



Article citation info:

Özcan E, Yumuşak R, Eren T. A novel approach to optimize the maintenance strategies: a case in the hydroelectric power plant. *Eksploracja i Niezawodność – Maintenance and Reliability* 2021; 23 (2): 324–337, <http://doi.org/10.17531/ein.2021.2.12>.

A novel approach to optimize the maintenance strategies: a case in the hydroelectric power plant

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Highlights

- The maintenance strategy optimization model, which takes into account the wear rate, has been proposed.
- AHP, COPRAS and integer programming methods are used.
- The problem is addressed in the system dimension.
- A feasible model has been proposed.

Abstract

Countries need to develop sustainable energy policies based on the principles of environmental sensitivity, reliability, efficiency, economy and uninterrupted service and to maintain their energy supply in order to increase their global competitiveness. In addition to this impact of sustainable energy supply on the global world, maintenance processes in power plants require high costs due to allocated time, materials and labor, and generation loss. Thus, the maintenance needs to be managed within a system. This makes analytical and feasible maintenance planning a necessity in power plants. In this context, this study focuses on maintenance strategy optimization which is the first phase of maintenance planning for one of the large-scale hydroelectric power plants with a direct effect on Turkey's energy supply security with its one fifth share in total generation. In this study, a new model is proposed for the maintenance strategy optimization problem considering the multi-objective and multi-criteria structure of hydroelectric power plants with hundreds of complex equipment and the direct effect of these equipment on uninterrupted and cost-effective electricity generation. In the model, two multi-criteria decision-making methods, AHP and COPRAS methods, are integrated with integer programming method and optimal maintenance strategies are obtained for 571 equipment.

Keywords

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maintenance management, maintenance strategy optimization, multi-criteria decision making, AHP, COPRAS, integer programming.

Abbreviations: AHP, Analytic hierarchy process; COPRAS, Complex Proportional Assessment; ELECTRE, ELimination Et Choix Traduisant la REalité; GP, goal programming; IP, integer programming; MCDM, multi-criteria decision-making; HPP, hydroelectric power plant; MSO, maintenance strategy optimization; SAW, Simple Additive Weighting; TOPSIS, Technique for Order of Preference by Similarity to Ideal Solution; VIKOR, Visekriterijumska Optimizacija I Kompromisno Resenje.

1. Introduction

Maintenance is a set of activities to assess and maintain the capabilities of instruments or equipment. However, another task of maintenance is to restore machinery or equipment that has lost its function back to its previous state [37]. Maintenance and repair activities are of great importance for any industrial plant to achieve sustainable generation, because failures resulting from improper planning of maintenance lead to generation losses and costly maintenance and repair expenses with the halt of generation. In addition to maintenance costs, generation halts endanger supply security, rendering enterprises unable to compete in highly competitive markets. Moreover, poor management of the maintenance process can lead to businesses being eliminated from markets. Furthermore, maintenance is a costly process in terms of time, labor requirement and material [43]. As maintenance

planning is important and costly, it is critical to determine optimal maintenance strategies to be applied to the machine or equipment. This is because wrong maintenance strategies applied will generate major obstacles in achieving sustainable generation. For example, it not only increases the likelihood of equipment failure but also leads to high maintenance costs and reduced product quality [26]. Considering many factors such as cost, security of supply and product quality, it can be concluded that determining the maintenance strategies to be applied to the equipment is an indispensable first stage of an effective and feasible maintenance planning. This is because all maintenance and repair activities are performed according to the selected maintenance strategies [52]. There are many maintenance strategies in the literature: reliability-based maintenance [64], condition-based maintenance [2], risk-based maintenance [48], preventive maintenance [32], predictive maintenance [39], corrective maintenance [60], and lastly

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revision maintenance [44]. Among these strategies, four maintenance strategies are applied in HPP, where this study is implemented:

Corrective Maintenance Strategy: This maintenance strategy allows failure to occur before maintenance is performed. Corrective maintenance is a failure-based maintenance that is performed after a corrective or when an obvious probability of failure is detected. The purpose of this maintenance is to return the system to the state where it can perform its required function in the minimum possible time. A primitive type of maintenance, corrective maintenance does not take into account the losses caused by malfunctions and failures [60].

Preventive (Periodical) Maintenance Strategy: It is carried out according to predetermined periods or foreseen criteria. It is done to prevent the deterioration of the functioning of a product or to reduce the possibility thereof [32]. This type of maintenance aims to increase the reliability and availability of equipment by minimizing the number of failures and eliminating the need for unplanned corrective maintenance [61].

Predictive Maintenance Strategy: The goal of predictive maintenance is to reduce downtime and maintenance costs on the premise of zero failure generation by monitoring the operating status of the equipment and predicting when an equipment failure can occur [39]. Through prediction, it provides maintenance planning for future potential failures before the failure occurs. Ideally, the maintenance program is optimized to minimize maintenance costs and achieve zero failure generation [40].

Revision Maintenance Strategy: This is the maintenance strategy that involves the implementation of positive changes in the design, operation method, operating conditions, installation, scheduling and maintenance methods of the relevant machine/equipment in order to achieve the functions expected from the machine/equipment at the highest level [44].

As mentioned above, the most critical phase of maintenance management is maintenance planning. The first and indispensable stage of maintenance planning is the selection of the appropriate maintenance strategy. This selection problem is a very complex problem due to the fact that the system units have many and different functions, obtaining the data reflecting the system is difficult, and it contains many quantitative and qualitative criteria [42]. To solve this problem, researchers presented their solutions by using different methods in different application areas. With the recognition of the importance of maintenance management, the interest in the problem of maintenance strategy selection has increased in the literature in recent years. Increasing interest led researchers to compile and review published studies and as a result, two literature reviews on this subject were published in 2015. One of these two reviews was written by Ding and Kamaruddin [16]. In this review, researchers explained the problem of maintenance strategy selection in detail and evaluated the studies in a broad perspective and classified them into three groups. The other review was conducted by Shafiee [52]. Unlike Ding and Kamaruddin's study, Shafiee limited the studies on the basis of the methods used and evaluated them from a different perspective. Because of the multi-criteria and multi-objective structure of the problem, multi-criteria decision making methods are among the most preferred methods. Shafiee [52] evaluated this situation in detail by examining the MCDM methods used for maintenance strategy selection. Among the multi-criteria decision making methods, the most commonly used methods for the maintenance strategy selection problem in the literature are AHP [25], ANP [34], TOPSIS [17], SAW [50], ELECTRE [58], and VIKOR [38]. Instead of finding a solution to the problem of selecting a maintenance strategy using only one multi-criteria decision making method, some researchers have solved the problem using a combination of multi-criteria decision making methods. By using a combination of different decision making methods, these researchers have provided a different perspective to the problem of maintenance strategy selection. This has been of interest to researchers, and as a result, new studies have been published using the combination of AHP-TOPSIS [46], ANP-TOPSIS [47], ANP-ELECTRE [14], FAHP-VIKOR [28], AHP-PROMETHEE

