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SELECTING THE MOST EFFICIENT MAINTENANCE APPROACH USING AHP MULTIPLE CRITERIA DECISION MAKING AT HADITHA HYDROPOWER PLANT

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Hydropower plants are crucial to society. Maintenance becomes vital for the prevention of unforeseen stoppages and a complete breakdown of the machine in a hydropower plant. The deterioration of these assets and the optimal allocation of a limited budget for their maintenance correspond to crucial challenges for hydropower plant utility managers. Decision makers should be assisted with optimal solutions to select the best maintenance. We assess the most popular maintenance approaches, utilizing the Multiple Criteria Decision Making (MCDM) evaluation methodology. Analytic hierarchy process (AHP), an effective method that can solve a multiple criteria decision making problem, was applied to the problem of hydropower plants' maintenance to gain a scientific and objective view on maintenance scheduling.

Keywords: Maintenance, multiple criteria, decision making, AHP

1. INTRODUCTION

Haditha HPP represents an example of our case study because of the severe adverse effect of cavitation in the hydropower plant and also in order to determine how to select the most efficient maintenance approach. This plant is situated on the Euphrates River in Iraq, it contains six vertical type Kaplan turbines, with a unit capacity of 110 MW (Table 1), and currently it is the largest fully operated hydropower plant in Iraq. Due to high energy demand, and with the low flow rates in the

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river, the plant is not at its optimal operating regime, and most of the time below the minimum required water head. These operational conditions resulted in very severe damage due to cavitation. This was manifested by high structural vibration, mainly due to the draft tube vortex, which caused numerous fatigue type failures in several mechanical parts, as illustrated in Figure 1.

Table 1. Haditha HPP Technical Specifications

Type of Turbine	6-K-50
Runner Diameter	6600 mm
Operating Head	H_{max} = 46.6 m H_{min} = 18 m
Unit Flow Rate	Q at H_{max} = 259 m^3/sec Q at H_{min} = 223 m^3/sec
Power:	P_{max} = 110 MW P_{min} = 3 3.5 MW

Fig. 1. Runner blade damage (top) and structural cracks in Haditha HPP (bottom)

Adding to that, the discharge ring and turbine blades underwent severe erosion, due to tip clearance and vortex cavitation, as shown in Figure 2.

If we are to provide a reliable supply of electricity, the equipment installed from the power station through transmission to distribution, needs to undergo regular maintenance. The maintenance crew must inspect equipment at regular intervals and make replacements or repairs with the following objectives:

– to prevent hazardous conditions from arising,
– to maintain or improve plant availability,
– to maintain the efficiency of the equipment, and so optimize fuel consumption and costs.

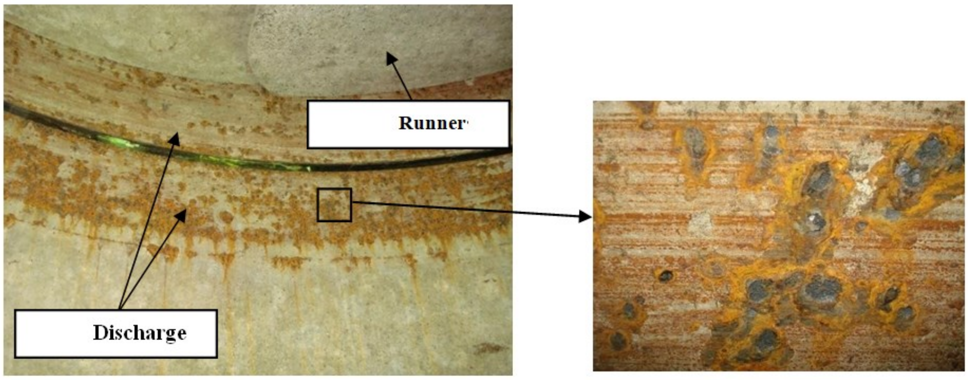


Fig. 2. Severe erosion of the discharge ring in Haditha HPP

We aim to perform the best maintenance possible, achieving the objectives indicated, with the least amount of waste, duplication of effort, waiting time for spare parts, tools, and even clearances and issue of permits to work.

2. MAINTENANCE STRATEGY

2.1. Variants of selecting the most efficient maintenance approach

The following terms are often applied to maintenance activities: breakdown maintenance, corrective maintenance, planned maintenance, preventive maintenance, predictive maintenance, Reliability Centered Maintenance (RCM), running plant inspection and running maintenance.

Breakdown Maintenance

This indeed implies no maintenance or "run to failure". In this situation, the policy of the company management is to run the plant with the very minimum number of personnel, and hope that it keeps running to maximize the return on investment.

If there is a failure and consequent breakdown, the company would likely have to hire a maintenance contractor to perform the necessary overhaul and rebuild (Mobley, 2002). This activity would not only be expensive, but probably would require an extended outage while waiting for the delivery of spare parts. The breakdown may occur ultimately if small defects are not attended to by corrective maintenance.

Corrective Maintenance

One thing we have to remember is that not all maintenance activities can be covered by the preventive maintenance schedule, because incidental defects may occur to items of the plant at any time. Typically, examples are such problems as:

- Leaking pump glands,
- Feed pump re-circulating valve jammed in the open position,
- Boiler tube leak,
- Circulating water pump, high vibration and noise,
- Soot blower leakage.

