7], and Velmurugan and Dhingra [17], Rocha and Rodrigues [18]. Ding and Kamaruddin [7], presented the differences of the studies in the literature according to the used methods by classifying the maintenance strategy optimization papers into three groups (certainty category contains graphical based models, risk category contains mathematical based models, simulation-based models and artificial intelligence-based models, and uncertainty category contains heuristically based models, hazard-based models and multi-criteria-based models). Although the specific fields or sectors they address in their literature review are different, a conceptual framework based primarily on maintenance theory is desired to be developed.

As a system, maintenance plays an important role in reducing costs and minimizing equipment downtime. At the same time, it has great importance to increase productivity and reliability. These studies, which emphasize the importance of the maintenance concept, differ in many areas and solution methodologies used. In terms of energy sector, Andrawus et al. [19], Nilsson and Bertling [20], Wang et al. [21], Srivastava et al. [22], Shayesteh et al. [23] aims to reduce maintenance costs and to prevent failures in the units. The solution methodologies have differed when performing these basic objectives. Andrawus et al. [19], Nilsson and Bertling [20] have studied on wind turbines. The researchers focused on five types of maintenance policy. Maintenance activities vary according to the changing area or equipment. As the size and complexity of the enterprises increase in the studies having different fields of application, the errors experienced in a small system can affect the whole system suddenly. It is noted that this may sometimes lead to the closure of the entire system and a large loss of money.

Sharma et al. [24], Braglia et al. [25], Muinde [26] studied on industrial equipment, Saassouh et al. [27], Sadeghi et al. [28] focused on the selection of maintenance policy on technical equipment in different sectors. It is seen as a difficult decision to select the maintenance policy, which is known as the principle that determines which parameters require maintenance action. For this selection problem, Sharma et al. [24] used the fuzzy language models, Braglia et al. [25] used integer linear programming and Muinde [26] used AHP method.

Ilangkumaran and Kumanan [29], Siew-Hong and Kamaruddin [30], Odeyale et al. [31], Goossens and Basten [32], Mollaverdi and Abdollahi [33], Baidya et al. [34], Borjalilu and Ghambari [35] used MCDM methods for the selection of maintenance policy in the manufacturing industry. In the manufacturing industries,

it is important to reduce the costs and to have a higher productivity production line as they face more competitiveness among each other. Therefore, in order to prevent both the production line and effective maintenance, the most appropriate maintenance policy should be determined.

The purpose of maintenance policies is to provide the operation of the equipment, to detect faults and to prevent functional failures. Applications in the foundry industry and ship industry, Joshua et al. [36], Zhao and Yang [37], Emovon et al. [38] used MCDM methods and genetic algorithm method. It is a complex process since determining the maintenance tasks, evaluating alternative maintenance strategies and taking into consideration the various criteria and sub-criteria such as cost, security, strategy and time requirements in the decision-making process. At the same time, the level of uncertainty in these decision-making processes is critical for decision makers. Mechefske and Wang [39], Jafari et al. [40], Bashiri et al. [41], Seitia et al. [42], Nguyen and Chou [43] used fuzzy expressions for these uncertainty levels. In this way, decision makers can comment on the importance of the criteria that affect the process and the evaluation of alternatives. Studies show that maintenance activities are no longer regarded as an undesirable situation for enterprises but rather as a long-term profit provider when evaluated effectively. The system of designing maintenance policies in enterprises is carried out for the purpose of improvement. As mentioned, each enterprise has its own structure and maintenance policies are shaped according to this structure. The determination of the best care policy is also stated as an important process in enterprises consisting of more than one system. Factors that are effective in determining these policies should also be considered. Researchers use MCDM methods in order to evaluate the factors affecting the process while determining appropriate maintenance policies for system components in their application areas.