[19], FAHP-CODAS [45], ANP-DEMATEL [1], and AHP-COPRAS [22] to solve the maintenance strategy selection problem. The analytical level of the solution increased with the combined use of multi-criteria decision making methods, but these methods were insufficient in systems where the problem size increased. At this point, researchers have solved the problem of maintenance strategy selection for multiple equipment by using GP, one of the multi-criteria decision making methods [4, 8, 24, 29]. At this stage, the maintenance strategy selection problem has been replaced by MSO. GP method can also be integrated with multi-criteria decision making methods. For example, Bertolini and Bevilacqua [8] have determined the optimal maintenance strategy for centrifugal pumps in an oil refinery with the integration of AHP and GP methods. GP method has taken its place in the literature as a solution method for multi-objective MSO for multiple equipment. However, presence of more than one goal in GP method increases the complexity the problem and generates problems in obtaining the optimal result. In addition, more than one goal brings out the need for more data. Because of these disadvantages, research has shifted to IP as an alternative to GP method [51]. For example, Braglia et al. [9] used the failure mode effect analysis and IP methods to determine the costs of each strategy and which maintenance implementation was applicable to each failure. In this study, IP method was used since a single-goal model aimed at minimizing generation downtime was established and an optimal solution was sought for a very complex MSO problem since the plant consisted of hundreds of equipment.

When the application areas of the MSO problem, are examined, there are studies in many sectors including transportation [25], automotive [35], textiles [55] and machining [62]. There are many studies in the energy sector in which this study is conducted [53]. Williams and Patelli [23] found the optimal maintenance strategy for the IEEE-24 RTS equipment in a HPP with the Monte Carlo Simulation. Özcan et al. [44] performed a multi-objective MSO for 9 critical equipment in a HPP using AHP-TOPSIS and GP methods. In another study, Özcan et al. [42] calculated the criticality levels of the equipment in a HPP with AHP-TOPSIS methods. They proposed a model aimed at cost minimization by using these calculations in IP method. As a result, Özcan et al. [42] obtained optimal maintenance strategies for the seven electrical equipment groups. In the present study, a mathematical model was proposed to determine the maintenance strategies to be applied to all electrical equipment in a HPP MSO was performed for a total of 571 equipment. The model included the four maintenance strategies described in detail above. In the solution methodology, AHP and COPRAS –two multi-criteria decision making methods– were used for the calculation of some parameters. These parameters were then used in the IP model to obtain optimal maintenance strategies for 571 equipment. Based on the results obtained, the contributions of the model to the literature are as follows:

- MSO problem was solved within the system at a power plant for the first time. For example, while only critical equipment has been identified in the power plant and solutions have been proposed for only these equipment in the literature [42, 44], a solution was obtained in this study for all electric equipment in the plant. In the proposed model, optimal maintenance strategies of 571 equipment have been determined. With this study, a model yielding optimal results for such a large problem has been proposed for the first time in the literature within the context of MSO.
- Since the problem is handled at the system level and the plant consists of units, the problem includes identical equipment. However, since these equipment are located in different units, they have been subjected to different generation and maintenance processes. These generation and maintenance activities have generated wear differences between identical equipment. Due to failures caused by them, the resulting wear differences directly affect the maintenance strategy to be applied to identical equipment located in different units. In this study, the effect of wear was calculated by AHP which is one of the MCDM methods and reflected to the

model for the first time in the literature and real life consistency of the model was achieved.

- In the literature, single-goal models, usually involving cost minimization, or multi-goal models involving minimization of maintenance times, maintenance costs, downtime, etc., have been proposed in general. In this study, a model has been proposed to reflect the real life characteristics of the system by expressing many goals with a single goal -by minimizing the generation downtime of the system. In other words, the goal of minimizing generation stops generates a context including a set of objectives such as cost minimization, minimizing risk factors and reliability maximization.
- The integration of AHP-COPRAS-IP methods has been used for the MSO problem for the first time in the literature. In addition, the problem was removed from subjectivity by following a five step solution methodology. With the analytically obtained solution combination of decision problems within the scope of the study consisting of determination of equipment wear rates, determination of criticality levels of equipment for the plant and determination of the added value provided by each maintenance strategy to the plant, and optimal assignment of maintenance strategies to the equipment were achieved by taking into account the real life dynamics of the system.

In the second section of the study, the methods used and the reasons for using these methods are presented based on the advantages of the methods. In the third section, the application details of the study are presented, and in the fourth section and fifth section the results of the proposed model are evaluated and the study is completed by emphasizing the recommendations.

2. Methods

In this study, MSO problem of electrical equipment in a HPP is handled. First of all, the wear rate of nine units was calculated in order to reflect the differences of identical equipment to the model. Considering the multi-criteria structure of the problem, AHP method, which is frequently used in the literature and provides ease of use and flexibility in method integrations, was used for this calculation. In the second stage of the study, the added value of each maintenance strategy to the plant was calculated. At this stage, AHP method was used again because the multi-criteria nature and hierarchical structure of the problem. In the third stage of the problem, the criticality levels of the electrical equipment were determined. Although AHP-TOPSIS [44] integration is frequently used in the literature for this problem, AHP-COPRAS combination is used in this study. The equipment criticality levels need to be expressed over 100 in the mathematical model. Moreover, COPRAS method is more advantageous than TOPSIS method for the studies involving opposite criteria since the criteria are divided into two as useful and useless criteria and the algorithm is operated according to this separation [41]. Finally, the dynamics of the system are reflected in the model by using the parameters formed as a result of these three stages in the IP model. Details of the methods are provided further down in this section.

2.1. AHP

AHP is a method developed by Saaty and frequently used in many types of decision-making problems. This method gives the decision maker the opportunity to evaluate the criteria and alternatives in the decision-making process by analytically prioritizing them [49]. AHP is a widely used method in which ideas of groups are shared and the targets and alternatives are analyzed in order to obtain the best results. AHP method has been used in many fields of application including construction sector [15], health sector [11, 54], transport sector [10] and energy [56]. Furthermore, it has been preferred as a solution algo-

rithm for many problems from efficiency assessment [56] to technology selection [5], from site selection [18] to maintenance planning [7, 13]. AHP method has been chosen as the solution method because it has the flexibility of integration with different methods such as reduction of subjectivity and linear programming and fuzzy logic [59].

Application steps of AHP are given below [49]:

Step 1: The purpose of the decision-maker is to include the criteria and alternatives that affect this purpose, and to determine the relation-

Table 1. Saaty's preference scale [49]

Importance Values	Value Definitions
1	Equal importance of both factors
3	Factor 1 is more important than factor 2
5	Factor 1 is much more important than factor 2
7	Factor 1 has a very strong importance compared to factor 2
9	Factor 1 has an absolute superior importance to factor 2
2, 4, 6, 8	Intermediate values - when compromise is needed

ships between them and to compose a hierarchical structure.