Some of these items require an outage for correction, for example, the boiler tube leak. Others, such as the circulating water pump problem (Vandagriff, 2001), may require a reduction in output to say, 50%. Other items could be isolated for repair while the plant remains on load. This is especially true where redundant stand-by equipment is available, for example in the case of condensate pumps and feed pumps.

Planned Maintenance

The exact opposite of breakdown maintenance is "planned maintenance". In this case, every item of the plant is listed and dates are selected for specific maintenance tasks to be performed. The master schedule looks ahead for several years (Gulati, Smith, 2009), including repeat inspections of each item of equipment. The time interval between inspections is determined with reference to: Manufacturer's recommendations, Total operating hours and output, Industry standards, where available, Experience with similar equipment, Actual operating mode of the plant, such as base load or two-shift operation, Consequences of failure – that is, its effect on availability.

The main advantage of planned maintenance is that any required outage can be scheduled with load dispatch to provide sufficient lead time to make alternative power generation available on the system (Lai, 2003). Long term planning can also ensure that the required spare parts have been purchased and are available on site. This long term planning also allows manpower requirements to be scheduled and distributed evenly across the time period.

By following a planned maintenance program, every item of equipment is inspected at regularly scheduled intervals. In this manner, degradation of the equipment can be noted and recorded and any necessary repairs or replacements carried out at the same time. It is expected that this activity should help prevent sudden failure or breakdown of the equipment. For this reason, this type of maintenance is also known as preventive maintenance and the acronym P.M. is applied not only to preventive maintenance and planned maintenance, but also to the term "programmed maintenance" (Lenahan, 2006). For each item of equipment, specific P.M. procedures must be prepared, describing in detail the maintenance tasks to be carried out.

Preventive maintenance

There are various definitions of preventive maintenance, but every kind of preventive maintenance using the implementation of preventive maintenance varies. Some applications are limited and contain only lubrication and minor adjustments. Extensive preventive maintenance programs schedule repairs, lubrication, adjustments, and machine rebuilds for all important plant machinery. The normal denominator for many of these preventive maintenance programs may be the scheduling guideline-time. All preventive maintenance administration programs assume that devices will degrade within the right timeframe typical of their unique classification. For example, an individual stage, horizontal split-case centrifugal pump will run 1.5 years before it should be rebuilt normally. Using preventive management methods, the pump will be taken off, rebuilt and serviced after 17 months of operation (Mobley, 2002).

Predictive maintenance

In recent years, attempts have been made to improve the effectiveness of the maintenance effort by refining the preventive maintenance (P.M.) program with the application of:
– Reliability Centered Maintenance (known as RCM),
– Predictive Maintenance.

RCM

Personnel involved in the operation and maintenance of the plant instinctively prioritize maintenance actions according to the criticality of the equipment in question. We aim to preserve the reliability of critical functions. Hopefully this instinctive reasoning is reflected in the maintenance actions and frequency indicated in schedules that we have all helped to prepare, and continue to review and refine.

To ensure that this happens, the RCM procedure provides a formalized approach to preparing or modifying the P.M. program, based on an analysis of probable equipment failures, and consequent outcomes (Eti, Ogaji, Probert, 2007). Each plant system, such as the feed water, main steam, compressed air system, fuel supply, etc. is broken down into components and studied to identify:
– The likely mode of failure for critical items.
– Preventive maintenance tasks and the frequency required to prevent such a failure.
– The effect of the failure of each system component.
– Critical ranking regarding output generation and availability.

It is probable that such a study will discover areas where insufficient maintenance is currently planned, and others which can be reduced or eliminated. The goal is to modify the existing P.M. program with the objective of increasing plant reliability and reducing maintenance costs.

Predictive Maintenance

Using condition monitoring techniques, predictive maintenance determines equipment condition, and aims to identify potential failures before a forced outage occurs. The following case study provides an example (Borris, 2006).

At the same plant, after just a few years of operation, the boilers suffered a repeated number of superheated tube leaks. An investigation showed that this was due to thinning of the tube walls due to high temperature corrosion from the vanadium contained in the fuel ash. The boilers were fired by heavy oil. Some attempts were made to improve the quality of fuel purchased, and several additives were tried. However, the right solution to the outage problem came through the process of condition monitoring.

This activity revolved around measuring the superheated tube wall thickness at the known areas of failure, using ultrasonic testing techniques. This task was carried out at regular intervals when the boilers were taken out of service for cleaning (Eti, Ogaji, Probert, 2007). By measuring the wall thickness and plotting the values on a chart, the prediction could be made of the probable date when the tube wastage would reach its established limit. This allowed the staff to plan and determine which particular tube bends needed to be replaced during the next outage. As a result, the tube-bend spares, tools and manpower could be made available at that time.

When these boilers moved from a six month to a one-year outage interval for cleaning, the tube inspection program continued as before, and so on to this present day, 25 years later. At each annual outage, a certain number of tubes are replaced, based on earlier readings (Woo, Lu, 1981). The overall consequence of applying this type of "predictive maintenance" is that tube failure and, consequently, forced outages are very rare. Thus the economic savings are considerable.