Tu et al. [44] studied on the special equipment of a system, Ibraheem and Atia [45] focused on the transport industry, Azadeh et al. [46] worked in a system, Carnero and Gomez [47] studied health centers power distribution systems, Pun et al. [48] focused on selecting the most appropriate maintenance strategy in building facilities. Selecting of the maintenance strategy for equipment is a critical decision process for businesses. For this reason, an adequate maintenance program is required for the reliability of the system. At the same time, in addition to the effective role of care in increasing the efficiency of the system, the evaluation of different risk factors and the reduction of these risks have come to the forefront. This has led to an increase in the interest of the researchers on the care strategy selection problem and the popularization of this problem type in the literature.

As can be seen in above-mentioned studies, limited study about maintenance strategy selection or maintenance policy optimization problem that uses the PROMETHEE method has been referred. However, PROMETHEE is one of the efficient and practical outranking algorithms

among MCDM methods such as TOPSIS, Elemination and Choice Translating Reality English (ELECTRE), Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) etc. Based on this remarkable situation, a comprehensive research has been carried out on academic databases such as Ebsco Academic Search Complete, Emerald Insight, IEEE Xplore, Science Direct, Springerlink Journals, and Taylor and Francis. As a result of this extensive investigation, very few studies cover the most suitable strategy selection among some alternative maintenance strategies such as corrective, preventive or predictive, similar to the above-mentioned studies in the literature. Among the studies regarding the maintenance problems in which the PROMETHEE method is used, the following may be cited: Faghihinia and Mollaverdi [49] used the PROMETHEE method with Bayesian approach for preventive maintenance planning which determines the best compromise time for replacement of a certain item based on reliability, maintenance cost, and maintenance downtime. Cavalcante et al. [50] have also dealt with the problem of replacement in service production systems, and they have integrated PROMETHEE and Bayesian approach by considering two criteria. Besides these studies, Almeida-Filho et al. [51] constructed a decision support system to support the maintenance planning activities in an electrical power distribution company. They aimed to determine the order of priority in which potential failure repair orders should be conducted by using PROMETHEE. Chareonsuk et al. [52] have discussed the problem of determining optimal preventive maintenance intervals for components in a paper production system and PROMETHEE is used to solve the problem.

Cavalcante et al. [50], aimed to evaluate the contradictions between effective criteria on preventive maintenance system. Considering this contradiction, they examined how the decision-makers influence their preferences on the problem. In this study, unlike Cavalcante et al. [50], the most suitable one among 4 different maintenance strategies is chosen. In addition, with the case study in hydroelectric power plants, renewable energy resources are stripped from the studies with optimization of maintenance strategy.

In the literature, researchers focused on the selection of investment projects on renewable energy sources among following studies: Lin et al. [53], Maghsoodi et al. [54], Karunathilake et al. [55] evaluated the renewable energy alternatives. In these studies which emphasize the importance of renewable energy sources, alternatives are evaluated. In this study, the importance of this energy source on hydroelectric energy which is among the renewable energy sources is mentioned. In this power plant, the importance of maintenance management in order to ensure uninterrupted production is mentioned. The most important equipment is determined, and the most appropriate maintenance strategy optimization has been realized.

Another important issue that attracts attention in the literature review carried out in the scope of this study, is the fact that hydroelectric power plants are not chosen as implementation area for maintenance strategy selection problem. But, hydroelectric energy has the potential to meet daily electricity needs. At the same time, it plays an important role today due to its flexibility in meeting the intense and unexpected power demand [3]. In addition to this, the lack of the studies about maintenance strategy selection or maintenance policy optimization problem that uses the PROMETHEE method, are the main purposes of selection of method and implementation area for maintenance strategy selection which is a crucial optimization problem for a power plant within the scope of this study [56-57]. Özcan et al. [57] used the goal programming and solved this problem for the first time in the literature for hydroelectric power plants. For the first time in the literature they have closed the gap rising from the lack of application results in the literature by giving the performance of the proposed approach from determined parameters.

In the light of all these explanations above, the contributions of our study to the literature are listed below:

- The obtained results are consistent with the real-life power plant operational rules.

- Proposed approach has been applied in selected hydroelectric power plant, and it has been determined that there has been no malfunction caused by the main power transformer. This is a means of 100% improvement. Thus, this study contributes to close the gap in the literature.