Step 2: It is carried out by experts by comparing all criteria and alternatives according to their degree of importance. At this stage, the significance scale, which is developed by Saaty and given in Table 1, is used.

Step 3: Normalization process is done. This normalization is performed by dividing each value in each matrix by column totals (Eq. 1):

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}} \quad i, j = 1, 2, \dots, n \quad (1)$$

Step 4: After normalization, the priority or weight vectors for the items compared in the hierarchy are calculated [Eq. 2]:

$$w_i = \sum_{j=1}^n b_{ij} / n \quad i, j = 1, 2, \dots, n \quad (2)$$

Step 5: The consistency rate (CR) is calculated. CR is calculated by applying equations Eq. 3, Eq. 4, Eq. 5, Eq. 6 respectively:

$$E_i = d_i / w_i \quad i = 1, 2, \dots, n \quad (3)$$

$$\lambda = \sum_{i=1}^n E_i / n \quad i = 1, 2, \dots, n \quad (4)$$

$$CI = (\lambda - n) / (n - 1) \quad (5)$$

$$CR = CI / RI \quad (6)$$

Table 2. RI Values

n	1	2	3	4	5	6	8	9	10	11	12	13
RI	0	0	0,58	0,9	1,12	1,24	1,41	1,45	1,49	1,51	1,48	1,56

Table 2 is used to calculate Eq. 6. If CR less than 0.1 indicates that the application is consistent. Otherwise, the pairwise comparison matrices are revised, and the steps are repeated.

Step 6: In the analysis phase of AHP scores, the highest value alternative is chosen as the best alternative.

2.2. COPRAS

COPRAS, which is one of the MCDM methods, was developed in 1996 [63]. COPRAS can be used for maximum and minimum criteria values in multi-criteria evaluation. COPRAS method can be easily applied to problems involving complex criteria and numerous alternatives. Thanks to these features, it has been applied in many different fields in the literature. COPRAS method successfully solved different problems in different sectors from agriculture [3] to information sector, from investment evaluation [27] to supply chain management [12]. One of the most important features of COPRAS method is that it shows the degree of benefit of alternatives. It compares the evaluated alternatives with each other and expresses in percentage how good or bad the other alternatives are. In addition, it evaluates the criteria as useful and useless criteria and eliminates the need to make calculations on opposite criteria [63].

Application steps of COPRAS are given below [63]:

Step 1. The first step is to compose the decision matrix. Decision matrix (X) is formed as shown in Eq. 7. m is the number of alternatives and n is the number of criteria:

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \quad (7)$$

Step 2: In the second step, the decision matrix is normalized. Normalization process is carried out with the help of Eq. 8:

$$x_{ij}^* = \frac{x_{ij}}{\sum_{i=1}^m x_{ij}} \quad j = 1, 2, \dots, n \quad (8)$$

Step 3: The weighted normalized decision matrix is obtained by using the normalized decision matrix with the weight values of each evaluation criterion represented as w_j . Normalized decision matrix expressed by D is formed with the help of Eq. 9:

$$D = d_{ij} = w_j * x_{ij}^* \quad i = 1, 2, \dots, m \quad j = 1, 2, \dots, n \quad (9)$$

Step 4: The sum of the values of the useful criteria in the weighted normalized decision matrix is shown as S_{i+} , for the useless criteria the sum is S_{i-} . Eq. 10 and Eq. 11 are used respectively for S_{i+} and S_{i-} calculations:

$$S_{i+} = \sum_{j=1}^k d_{ij} \quad j = 1, 2, \dots, k \quad (10)$$

$$S_{i-} = \sum_{j=k+1}^n d_{ij} \quad j = k+1, k+2, \dots, n \quad (11)$$

Step 5. The relative importance value (Q_i) is calculated using Eq. 12 for each alternative. The alternative with the highest Q_i value means the best alternative:

$$Q_i = S_{i+} + \frac{\sum_{i=1}^m S_{i-}}{S_{i-} * \sum_{i=1}^m \frac{1}{S_{i-}}} \quad i = 1, 2, \dots, m \quad (12)$$

Step 6: In this step, the highest relative priority value is determined with the help of Eq. 13:

$$Q_{max} = \max \{Q_i\} \quad i = 1, 2, \dots, m \quad (13)$$

Step 7: In the last step, the performance index (P_i) for each alternative is calculated using Eq. 14. The alternative with a P_i of 100 is considered as the best alternative. The order in which the alternatives should be preferred is obtained by ordering the performance index in descending order:

$$P_i = \frac{Q_i}{Q_{max}} * 100\% \quad i = 1, 2, \dots, m \quad (14)$$

2.3. Integer Programming (IP)

IP is the solution method in which some or all of the problem variables take integer values. Gomory suggested that by making small changes with the intersecting planes in the simplex algorithm, integer results could be obtained, and this led to an important breakthrough in IP [30]. After Gomory's study, different types of integer programming such as 0-1 and mixed IP came to the fore with various studies. The general form of the IP model is given below [57]:

$$\begin{aligned} \text{Max (Min)} \quad & z = g_0(x_1, x_2, \dots, x_n) \\ \text{St.} \quad & \\ & g_i(x_1, x_2, \dots, x_n) \begin{cases} \leq \\ = \\ \geq \end{cases} b_i, \quad i \in M \equiv \{1, 2, \dots, m\} \\ & x_j \geq 0, \quad j \in N \equiv \{1, 2, \dots, n\} \\ & x_j = \text{integer} \quad j \in I \subseteq N \end{aligned} \quad (15)$$

IP has taken its place in the literature with effective results for different kinds of problems in many areas such as transportation [31], health [6], industry [33], and energy [20, 21].

3. Case study

The MSO which is an indispensable first phase of maintenance planning for one of the large-scale HPP with a direct effect on Turkey's energy supply security with its one fifth share in total generation is addressed in the study. Besides their share in energy generation, HPP are of great importance for environmentally friendly electricity generation since they are one of the renewable energy sources. Moreover, the most problematic phase in electricity generation is electricity transmission. The problems experienced in this phase especially reduce the output of the plant. For this reason, in the present study, all electrical equipment in a HPP are handled within the system. Optimal maintenance strategies are obtained for 571 equipment in total. These equipment include current transformers, voltage transformers, breakers, disconnectors, main power transformers, drive motors, auxiliary transformers, excitation transformers, slipping and carbon brushes, relays, transformer expansion tanks, bushings, generator rotors and generator stators and subcomponents of these equipment groups. It is formed. The proposed mathematical model serves to identify optimal maintenance strategies for 571 electrical equipment in the plant, increasing both efficiency and energy supply security. This study consists of four basic stages. Firstly, the wear rate of nine units was calculated by AHP method in order to reflect the differences of identical equipment to the model. In the second stage of the study, the added value provided by each maintenance strategy to the plant was obtained by AHP method. In the third stage, criticality levels of the equipment examined in the study were calculated for the plant. AHP-COPRAS

integration, which is a multi-criteria decision making method, was used for this calculation. Plant experts were consulted to collect data during the implementation steps of the AHP method, which was used in three stages. The data were obtained with the help of 8 power plant experts (industrial, electrical, electrical-electronic and mechanical engineers) each of whom had 10 to 25 years of experience in operation and maintenance of HPP and by taking into account the real life operating rules of the HPP. Finally, optimal maintenance strategies were obtained by using the parameters calculated in these three stages in the IP model. The implementation steps of the new model proposed in this study are summarized in Figure 1.