2.2. Criteria for selecting the most efficient maintenance approach

There are many criteria which indicate the most effective maintenance approach at the Haditha hydropower plant. Some of them interfere with each other. As a result, the criteria can be separated into independent criteria as follows:

Personnel resources

A professional crew that can do the required job at a high quality, in a short time, with few numbers (workers) and low costs.

Spare parts resources

Each kind of maintenance needs specific kinds of tools and spare parts. It could be difficult for them to be available for every kind of maintenance during the working groups.

Component states

Means components are groove; or means the worst state of the components.

Failure severity

The degree of failure has to be one of the criteria that should be taken into consideration before selecting the type of maintenance.

Maintenance time

The time of conducting maintenance (season) and the date of high level of power consumption has a real effect on selecting the kind of maintenance. The duration of the maintenance process may be involved with these criteria as well.

Maintenance costs

Each type of maintenance has a particular cost range that differs from others. The level of complexity or ease of the technical process creates the whole maintenance cost.

Maintenance Safety

It includes the safety status for man and machine. The higher the danger, the lower the acceptance of the DM solutions.

3. MULTIPLE CRITERIA DECISION MAKING

3.1. Definition of multiple criteria of decision making

MCDM or MCDA are famous acronyms for multiple-criteria decision making and multiple-criteria decision analysis. MCDM is concerned with structuring and solving decision and planning problems concerning multiple criteria (Belton; Stewart, 2002). The goal is to aid the decisions of manufacturers facing such problems. Commonly, there will not exist a unique optimal solution for such problems in reality, it is necessary to use the decision maker's choices to differentiate between alternatives (Zionts, 2012).

3.2. Steps of decision making

A decision making process involves the following steps to be followed (Boulding et al., 1994; Herrera, Herrera-Viedma, 2000):

1. Identifying the objective/goal of the decision making process.
2. Selection of the Criteria/Parameters/Factors/Decider.
3. Selection of the Alternatives.
4. Selection of the weighing methods to represent importance.
5. Method of Aggregation.
6. Decision making based on the Aggregation results.

3.3. Working principle

The MCDM process follows a universal working principle as described below (Majumder, 2015):

1. Selection of Criteria
   Selected criteria must be:
   – Coherent with the decision,
   – Independent of each other,
   – Represented in the same scale,
   – Measurable,
   – Not unrelated to the alternatives.
2. Selection of Alternatives
   Selected alternatives must be:
   – Available,
   – Comparable,
   – Real not ideal,
   – Practical/Feasible.
3. Selection of the Weighing Methods to Represent Importance
   The weight determination methods can be either compensatory or outrankable.

4. ANALYTIC HIERARCHY PROCESS AHP

4.1. Introduction

AHP has particular application in group decision making and is used around the world in a wide variety of decision situations, in fields such as government, business, industry, healthcare, and education (Petkov, et al., 2007).

Rather than prescribing a "correct" decision, the AHP helps decision makers find one that best suits their goal and their understanding of the problem. It provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions (Xi, Qin, 2013).

Users of the AHP first decompose their decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently.

The elements of the hierarchy can relate to any aspect of the decision problem, tangible or intangible, carefully measured or roughly estimated, well or poorly understood, anything at all that applies to the decision at hand. Once the hierarchy is built, the decision makers systematically evaluate its various elements by comparing them to one another two at a time, with respect to their impact on an element above them in the hierarchy. In making the comparisons, the decision makers can use concrete data about the elements, but they typically use their judgments about the elements' relative meaning and importance (Beria, Maltese, Mariotti, 2012). It is the essence of the AHP that human judgments, and not just the underlying information, can be used to perform the evaluations.

The AHP converts these evaluations to numerical values that can be processed and compared over the entire range of the problem. A numerical weight or priority is derived for each element of the hierarchy, allowing diverse and often incommensurable elements to be compared to one another rationally and consistently (Dezert, et al., 2010). This capability distinguishes the AHP from other decision making techniques. In the final step of the process, numerical priorities are calculated for each of the decision alternatives. These numbers represent the alternatives' relative ability to achieve the decision goal, so they allow a straightforward consideration of the various courses of action (Dulmin, Mininno, 2003).

4.2. Analytical Hierarchy Process (AHP)

The AHP method consists of three levels of hierarchy. The first hierarchy level is the goal of the decision making (Saaty, 2008), the second level of hierarchy is how each of the existing criteria contributes to the goal achievement, and the last level of hierarchy is to find out how each of the alternatives contributes to each of the criteria Figure 3.

There are three basic principles in the AHP method, which are as follows (Saaty, 2008):

– Decomposition

After the problem has been defined, it is necessary to perform a decomposition, which is dividing a problem into some smaller parts. The division process will result in some levels of a problem. That's why this process of analysis is named hierarchy.

– Comparative Judgment

This principle assesses the relative need for two components in a particular level related to the people at more impressive range. This assessment is the primary point of the AHP method because the priority is influenced by its elements. This assessment result can be viewed better if shown using the pairwise comparison atrix.