- Despite its advantages, very few scientific studies about maintenance strategy selection or maintenance policy optimization problem that use the PROMETHEE. However, the maintenance strategy selection problem has never been solved for energy generation facilities by using these combined MCDM approach (AHP-TOPSIS-PROMETHEE) in the literature. Furthermore, the maintenance strategy selection problem has only been handled for hydroelectric power plants in the literature by Özcan et al. despite the importance of these critical plants for world energy mix. In this context, with method and application field selection as well as the other additive effects, it is thought that this study can shed light on future researches.

- In maintenance strategy selection, maintenance management or maintenance planning literature, generally two MCDM methods are combined for evaluations. However, in this study, three methods are combined for increasing level of analyticity of the evaluations. Consistent results from equipment selection to ranking the alternative strategies verify this.

3. MULTI CRITERIA DECISION MAKING METHODS

There are many different applications in literature by using AHP-TOPSIS-PROMETHEE combination. This provides effective results in decision making processes. Some examples are given follows: Geyik et al. [58] and Alver et al. [59] (education), Taş et al. [60] and Hamurcu and Eren [61] (transportation), Gür and Eren [62], Asoğlu and Eren [63], Ayan et al. [64] and Taş et al. [65] (health), Özcan et al. [66] (energy), Geyik and Eren [67] (sports).

The main reason for the frequent use of these methods is that these methods have relative advantages. AHP is a method of measurement through mainly based on priorities obtained by pairwise comparisons and relies on the judgements of experts to derive priority scales. The method is easy to understand and implement, also it can help to improve decision-making process. It makes the decision-making process formal and systematic, and ensures that the right decisions are made. AHP has a structure that simplifies complex problems, and it is suitable for use in group decisions [68,69]. Hwang and Yoon propose that the ranking of alternatives will be based on the shortest distance from the positive ideal solution and the farthest from the negative ideal solution in TOPSIS algorithm. In other words, TOPSIS is based on the main principle of the proximity of decision points to the ideal solution. Ease of application, understandability, computational efficiency and the results it offers consistent with real life are the most

important advantages of TOPSIS [70]. PROMETHEE method was developed by Jean-Pierre Brans in 1982 and belongs to the category of outranking methods among MCDM approaches. It proceeds to a pairwise comparison of alternatives in each single criterion based on the partial binary relations. The main features of the PROMETHEE method are simplicity, clarity and stability. It is possible to make both partial (PROMETHEE I) and full ranking (PROMETHEE II) on a finite number of alternatives by PROMETHEE method [71].

The application steps of the used methods are presented in Figure 2 briefly. For detailed implementation steps of the methods, see also [69-71].

4. CASE STUDY

Energy demand in Turkey in recent years has increased by 5.6%. The reason for this is population growth, industrialization and constantly developing technology. At the same period, electricity consumption per capita has also increased from 2,052 kWh to 3,373 kWh with the rate of 64.4% in Turkey and hydroelectric power plants met about one quarter of this significant increased demand as of the end of 2018 [57]. Therefore, it is required to carry out the management of maintenance processes in these power plants within a well-designed system to perform uninterrupted, efficient and low-cost energy generation.

The most important stage in maintenance management is the selection of equipment-based maintenance strategy. This situation was taken into consideration in this study. in this study, the maintenance strategy selection is carried out for the most important electrical equipment in a large-scale hydroelectric power plant through the combined AHP-TOPSIS-PROMETHEE approach.

4.1. Equipment Selection

There are thousands of equipment in a hydroelectric power plant. Among these equipment, main titles of retention structure (dam, tunnel or open channel, regulator), intake structure, transmission line or penstocks, spiral casing, turbine, generator, transformers and switchyard equipment. This equipment can be handled under 3 main titles as electrical, mechanical and instrumentation and control (I&C). Each group of equipment is critical to power plants. But the main scope of this study is limited to electrical equipment as transmission of electricity energy is a problematic process in power plant [57].