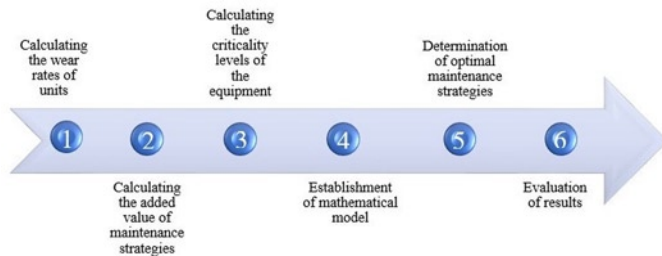


Fig. 1. Application steps

The power plant is composed of nine units. These units were commissioned at different times and different generation plans were implemented. This has caused wear differences between the units. One of the factors in determining the maintenance strategy is the wear rate of the equipment. This is because equipment with the same function and quality may require different maintenance practices as a result of different generation activities. Different maintenance practices require different maintenance strategies. In other words, wear rates affect MSO. In today's power plant operating conditions, it is not possible to calculate the wear rate of each equipment in HPP consisting of thousands of equipment, because of the difficulty in obtaining data and not being able to express completely different equipment with common parameters. In this study, calculating the wear rates of each unit was proposed as a solution.

3.1. Calculating the Wear Rates of Units

HPP are massive infrastructure investments. Therefore, it may not be possible to put all units into generation at the same time. The power plant discussed in this study consists of nine units. These units were activated at different times and different generation plans were implemented. This situation has caused differences in wear rate between the units. In fact, the model needs to be solved by taking into account the wear rate of each equipment. However, since the plant is composed of thousands of pieces of equipment and it is not possible to collect data for each equipment with common parameters in today's conditions, a MSO model that takes into account wear rates by calculating unit based wear rate is proposed for the first time in the literature. Three criteria were taken into account in the calculation of wear rate. These criteria are the date when the unit was commissioned, work time, and generation quantity. Wear rates for nine units were calculated according to these criteria. Considering the multi-criteria structure of the problem, AHP, which is the most used MCDM method in the literature by providing ease of solution to complex problems, was chosen. Expert opinions were used in the method. First, the criteria weights were generated. The steps of the AHP method described in

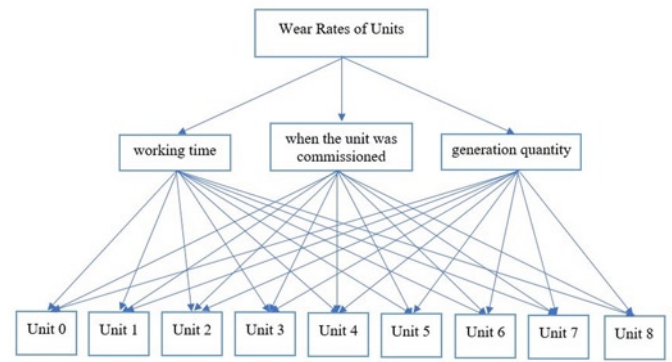


Fig. 2. Hierarchical structure

Section 2.1 were applied at this stage. In the solution phase, a hierarchical structure was composed first. The hierarchical structure composed is given in Figure 2.

After the hierarchical structure was composed, it was passed to the stage where the weights of each criterion were determined. First, pairwise comparison matrices were composed. The pairwise comparison matrix composed is given in Table 3.

Table 3. The pairwise comparison matrix of the criteria

	When the unit was commissioned	Working time	Generation quantity
When the unit was commissioned	1	3	5
Working time	0.333	1	3
Generation quantity	0.200	0.333	1

For the calculation of criterion weights, the row averages of the values in the normalized decision matrix are taken. The weights formed after the process are given in Table 4.

As a result of the application, it is seen that the most important criterion is when the unit was commissioned with a weight of 0.63. This was followed by working time with a weight of 0.26. Finally, the weight of generation quantity was calculated as 0.11. The CR was 0.03.

Table 4. Criteria weights

Criteria	Weight
When the unit was commissioned	0.633
Working time	0.261
Generation quantity	0.106

Table 5. Weight vectors and CR values

When the unit was commissioned			Working time			Generation quantity		
Unit number	Weight vector	CR	Unit number	Weight vector	CR	Unit number	Weight vector	CR
U0	0.019	0.079	U0	0.017	0.067	U0	0.019	0.028
U1	0.028		U1	0.030		U1	0.030	
U2	0.028		U2	0.031		U2	0.047	
U3	0.251		U3	0.222		U3	0.303	
U4	0.056		U4	0.063		U4	0.047	
U5	0.251		U5	0.117		U5	0.212	
U6	0.056		U6	0.072		U6	0.077	
U7	0.071		U7	0.117		U7	0.110	
U8	0.242		U8	0.331		U8	0.156	

After the criterion weights were calculated, alternatives were evaluated for each criterion. Paired comparison matrices composed for each criterion are given in Appendix A. The results obtained when the steps given in Section 2.1 are applied in paired comparison matrices are given in Table 5.

Table 6. Wear rates of units

Unit number	AHP scores	Wear rates
U0	0.018	7.205
U1	0.028	11.13
U2	0.031	12.061
U3	0.249	97.187
U4	0.057	22.077
U5	0.212	82.778
U6	0.062	24.289
U7	0.087	33.979
U8	0.256	100

The wear rates of the nine units were calculated using the criterion weights obtained. By taking the ratio of the largest of the weights obtained by AHP to 100 and the wear rates were updated and re-expressed over 100. The results are given in Table 6. When the results are examined, it is seen that Unit 3, Unit 5 and Unit 8 are more worn than other units.

The benefits of each maintenance strategy to the plant are different. These differences are one of the main factors affecting the optimization of maintenance strategy. For this reason, in the second stage of the study, the added value provided to the plant by the four maintenance strategies discussed was measured.

3.2. Calculating the Added Value of Maintenance Strategies

The parameter that must be considered in problem solving for MSO is the added value of strategies provided to the whole system. This is because maintenance strategies have positive and negative effects reflected in the system in which they are applied. For example, the reduction of failures and increase in productivity as a result of the implementation of the maintenance strategy is a positive effect, while the cost items for the implementation of the strategy are a negative effect. For this reason, it is necessary to calculate the added value provided by the strategies to the plant and determine the maintenance strategy according to these values. In the present study, four maintenance strategies have been evaluated by taking into consideration the benefits, cost of maintenance process, duration and requirements for implementation of the strategy. This evaluation was made by AHP which is one of the multi-criteria decision making methods. The maintenance strategies implemented in the HPP detailed in Chapter 1 are summarized below.