– Synthesis of Priority

From each Pairwise comparison matrix, the eigenvector value can be determined to obtain local priority. As the pairwise assessment matrix comes in each known level, the global priority can be obtained by synthesizing between those local priorities. The task of synthesizing differs according to each hierarchy. To rank the components in accordance to its family member importance through synthesizing procedure is named priority setting. The ratio-scale form is used as an input in the AHP method, which states one's perception when facing the decision making situation. The values in the ratio are then organized in a matrix, which is called the pairwise comparison matrix. Due to the limitation of human beings' brain capability, the ratio-scale is limited as well. In the AHP method, the scale range of 1–9 is assumed to sufficiently represent human beings' perception. The reason why the AHP method limits the ratio-scale to 1–9 is that research conducted by a psychologist (Arifin, 2011) shows that human beings cannot simultaneously compare more than seven objects, either it increases or decreases two objects. In such conditions, human beings will lose their consistency in making the comparison. The Standard Preference Scale used in the AHP method is provided in Table 2 as follows:

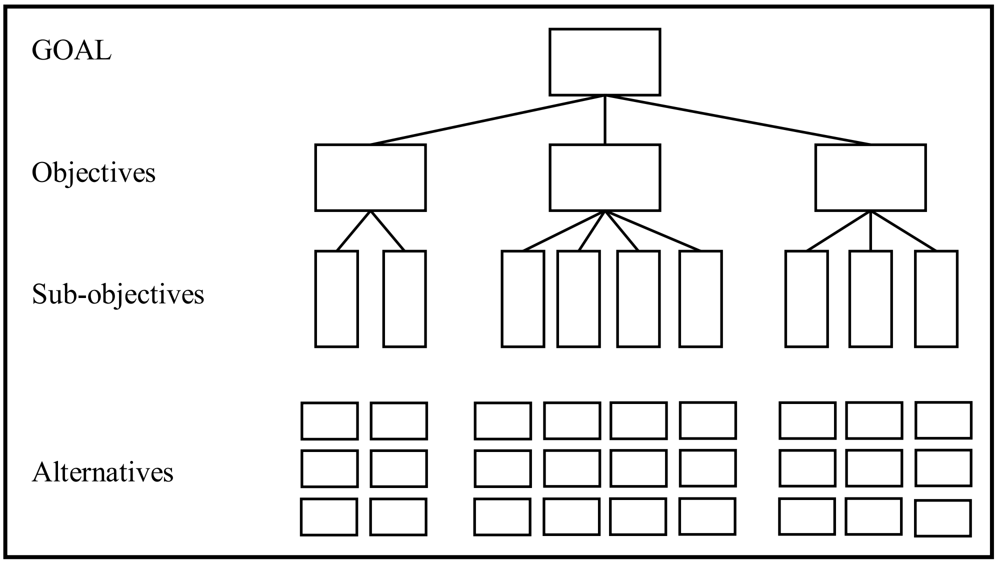


Fig. 3. The Hierarchy level of decision making (Scribd)

Table 2. Preference scale for pairwise comparisons (Scribd)

Preference level	Numerical value
Equally preferred	1
Equally to moderately preferred	2
Moderately preferred	3
Moderately to strong preferred	4
Strongly preferred	5
Strongly to very strongly preferred	6
Very strongly preferred	7
Very strongly to extremely preferred	8
Extremely preferred	9

4.3. Test of Consistency

According to Taylor (Taylor, Bernard, 2002), each human being ideally wants consistent decisions. On the contrary, there are many cases in which the decision makers cannot make perfectly consistent decisions.

The AHP method can tolerate the inconsistency by providing a measurement of assessment inconsistency. This measurement is one of the important elements in the priority determination process according to the pairwise comparison. The higher the consistency ratio, the assessment result becomes more inconsistent. The acceptable consistency ratio is less than or equal to 10 percent, although in some cases the consistency ratio which is higher than 10 percent is still considered acceptable (Arifin, 2011). The Consistency Index (CI) can be calculated by using formula as follows (Taylor, Bernard, 2002):

$$CI = \frac{max.eigenvalue - 1}{n - 1} \quad (1)$$

$$max.eigenvalue = \sum_i w_i c_i \quad (2)$$

After acquiring the Consistency Index (CI), the next step is calculating the Consistency Ratio (CR) by using the formula (3):

$$CR = \frac{CI}{RI} \quad (3)$$

where: n is the amount of items compared, w_i is weight, c_i is the sum of a column, CR is the Consistency Ratio, CI is the Consistency Index, RI is the Random Consistency Index.

The Random Consistency Index (RI) can be observed in Table 3 as follows:

Table 3. Random Consistency Index (Revoledu)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

If $CR \geq 10\%$, the data acquired is inconsistent
If $CR < 10\%$, the data acquired is consistent

The test of consistency result will be beneficial in the AHP method. If the test result is inconsistent ($CR \geq 10\%$), then the result from the AHP method will be of no use in the decision making.

4.4. The Expert Choice software

The Expert Choice software is a multi-objective decision support tool based on the Analytic Hierarchy Process (AHP) (Malczewski, 2006), a mathematical theory first developed at the Wharton School of the University of Pennsylvania by one of Expert Choice's founders, Thomas Saaty (1977). The AHP is a powerful and comprehensive methodology designed to facilitate sound decision making by using both empirical data as well as subjective judgments of the decision-maker(s) (Shahriar et al., 2007).

The AHP assists with the decision making process by providing decision-makers with a structure for organizing and evaluating the importance of various objectives and the preferences of alternative solutions to a decision.