Following the restriction of study's scope to electrical equipment, the stage is launched for determination of the criticality level of equipment for the power plant. At this stage which is performed according to TOPSIS methodology, evaluation criteria presented in Table 1 are identified at first. Evaluation criteria are determined considering all factors which effect the criticality level of each equipment for the power plant based on the ideas of power plant experts and they are determined so that all criteria will be related to each equipment group.
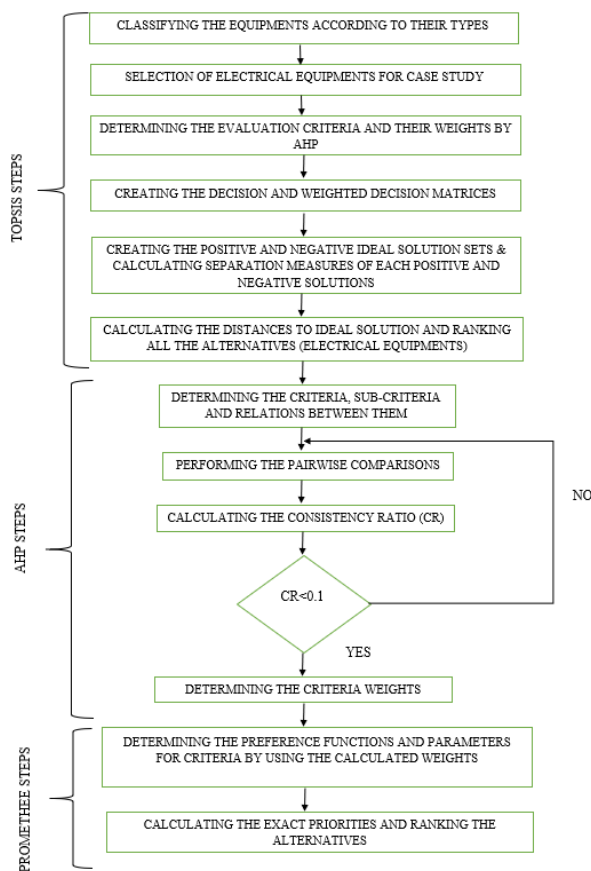

Figure 2. Application steps of study

Each equipment is assigned a linguistic value according to each criterion using the parameters defined under the criteria. In order to realize the hypothesis of "all indications being numerical" required for implementation of TOPSIS method, numerical equivalents of the parameters are created utilizing power plant specialists' ideas. When determining numerical equivalents of the parameters, a scale composed of integers between 0-10 is used and the highest score is assigned to the parameters which directly affect electricity generation in the power plant. Other parameter scores are determined considering both the highest scores given among all criteria and the scores given between each criterion. Upon the completion of this stage, initial

decision matrix is formed as the dimension of 1,404 x 9 as the power plant has 1,404 electrical equipment.

At the first stage, taking into consideration 9 criteria (determined by the power plant specialists who are industrial, mechanical, electrical and electronics engineers and they have minimum 15 years' experience), criteria weights are calculated by AHP in order to establish 1,404 electrical equipment priorities. CR of pairwise comparison matrix created among criteria is found as 0.051 and the weights of 9 criteria as a result of the calculations made on consistent matrix is given in Table 2.

Using criteria weights obtained with AHP and Eq. 4, weighted normalized decision matrix is created and ideal

Table 1. Evaluation criteria [57]

	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 hours	2
		Less than 2 hours	1
C8	Detectability of failure	Difficult	3
		Easy	1
C9	Additional work requirement	Required	5
		Not required	1

and negative ideal solution sets are determined using Eq. 5 and Eq. 6. Then, ideal and negative ideal separation measures are calculated for each equipment respectively with Eq. 7 and Eq. 8 and equipment priority scores (C*) defined as relative closeness of each equipment to ideal solution is calculated with Eq. 9.