Corrective Maintenance Strategy: Repair and/or maintenance activities carried out in the event that the machine/equipment is unable to perform the task expected of it, to ensure that the machine/equipment is capable of operating in line with its design specifications [44].

Preventive (Periodical) Maintenance Strategy: Maintenance activities carried out within a timetable for the machine/equipment to operate uninterruptedly and in line with the expected design specifications.

Predictive Maintenance Strategy: Maintenance activities which include monitoring of machine/equipment during operation by using modern measurement and signal-processing methods and taking necessary measures according to measurement results before failure occurs [43].

Revision Maintenance Strategy: It is a maintenance strategy which is done periodically (e.g. every 8000 hours or 5 years) to all critical equipment in the power plant units, which requires a long time (like 2 months) and in which the power plant unit downtime is mandatory [44].

The four maintenance strategies were evaluated under the criteria of benefit, cost, duration and requirements. First, a hierarchical structure was composed. The hierarchical structure composed is given in Figure 3.

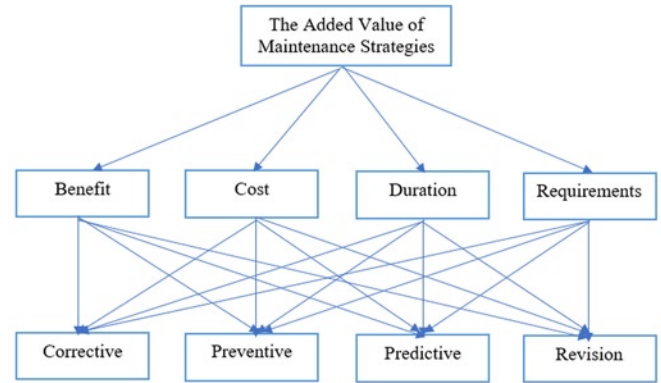


Fig. 3. Hierarchical structure

Table 7. The pairwise comparison matrix of the criteria

	Benefit	Cost	Duration	Requirements
Benefit	1	3	7	5
Cost	0.333	1	4	2
Duration	0.143	0.250	1	0.5
Requirements	0.200	0.500	2	1

Secondly, criteria weights were obtained by the AHP method. The pairwise comparison matrix of the criteria is given in Table 7.

Benchmark weights were found to be 0.579 for benefit, 0.233 for cost, 0.067 for duration, and 0.121 for requirements. When the criteria weights are evaluated, it is seen that the most important criterion is benefit. In the next step of the algorithm, the benefit values of the maintenance strategies were calculated by using the criterion weights obtained.

After the criterion weights were determined, the alternatives for each criterion were compared. Paired comparison matrices and CR values made in terms of criteria are given in Table 8.

It is seen that revision maintenance strategy provides the greatest added value. Corrective maintenance strategy is the maintenance strategy with the lowest added value. The results are given in Table 9.

Another factor affecting MSO is the criticality level of the equipment with respect to the power plant. In other words, it is a quantitative expression of the role of each equipment in electricity generation. In the third stage of the study, criticality levels of the equipment were calculated.

3.3. Calculating the Criticality Levels of the Equipment

The present study aims to assess and determine which maintenance strategies should be applied to 571 pieces of electrical equipment. In this problem, the maintenance strategy needs to be selected according to the equipment. Mathematical models should be used to obtain an optimal solution with a high analytical level not influenced by subjective judgments. In the mathematical model, qualitative data should be converted into quantitative data in order to reflect different aspects of the equipment. For this reason, the criticality levels of the equipment

Table 8. The pairwise comparison matrix of the criteria and CR values

Criteria	The pairwise comparison matrix of the criteria					CR
Benefit		Corrective	Revision	Predictive	Preventive	0.03
	Corrective	1	0.111	0.143	0.2	
	Revision	9	1	3	2	
	Predictive	7	0.33	1	0.5	
	Preventive	5	0.5	2	1	
Cost		Corrective	Revision	Predictive	Preventive	0.02
	Corrective	1	0.2	0.125	0.143	
	Revision	5	1	0.25	0.333	
	Predictive	8	4	1	2	
	Preventive	7	3	0.5	1	
Duration		Corrective	Revision	Predictive	Preventive	0.03
	Corrective	1	0.167	0.125	0.143	
	Revision	6	1	0.333	0.333	
	Predictive	8	3	1	0.5	
	Preventive	7	3	2	1	
Requirements		Corrective	Revision	Predictive	Preventive	0.06
	Corrective	1	0.167	0.111	0.333	
	Revision	6	1	0.25	4	
	Predictive	9	4	1	7	
	Preventive	3	0.25	0.143	1	

Table 9. Maintenance strategy added values

Maintenance strategy	Added values
Corrective	0.045
Revision	0.358
Predictive	0.325
Preventive	0.272

Table 10. The pairwise comparison matrix of the criteria

	C1	C2	C3	C4	C5	C6	C7
C1	1	0.200	0.250	0.125	2	0.500	0.500
C2	5	1	4	0.333	9	5	7
C3	4	0.250	1	0.200	4	3	2
C4	8	3	5	1	9	5	7
C5	0.500	0.111	0.250	0.111	1	2	0.333
C6	2	0.200	0.333	0.200	0.500	1	2
C7	2	0.143	0.500	0.143	3	0.500	1

for the plant should be determined. At this stage, the criteria affecting the criticality level were determined initially in accordance with the studies in the literature and expert opinions [42, 44]. Since the effect levels of these criteria are not equal, criterion weights should be determined. At this stage, weighting was performed with AHP, one of the multi-criteria decision making methods. The implementation steps given in Section 2.1 were carried out with the data obtained from

Table 11. Criteria weights

Criteria	Code	Weight values
System backup	C1	0.042
Pre-maintenance conditions	C2	0.271
Failure period	C3	0.118
Possible results	C4	0.406
Availability of measuring equipment	C5	0.042
Processing time	C6	0.062
Fault detection	C7	0.059

the plant experts. The pairwise comparison matrix composed by the experts is given in Table 10.

The CR value was 0.089. The criteria and their weights are given in Table 11.

After determining the criterion weights, the necessary data to calculate the criticality levels of the equipment were collected. Data for seven criteria were collected for 571 pieces of equipment, but because the size of the data set is large, only the data for some pieces of equipment are given in Table 4. Using the data of 571 pieces of equipment, the criticality levels of the equipment were calculated by performing the COPRAS steps described in Section 2.2. Critical levels of some equipment are given in Table 12.