The following are the steps used in AHP and Expert Choice:

– Brainstorm and structure a decision problem as a hierarchical model,
– Set the type and mode of pairwise comparisons or data grid functions,
– Group enable the model,
– Import data to Expert Choice from external databases,
– If applicable, pairwise compare the alternatives for their preference with respect to the objectives, or assess them using one of the following: ratings or step functions, utility curves, or entering priorities directly,
– Pairwise compare the objectives and sub-objectives for their importance to the decision,
– Synthesize to determine the best alternative,
– Perform sensitivity analysis,
– Export data to external databases,
– Perform resource allocations using Expert Choice's 'Resource Aligner' to optimize alternative projects subject to budgetary and other constraints.

Expert Choice includes a unique approach to using pair smart comparisons to de-rive priorities that may more accurately reflect perceptions and ideals than almost all other ways. Professional Choice synthesizes or combines the priorities that are derived for every element of the problem to get the general priorities of the alternatives (Ishizaka, Labib, 2009). By carrying out "what-if" and sensitivity analyses, it could quickly be determined what sort of change in the need for an objective would impact the alternatives of preference. If the results of the decision model differ from the decision-makers' intuition, it is possible to modify the model and/or judgments until the model incorporates this intuition. Then the model results will either change to conform to the "gut" feeling, or the intuition will change based upon the modeling (Schinas, 2005). In the former case, not only the "gut" feeling will be verified, but also a detailed justification will be available if one is required. In the latter case, the decision-makers will have learned something and avoided a costly mistake.

Expert Choice facilitates the synthesis of different peoples' judgments. Expert Choice is also useful for forecasting, assessing risk and uncertainty, and deriving probability distributions.

The model of multiple criteria decision making of equipment maintenance in Haditha hydropower station can generally be divided into three levels: goals and objectives, criteria based on the mentioned goal, and alternatives that should be compared in relation to the criteria (Figure 4).

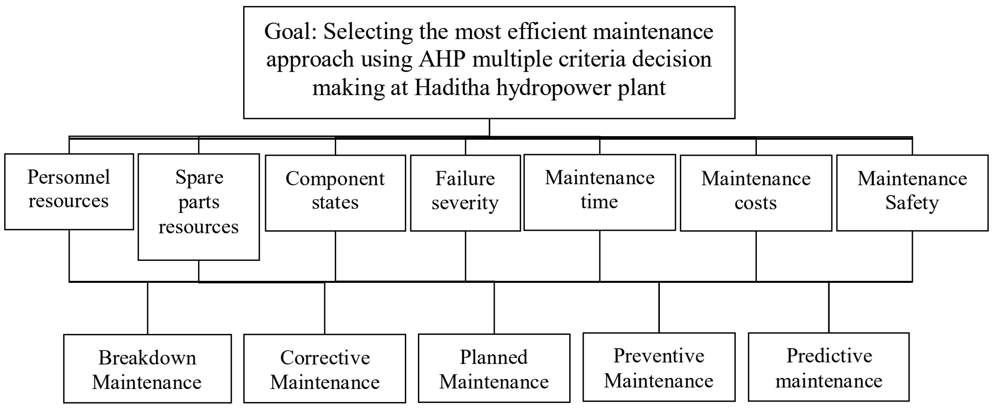


Fig. 4. Structuring of AHP

4.5. Using the Expert Choice software

The main steps of EC software are as follows:

Finding the overall levels of the hierarchy structure (goals, criteria concerning the mentioned goals and the alternatives according to the criteria). If there are sub-criteria for each root of the main criteria, it should be branched (Figures 5, 7).

Conducting the pairwise comparison of the criteria with respect to goals. It can be done numerically from 0–9. The comparison can also be done visually by sliding the pointer to which criteria are more important than the others as shown in Figure 6.

Making the pairwise comparison of alternatives with respect to each one of the mentioned criteria (one by one) as shown in Figures 8–14.

Synthesizing results to obtain sensitivity graphs (Figures 15–19) in order to see the optimum compromise solution.

It is very important to take into consideration the number of inconsistencies after submitting each number of comparison. It should not exceed 0.1 as an overall value for each matrix.