4 types of maintenance strategy may be applied for main power transformer in the hydroelectric power plants. These are corrective maintenance strategy which involves repair in case of breakdown of equipment, predictive maintenance strategy which involves taking necessary measures as a result of tests and measurements

Table 2. Criteria weights [57]

	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

According to the equipment priority scores calculated via TOPSIS, the most critical electrical equipment for the power plant is determined as generator stator, generator rotor and main power transformer with 0,8370501 C* value. Main power transformer decreases the current by increasing generator output voltage that is 15,75 kV to 380 kV and thus minimizes transmission losses. Furthermore, breakdown frequency and the durations of the preventive and revision maintenance of this equipment are generally greater than the others. When considering the necessity of shutting down the power plant unit during maintenance and troubleshooting period, main power transformer downtime will further affect the sustainable power generation negatively in the power plant. In the light of these explanations, main power transformer is selected for the maintenance strategy selection problem. At the same time, these realities about power plant operations prove the correctness of the analysis for executing to determine the importance levels of equipment in power plant too.

4.2. Ranking Alternative Strategies for Selected Equipment

Evaluation criteria used to determine criticality levels of the equipment in the power plant which are stated in Table 1 are also used for the maintenance strategy selection for main power transformer considering the importance of maintenance for the power plant's uninterrupted generation.

performed on equipment before any breakdown occurs, preventive maintenance strategy carried out in a specific period for uninterrupted running of equipment and revision maintenance strategy realized in all important equipment as a result of long term shut down of the power plant unit at planned intervals. In this scope, the most appropriate maintenance strategy selection problem is presented hierarchically in Fig. 2.

In the first step, characteristics of evaluation criteria weighted by AHP are determined. Maintenance pre-conditions, possible consequences, additional work requirement, failure period and troubleshooting time criteria show parallelism. As can be seen in Table 1, the parameters should be at the minimum level as the parameters under these criteria include breakdown of the equipment or the unit or incomplete tasks. As the criteria of detectability of failure, warehouse backup, availability of measurement equipment and static, dynamic and electrical feature of the equipment include parameters for prevention of breakdown and these parameters are expected to be at the maximum level. Decision matrix created in this scope is given in Table 3. In the normalization phase of the decision matrix, vector normalization was used among the normalization methods.
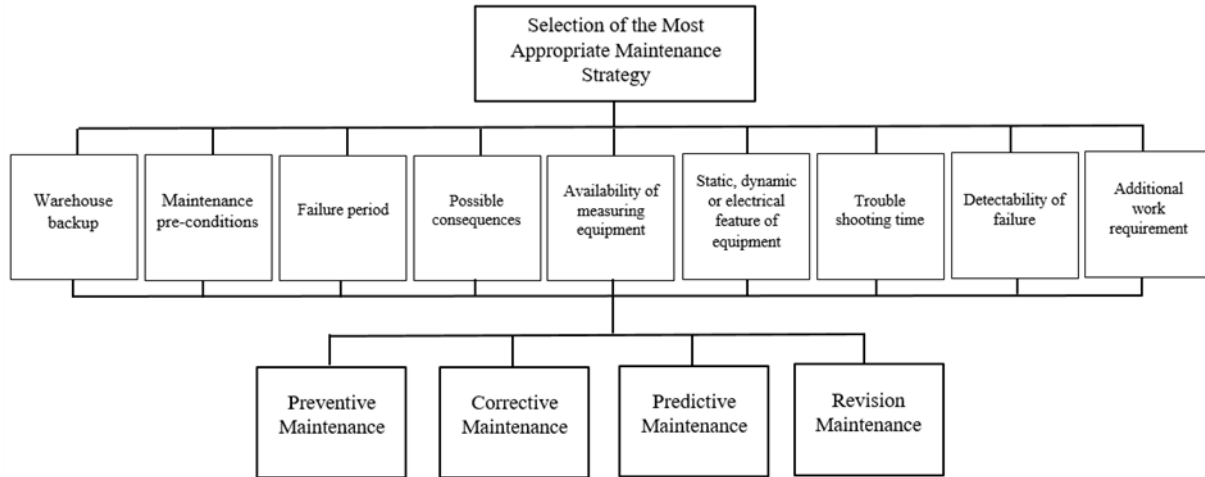
Figure 3. Hierarchical structure of the problem