The aim of this study is to ensure that optimal maintenance strategies are assigned to 571 electrical equipment. In the first three sections, the parameters required for this purpose were obtained. Once

Table 12. Equipment data and critical levels

Equipment Name	C1	C2	C3	C4	C5	C6	C7	Critical level
6.3 KV Breakers	4	6	3	7	3	4	3	85.784
A Busbar Disconnecter L1 Phase	1	7	5	10	3	4	3	100.000
Main Power Transformer Phase L1	1	7	3	10	3	4	3	95.716
Separator Motors L3 Phase	1	7	5	10	3	4	3	100.000
B Busbar Disconnecter L2 Phase	1	7	5	10	3	4	3	100.000
Unpressurized Oil Tank Cooling Pump Drive Motor	4	7	3	1	1	2	1	51.344
BCT 19 (6.3 MVA) Transformer	4	1	5	7	3	2	3	70.006
Generator Group Breaker	4	1	5	9	1	2	3	75.897
Generator Rotor	1	7	5	10	3	4	3	100.000
Generator Stator	1	7	5	10	3	4	3	100.000
Internal Need Transformer	1	6	3	10	3	4	3	92.254

these steps were completed, the optimal solution of the problem was obtained with mathematical modeling.

3.4. Maintenance Strategy Optimization (MSO)

In the last stage of the study, MSO was performed for 571 pieces of equipment. An IP model was established with the values obtained in the first three stages. The objective of the mathematical model is to minimize generation downtime. In other words, the proposed new model aims to minimize generation downtime due to maintenance management in the plant as a result of optimal maintenance strategies to be implemented. Unlike multiple-goal models, this model optimizes only one parameter, but it has more than one goal. This is because it serves the most basic purpose of the maintenance process. This is to fulfill the role of all equipment in the system for the purpose of sustainable generation. Reducing generation downtime includes many goals such as minimizing costs, maximizing supply security, and risk minimization. For example, maximizing supply security depends on minimizing generation downtimes. Eliminating situations that may lead to generation downtimes will increase supply security. Or, minimizing generation downtime will keep failure risks to a minimum. As a result, determining the most appropriate maintenance strategies as described in the first section has a direct impact on the goal of sustainable generation. When this effect is taken into consideration, since the aim of the model is minimization of generation stops, it includes other goals as well.

The notations and decision variables used in the model are described below.

Notations:

- i: Unit index (i=0,...,8)
- j: Equipment index (j=1,...,68)
- k: Maintenance strategy index(1=revision, 2=preventive, 3=predictive, 4=corrective)
- T_{ijk} : ith unit, jth equipment production downtime when kth maintenance strategy is applied
- D_{ijk} : ith unit, jth equipment kth maintenance strategy implementation time
- C_{ijk} : ith unit, jth equipment kth maintenance strategy implementation cost (sum of labor and material cost)
- Tc: Budget allocated for maintenance
- $X_{ijk} = \begin{cases} 1, & \text{if unit } i \text{ assigned to } j \text{ equipment in } k \text{th maintenance strategy} \\ 0, & \text{otherwise} \end{cases}$

- Td: Maintenance time (hours)
- CR_{ij} : ith unit to critical level of jth equipment
- Y_i : ith unit attrition rate
- W_k : kth weight of maintenance strategy

Decision variables:

$$i=0, \dots, m \quad j=1, \dots, n \quad k=1, \dots, l$$

Model formulation:

$$\text{Min } Z = \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^l T_{ijk} * X_{ijk} \tag{1}$$

$$\sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^l D_{ijk} * X_{ijk} \leq Td \tag{2}$$

$$\sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^l C_{ijk} * X_{ijk} \leq Tc \tag{3}$$

$$\sum_{k=1}^l X_{ijk} \geq 1 \quad i=0, \dots, m \quad j=1, \dots, n \tag{4}$$

If $CR_{ij} \geq 85$

$$\sum_{k=1}^l W_k X_{ijk} \geq 0.85 \quad i=0, \dots, m \quad j=1, \dots, n \tag{5}$$

If $CR_{ij} \geq 70 \vee CR_{ij} < 51$

$$\sum_{k=1}^l W_k X_{ijk} \geq 0.70 \quad i=0, \dots, m \quad j=1, \dots, n \tag{6}$$

$$\sum_{k=1}^l W_k X_{ijk} \leq 0.85 \quad i=0, \dots, m \quad j=1, \dots, n$$

If $CR_{ij} \geq 51 \vee CR_{ij} < 70$

$$\begin{aligned}
\sum_{k=1}^l W_k X_{ijk} &\geq 0.51 \quad i=0,\dots,m \quad j=1,\dots,n \\
\sum_{k=1}^l W_k X_{ijk} &\leq 0.70 \quad i=0,\dots,m \quad j=1,\dots,n \\
X_{ij1} &= 0 \quad i=0,\dots,m \quad j=1,\dots,n
\end{aligned} \quad (7)$$

Else if $CR_{ij} < 51$

$$\begin{aligned}
X_{ij1} &= 0 \quad i=0,\dots,m \quad j=1,\dots,n \\
X_{ij2} &= 0 \quad i=0,\dots,m \quad j=1,\dots,n \\
X_{ij3} &= 0 \quad i=0,\dots,m \quad j=1,\dots,n \\
X_{ij4} &= 1 \quad i=0,\dots,m \quad j=1,\dots,n
\end{aligned} \quad (9)$$

If $Y_i \geq 80 \wedge CR_{ij} \geq 70$

$$X_{ij2} = 1 \quad i=0,\dots,m \quad j=1,\dots,n \quad (10)$$

Formulation of the mathematical model is given below. Eq. 1 represents the objective function of the model. It means minimization of generation downtime. Eq. 2 indicates that the actual maintenance period should be less than or equal to the assigned maintenance period. Eq. 3 means that the total maintenance cost should be less than or equal to the total budget allocated for maintenance. Eq. 4 means that at least one maintenance strategy must be assigned to each equipment. Eq. 5- Eq. 9 are the constraints that make the assignments by taking into account the criticality levels of the equipment. The sum of the added value obtained from the maintenance strategies to be implemented should be proportional to the criticality level of the equipment. The threshold values were determined according to the pre-maintenance conditions and possible results, which were determined as the two most important criteria in the calculation of the critical levels of the equipment described in Section 3.3. Eq. 10 stated that periodic maintenance should be performed if the wear rate of the unit i is greater than or equal to 80 and the criticality level of the equipment is greater than or equal to 70. This constraint is added for units with high wear because of the high possibility of equipment failure. The reason for limiting the level of criticality is because this maintenance cost must be borne for critical equipment.