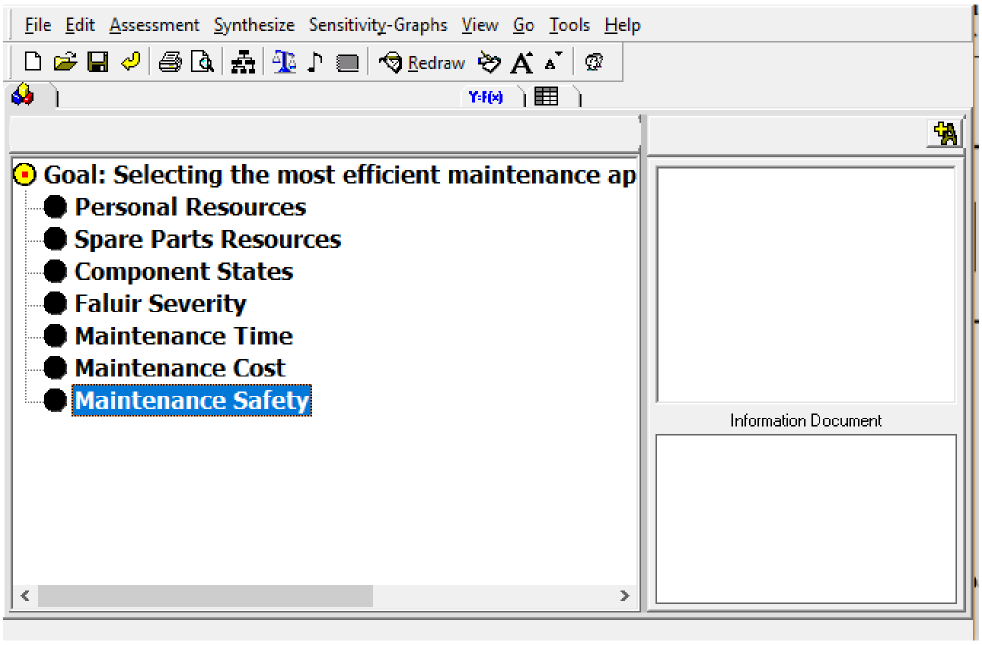


Fig. 5. Submitting goals and criteria

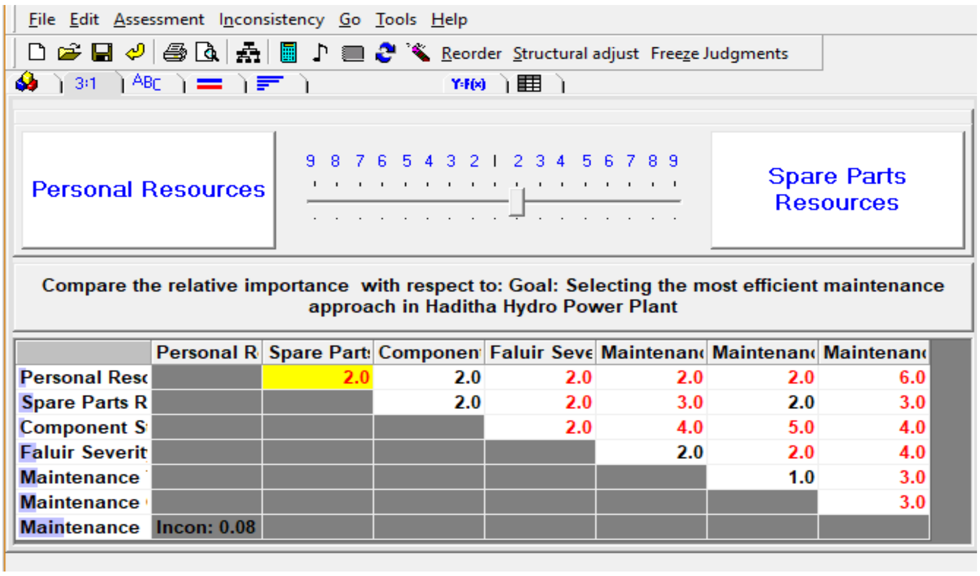


Fig. 6. Pairwise comparison of criteria