Table 3. Decision matrix

		Decision Points			
		Alternative Maintenance Strategies			Weights
	CM	PreM	PM	RM	w_i
C1	1	3	2	5	0,05
C2	8	2	4	2	0,24
C3	8	3	6	4	0,07
C4	8	3	6	1	0,40
C5	1	3	1	2	0,06
C6	1	3	2	4	0,05
C7	9	3	5	3	0,03
C8	1	3	1	2	0,06
C9	1	3	1	2	0,03

(Evaluation Factors — leftmost vertical label)

Selection is performed considering the data's qualification when determining preference functions. In this scope, fifth type that is linear function (if the decision maker wishes to prefer one of the alternatives having an approximate value for a criterion, this function is preferred for quantitative data) is used for maintenance pre-conditions and possible consequences criteria, third type is preferred that is V-shape function (if the decision maker wishes to prefer alternatives having a higher grade than the desired grade for criteria he has determined and also doesn't want to ignore those under the grade he has determined, this function which is preferred for quantitative data is used) for criteria of failure period, static, dynamic and electrical features of equipment and troubleshooting time, first type that is usual function is used for qualitative data for the criteria of detectability of failure, availability measuring equipment and additional work requirement and fourth type that is level function used for qualitative data is preferred for warehouse backup by identifying the range.

In this study, Visual PROMETHEE package program was used for PROMETHEE method [72]. In the PROMETHEE method, different preference functions have been determined for qualitative and quantitative values. In the determination of preference functions for the criteria, the structure of the criterion, the values it can take are taken into consideration. U-type, Usual and Gaussian type preference functions are used. Gauss type preference function is used for criteria with qualitative values. In the Yes-No decisions, the usual type preference function is used. The numerical equivalents of the criteria for the Gaussian preference type were used for the Q, P and S values. Data in this decision matrix formed by decision makers experienced in power plants are transferred to Visual PROMETHEE software. PROMETHEE II handles net superiority values obtained by subtracting negative superiority grades from positive superiority weights. In this scope, the order of alternative maintenance strategies is revision maintenance, predictive maintenance, preventive maintenance and corrective maintenance as can be seen in Table 4.

Table 4. PROMETHEE flow table

Rank	action	Phi	Phi+	Phi-
1	Revision Maintenance	0,7467	0,8183	0,0717
2	Predictive Maintenance	0,4783	0,6700	0,1917
3	PreventiveMaintenance	-0,3433	0,2750	0,6183
4	Corrective Maintenance	-0,8817	0,0200	0,9017

5. RESULTS AND DISCUSSION

The main goal of power plants is to contribute to energy supply security by performing uninterrupted, low cost, environmentally friendly and efficient electricity generation. The basic element to reach this goal is efficient management of maintenance process which brings together the costs arising from the requirements for man work, material and time, and resulting from the generation losses. In this context, maintenance management is analyzed in this study and it is found that the first stage of maintenance management is equipment-based maintenance strategy selection. The maintenance strategy selection problem focused in the study is handled in a large-scale hydroelectric power plant in Turkey and an application has been performed for the main power transformer among the electrical equipment of the power plant. In the application, 1,404 electrical equipment are evaluated according to 9 evaluation criteria the weights of which are calculated with AHP and identified together with the power plant specialists and this large equipment group has been subject to a rating system defining criticality level for the power plant and the main power transformer equipment is determined by TOPSIS. 9 evaluation criteria identified at the beginning and 4 maintenance strategies are evaluated via PROMETHEE method and it is found that the most appropriate maintenance strategy for the main power transformer is revision maintenance strategy as a result of the study.

Revision periods, planned at specific periods in order to perform long term maintenance of critical equipment which require unit shut down, are the most suitable periods for the main power transformer equipment maintenance in the electricity generation power plants. Because main power transformer which increases voltage of the energy generated in the power plant must be stopped for carrying out the annual maintenance. Also, a capacity of 40 men-hours (5 hours-work with 8 persons) is required for this maintenance and this period means an energy loss of 36 million kWh for a unit of 300 MW. Such a shutdown which causes an important financial loss can be considered reasonable only in revision periods for long term maintenances of the other important equipment.