4. Results and discussion

Maintenance is costly in terms of generation loss, time, labor and material requirements due to disruption of generation during the process, and is difficult to manage due to the inherent limitations of these components. In this context, MSO problem which is the indispensable first step of maintenance planning was discussed in this study. A HPP with nine units was investigated. In the HPP, which consists of thousands of equipment, electrical equipment was taken into consideration due to the major problems in the transmission of electricity. Optimal maintenance strategies were achieved for a total of 571 equipment. For these results, firstly the wear rate of nine units was calculated by AHP method in order to reveal the difference of wear between the units. Then, the benefit (added value) of the maintenance strategies to the plant was solved by AHP method. Afterwards, criticality levels of the studied equipment were solved by AHP-COPRAS integration. Three different parameters calculated were used in the 0-1 IP model. The objective of the mathematical model is minimization of generation stops. Minimizing generation downtime includes many goals such as minimizing costs, maximizing supply security, and minimizing risk. In this way, a single-goal model was used to reflect a multi-goal structure and a feasible model proposal was obtained. The model, whose canonical form is given in Section 3.4, has 2284 decision vari-

ables and 14 constraint sets. The model was solved by using ILOG CPLEX Studio IDE version 12.8. Optimal results were obtained in 1 second. As the number of equipment handled in this study was quite high, the results of all equipment could not be provided here. Several pieces of equipment with different wear rates and criticality levels were selected. The optimal maintenance strategies of these selected equipment are given in Table 13. All results of the model are given in Appendix B.

When the results of the mathematical model generated by IP method are evaluated, it is seen that if the criticality level of the equipment is greater than 85, all maintenance strategies except for corrective maintenance should be applied. This means that if the equipment is critical to the system, revision, periodic and predictive maintenance should be performed without waiting for equipment failure. This is because when these equipment fail; the unit shuts down and endangers energy supply security. For equipment with a criticality level of 70 to 85, revision, predictive and corrective maintenance strategies should be implemented. This is because this equipment does not cause generation downtime in case of failure, but generation resumes without backup. Operation without back-up (redundancy) poses the risk of generation downtime in case of any failure. In this case, major maintenance, which is revision maintenance, must be performed. In addition, equipment should be monitored continuously by predictive maintenance strategy. This monitoring will allow the equipment to be intervened before failure. In addition, if the equipment fails, corrective maintenance strategy should be applied. However, if the equipment is in one of the units with high wear rate, the probability of failure will be kept to a minimum by applying maintenance periodically instead of corrective maintenance. When equipment with a criticality level of 51 to 70 fails, the unit does not stop, but this may pose a problem in an emergency. For this reason, in order to prevent malfunctions, frequent periodical maintenance can be performed and monitoring the equipment regularly with predictive maintenance will be sufficient. Since equipment with a criticality level of less than 50 does not have any impact on the system –such as unit downtime or operation without backup–, only maintenance strategy that should be implemented is corrective maintenance. There are many academic studies in the literature to reduce maintenance costs and equipment failures in production facilities. Generally, a maintenance strategy that has to be implemented has been determined using a MCDM method for a single piece of equipment [26]. However, most production facilities, such as the hydroelectric power plant under consideration, consist of multiple intertwined equipment or sub-systems. This structure of the facility caused the necessity of determining the maintenance strategy within the system for the maintenance strategies determined by analytical methods to be applicable in the real manufacturing facilities. With this requirement, models providing MSO for more than one equipment have been proposed in the literature. Among these models, Bertolini and Bevilacqua [8], which consider the most equipment in the literature, discussed 10 centrifugal pumps. MSO for up to 14 equipment was performed for HPP [44]. In this study, a MSO was performed for all electrical equipment (571 equipment) in a hydroelectric power plant. Although the equipment features are the same, the wear and tear differences have occurred as a result of different maintenance and generation plans. Since these attrition differences are an important factor in determining the maintenance strategies to be applied, the attrition differences between the units are reflected in the proposed model. This approach has increased both the applicability of the optimal results to the real system and a MSO has been made by considering the attrition rates for the first time in the literature.

5. Conclusion

The main purpose of maintenance activities is to maximize the efficiency and effectiveness of production and increase reliability. This goal makes maintenance not an auxiliary process for production, mak-

Table 13. Optimal maintenance strategies of some equipment

Unit number	Equipment name	Criticality levels	Revision	Preventive	Predictive	Corrective
4	A busbar disconnecter L3 phase	100	✓	✓	✓	
7	Separator motors L3 phase	100	✓	✓	✓	
5	B busbar disconnecter L2 phase	100	✓	✓	✓	
1	Generator rotor	100	✓	✓	✓	
3	Generator stator	100	✓	✓	✓	
8	Main power transformer L1 phase	95.716	✓	✓	✓	
2	Warning transformer	95.716	✓	✓	✓	
5	Bearing Oil Pump Drives	92.62	✓	✓	✓	
1	Internal need transformer	92.254	✓	✓	✓	
8	Transformer bucholz relay	92.156	✓	✓	✓	
7	Transformer overcurrent relay	92.156	✓	✓	✓	
7	Transformer Expansion Tank	91.816	✓	✓	✓	
8	Transformer Expansion Tank	91.816	✓	✓	✓	
2	Slipring and carbon brushes	91.786	✓	✓	✓	
3	Slipring and carbon brushes	91.786	✓	✓	✓	
8	Transformer High Voltage Bushings	90.628	✓	✓	✓	
6	6.3 KV breakers	85.784	✓	✓	✓	
7	Servomotor pressure oil pumps drive motors	82.589	✓		✓	✓
8	Servomotor pressure oil pumps drive motors	82.589	✓	✓	✓	
1	Speed governor pressure oil pumps drive motors	78.305	✓		✓	✓
3	Speed governor pressure oil pumps drive motors	78.305	✓	✓	✓	
7	Speed regulator air compressors drive motors	78.305	✓		✓	✓
8	Speed regulator air compressors drive motors	78.305	✓	✓	✓	
0	Pump 1-2A drive motor	77.275	✓		✓	✓
0	Generator group breaker	75.897	✓		✓	✓
0	Deep well pump-1 drive motor	70.265	✓		✓	✓
0	BCT 19 (6.3 MVA) transformer	70.006	✓		✓	✓
0	BCT 22 (6.3 MVA) transformer	70.006	✓		✓	✓
0	High Pressure Air Compressor Drive Motors-a1	64.918		✓	✓	
0	220 V DC accumulators	59.9		✓	✓	
1	Cooler-1 fan-1	52.406		✓	✓	
6	Generator rotor lifting high pressure oil pump drive motor	51.923		✓	✓	
8	Generator rotor lifting high pressure oil pump drive motor	51.923		✓	✓	
6	Unpressurized oil tank cooling pump drive motor	51.344		✓	✓	
7	Leakage oil pump drive motor	35.069				✓
8	Exhaust fan drive motor	31.155				✓

ing it one of the basic processes for the production to reach a certain efficiency and efficiency target [36]. The indispensable and first step in managing this main process is MSO. In this context, in this study MSO problem is discussed in one of the large-scale HPP directly acting the Turkey’s energy supply security.