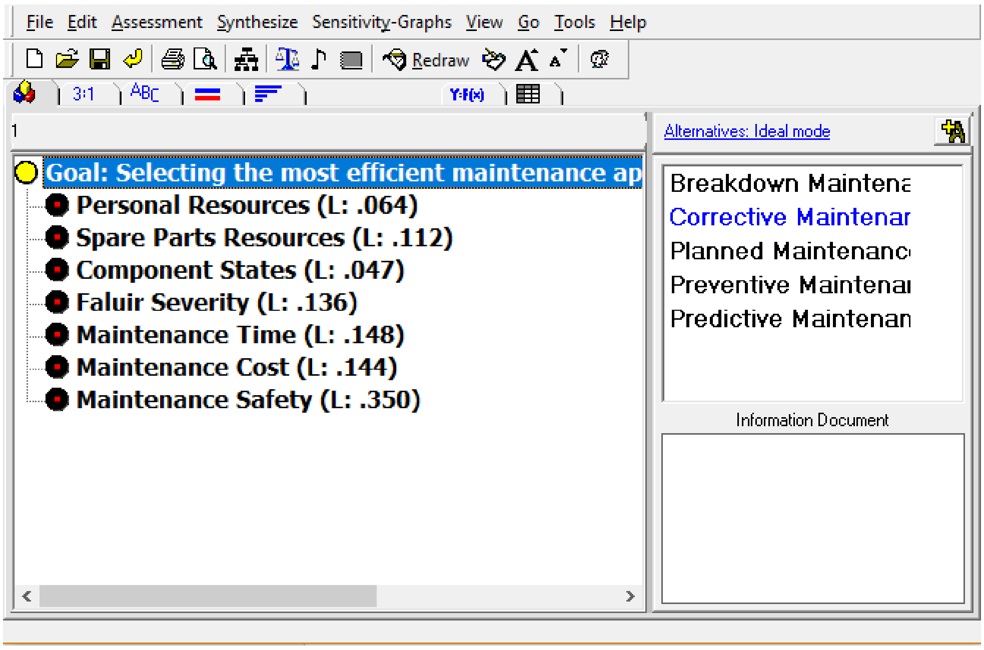


Fig. 7. Submitting alternatives

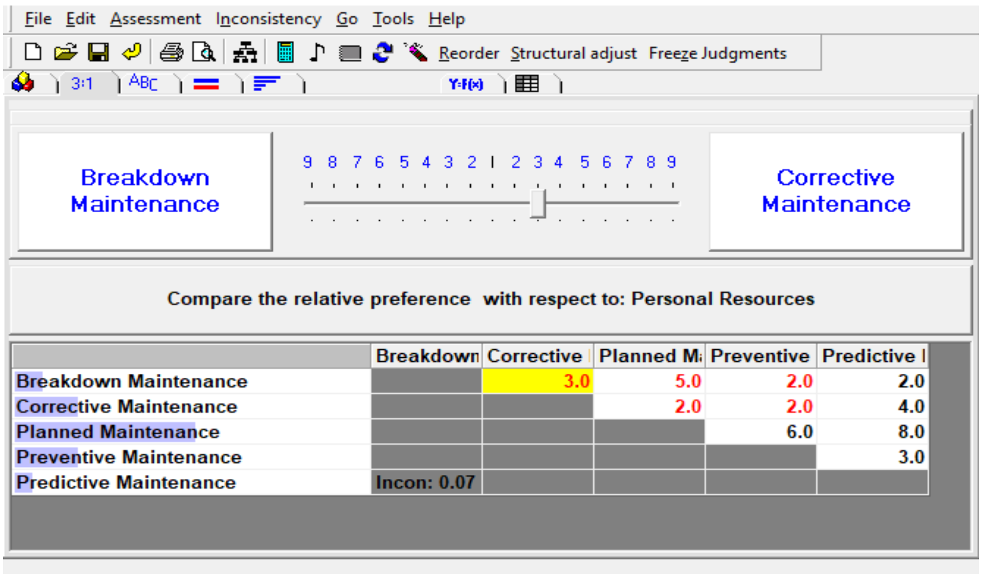
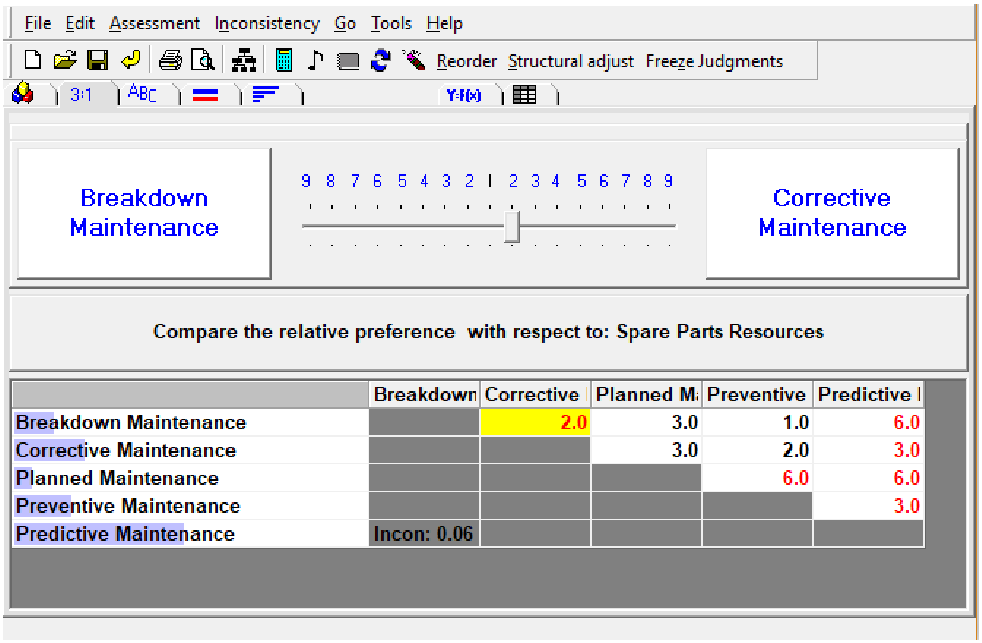
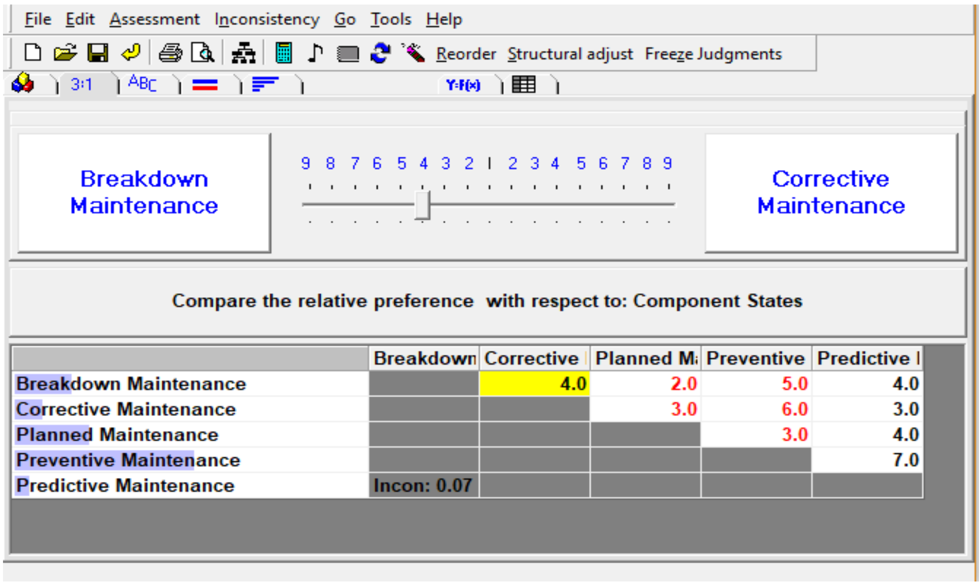