As a result of the evaluation performed with PROMETHEE, the second-best strategy after revision maintenance for the main power transformer is predictive maintenance. This strategy based on maintenance before equipment breakdown according to measurement results is irrevocable for the equipment considering the main power transformer's task. At the same time, these two maintenance strategies have been applied respectively and in integration as stated in previous section in selected hydroelectric power plant for 2017, and it has been determined that there has been no malfunction caused by the main power transformer. However, average 3-unit shutdown have been occurred annually in this power plant which adopted the corrective and revision maintenance strategy respectively before 2017. In this context, the literature contributes to the importance of the

study. Considering the results obtained in the proposed approach, it is seen that the study is applicable.

As stated in literature review section, despite its advantages, limited scientific study about maintenance strategy selection or maintenance policy optimization problem that uses the PROMETHEE method has been done. Furthermore, the maintenance strategy selection problem has never been handled for hydroelectric power plants except for Özcan et al. [57] in the literature despite the importance of these critical plants for world energy mix. In this context, with method and application field selection as well as the other additive effects, it is thought that this study can shed light on future researches.

Ding and Kamaruddin [7] 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. They have also specified that maintenance strategy selection models are limited to very specific problems, and few are applied to solve real-life problems.

However, proposed approach has been applied in selected hydroelectric power plant for 2017, and it has been determined that there has been no malfunction caused by the main power transformer. This is a means of 100% improvement. Thus, this study contributes to close the gap in the literature mentioned above.

The obtained results given in Table 4 are consistent with the power plant operational realities. Because, revision maintenance is the most extensive and unignorably strategy that must be carried out in power plants for all the most critical equipment regardless of the equipment type (electrical, mechanical or I&C), and it must be performed periodically (e.g. 8,000 hours or 5 years) and requires the long term (e.g. 2 months) shutdown of power plant unit. Concordantly, comprehensive maintenance activities carried out on the main power transformer which is the most critical electrical equipment in hydroelectric power plant, certainly requires power plant unit shut down. Therefore, the most suitable maintenance strategy for main power transformer is revision maintenance strategy in real-life.

No matter how carrying out the comprehensive and periodical maintenance activities (revision maintenance strategy) for main power transformer, failures such as expansion tank, buccholz relay etc. can be occur as a result of the effects of especially high pressure, temperature, voltage and current in real-life power plant operation. Therefore, especially to realize the uninterrupted power generation, predictive maintenance applications have critical importance for main power transformer. Because, predictive maintenance strategy consists of taking required measures for preventing the failures with I&C activities. In other words, inevitable main power transformer breakdowns can be determined and prevented by applying this maintenance strategy before the failures occur. Correspondingly, predictive maintenance has already obtained as the second most

important strategy and the consistency of proposed approach is supported.

6. CONCLUSION

In maintenance strategy selection, maintenance management or maintenance planning literature, generally two MCDM methods are combined for evaluations. However in this study, three methods are combined for increasing the analyticalness level of evaluations. Consistent results from equipment selection to ranking the alternative strategies verify this.

Consistent results obtained as a result of maintenance strategy selection for the main power transformer that is an electrical equipment is applicable for all mechanical, electrical and I&C equipment type. However, time required for evaluation will be pretty long taking thousands of equipment into consideration. Therefore, 3-dimensional matrix composed of alternatives (maintenance strategies), criteria and equipment can be solved via PROMETHEE in a further study. Additionally, in order to reduce operational time and apply the selection of the most appropriate maintenance strategy to all equipment of the power plant, multi-objective optimization models such as goal programming can be proposed/generated considering the multi-criteria and multi-objective characteristics of the problem and maintenance.

Main power transformers are critical equipment in all power generation plants. Considering the above-mentioned results consistent with the real life, proposed methodology is not only capable of contributing to the power plant, but also to the energy supply security of the country. Because, the frequency of the equipment will be reduced, or the equipment will not fail at all. Thus, generation stoppages due to main power transformer can be prevented. From this point of view, it can be said that the other most critical equipment of the power plants can be determined and evaluated for the most suitable maintenance strategy with proposed methodology for sustainable energy generation and providing the energy supply security.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

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