This study includes many combinations of methods to increase the applicability of the problem to a real plant and to increase the level of analytics. In this study consisting of four basic phases, the attrition rate of nine units was calculated by AHP method in order to reflect the differences of identical equipment from each other to the model in the first phase. In the second stage of the study, the added value provided by each maintenance strategy to the power plant was again obtained through the AHP method. In the third stage, the criticality levels of the

equipment discussed in terms of power plants were calculated. In this calculation, AHP-COPRAS integration was used. Finally, using the parameters calculated in these three stages in the IP model, optimal maintenance strategies were obtained for 571 equipment.

Although the proposed model deals with a HPP, various calculations have been made to reflect the dynamics of the system to the model. Although these calculations are made specific to the power plant under consideration, they can be adapted for other enterprises. Because in the model, the wear rate, the added value provided by the maintenance strategies to the system and the criticality levels of the equipment are calculated, and all these parameters are the factors that affect the selection of the maintenance strategy regardless of the system. However, the system under consideration should be analyzed

in detail in order to adapt the proposed model to different businesses. The proposed model is flexible in terms of adapting the specific constraints of the system to the model.

Contrary to the literature, the power plant has been evaluated on a system basis and for the first time in the literature, an optimal solution of such a large problem has been proposed. In addition, due to the different attrition rates between units, a constraint was written according

to the attrition rate and a solution for this situation was produced for the first time in the literature.

In the next stage of this study, mechanical equipment can be included with electrical equipment and the problem size can be increased. This will make it more difficult to obtain an optimal solution, therefore, intuitive approaches can be developed.

Acknowledgements

This study is supported by Kırkkale University Scientific Research Projects Coordination Unit within the scope of scientific research project numbered 2019/087 and 2020/001.

Appendix A

Criteria	The pairwise comparison matrix of the criteria									
when the unit was commissioned		U0	U1	U2	U3	U4	U5	U6	U7	U8
	U0	1	0.333	0.333	0.111	0.2	0.111	0.2	0.111	0.2
	U1	3	1	1	0.125	0.333	0.125	0.333	0.2	0.125
	U2	3	1	1	0.125	0.333	0.125	0.333	0.333	0.125
	U3	9	8	8	1	7	1	7	7	1
	U4	5	3	3	0.14	1	0.143	1	1	0.143
	U5	9	8	8	1	7	1	7	7	1
	U6	5	3	3	0.14	1	0.14	1	1	0.143
	U7	9	5	3	0.14	1	0.14	1	1	0.143
U8	5	8	8	1	7	1	7	7	1	
working time		U0	U1	U2	U3	U4	U5	U6	U7	U8
	U0	1	0.333	0.333	0.125	0.2	0.167	0.2	0.167	0.111
	U1	3	1	1	0.167	0.2	0.2	0.25	0.2	0.143
	U2	3	1	1	0.167	0.333	0.2	0.25	0.2	0.143
	U3	8	6	6	1	5	4	5	4	0.333
	U4	5	5	3	0.2	1	0.25	0.5	0.25	0.167
	U5	6	5	5	0.25	4	1	3	1	0.2
	U6	5	4	4	0.2	2	0.333	1	0.333	0.167
	U7	6	5	5	0.25	4	1	3	1	0.2
U8	9	7	7	3	6	5	6	5	1	
generation quantity		U0	U1	U2	U3	U4	U5	U6	U7	U8
	U0	1	0.333	0.25	0.111	0.25	0.143	0.2	0.167	0.143
	U1	3	1	0.5	0.143	0.5	0.167	0.2	0.167	0.143
	U2	4	2	1	0.167	1	0.2	0.5	0.333	0.25
	U3	9	7	6	1	6	2	5	4	3
	U4	4	2	1	0.17	1	0.2	0.5	0.333	0.25
	U5	7	6	5	0.5	5	1	4	3	2
	U6	5	5	2	0.2	2	0.25	1	0.5	0.333
	U7	6	6	3	0.25	3	0.33	2	1	0.5
U8	7	7	4	0.333	4	0.5	3	2	1	

Appendix B

Equipment number	Revision	Preventive	Predictive	Corrective	Equipment number	Revision	Preventive	Predictive	Corrective	Equipment number	Revision	Preventive	Predictive	Corrective
1-19		✓		✓	193-195	✓	✓	✓		391				✓
20-21	✓	✓	✓		196-197		✓	✓		392	✓	✓	✓	
22-27		✓		✓	198				✓	393	✓		✓	

28-49	✓	✓	✓		199	✓	✓	✓		394	✓	✓	✓	
51				✓	200-217		✓	✓		395-396	✓		✓	
52	✓	✓	✓		218-240	✓	✓	✓		397-399	✓	✓	✓	
53	✓		✓		242-253	✓	✓	✓		400-401	✓		✓	
54	✓	✓	✓		254	✓		✓		402				✓
55-56	✓		✓		255				✓	403	✓	✓	✓	
57-59	✓	✓	✓		256	✓	✓	✓		404-421	✓		✓	
60-61	✓		✓		257	✓		✓		422-444	✓	✓	✓	
62				✓	258	✓	✓	✓		445	✓		✓	
63	✓	✓	✓		259-260	✓		✓		446-457	✓	✓	✓	
64-81	✓		✓		261-263	✓	✓	✓		458	✓		✓	
82-104	✓	✓	✓		264-265	✓		✓		459				✓
105	✓		✓		266				✓	460	✓	✓	✓	
106-117	✓	✓	✓		267	✓	✓	✓		461	✓		✓	
118	✓		✓		268-285	✓		✓		462	✓	✓	✓	
119				✓	286-308	✓	✓	✓		463-464	✓		✓	
120	✓	✓	✓		309		✓	✓		465-467	✓	✓	✓	
121	✓		✓		310-321	✓	✓	✓		468-469	✓		✓	
122	✓	✓	✓		322		✓	✓		470				✓
123-124	✓		✓		323				✓	471	✓	✓	✓	
125-127	✓	✓	✓		324	✓	✓	✓		472-489	✓		✓	
128-129	✓		✓		325		✓	✓		490-526	✓	✓	✓	
130				✓	326	✓	✓	✓		527				✓
131	✓	✓	✓		327-328		✓	✓		528	✓	✓	✓	
132-149	✓		✓		329-331	✓	✓	✓		529		✓	✓	
150-172	✓	✓	✓		332-333		✓	✓		530	✓	✓	✓	
173		✓	✓		334				✓	531-532		✓	✓	
174-185	✓	✓	✓		335	✓	✓	✓		533-535	✓	✓	✓	
186		✓	✓		336-353		✓	✓		536-537		✓	✓	
187				✓	354-376	✓	✓	✓		538				✓
188	✓	✓	✓		377	✓		✓		539	✓	✓	✓	
189		✓	✓		378-389	✓	✓	✓		540-557		✓	✓	
190	✓	✓	✓		390	✓		✓		558-571	✓	✓	✓	
191-192		✓	✓											

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