Fig. 8. Alternative comparison with respect to personal resources



	Breakdown	Corrective	Planned M	Preventive	Predictive I
Breakdown Maintenance		2.0	3.0	1.0	6.0
Corrective Maintenance			3.0	2.0	3.0
Planned Maintenance				6.0	6.0
Preventive Maintenance					3.0
Predictive Maintenance	Incon: 0.06				

Fig. 9. Alternative comparison with respect to spare parts



	Breakdown	Corrective	Planned M	Preventive	Predictive I
Breakdown Maintenance		4.0	2.0	5.0	4.0
Corrective Maintenance			3.0	6.0	3.0
Planned Maintenance				3.0	4.0
Preventive Maintenance					7.0
Predictive Maintenance	Incon: 0.07				

Fig. 10. Alternative comparison with respect to component states

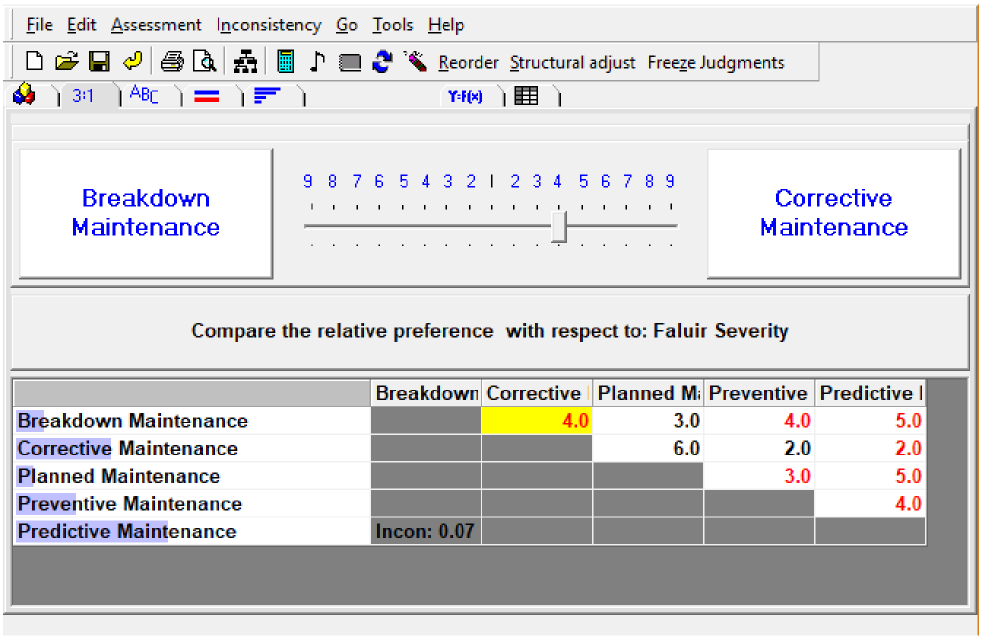


Fig. 11. Alternative comparison with respect to failure severity

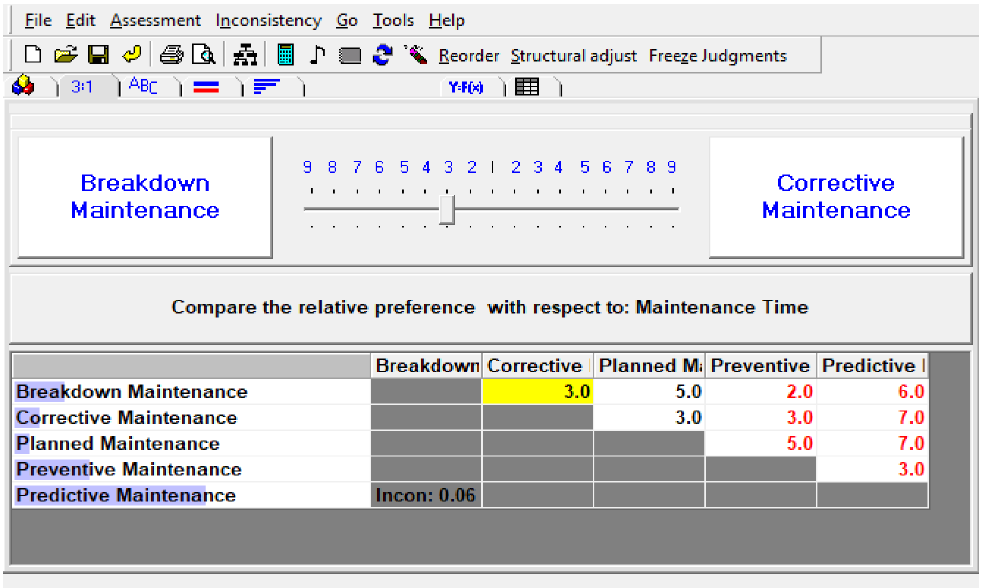


Fig. 12. Alternative comparison with respect to maintenance time

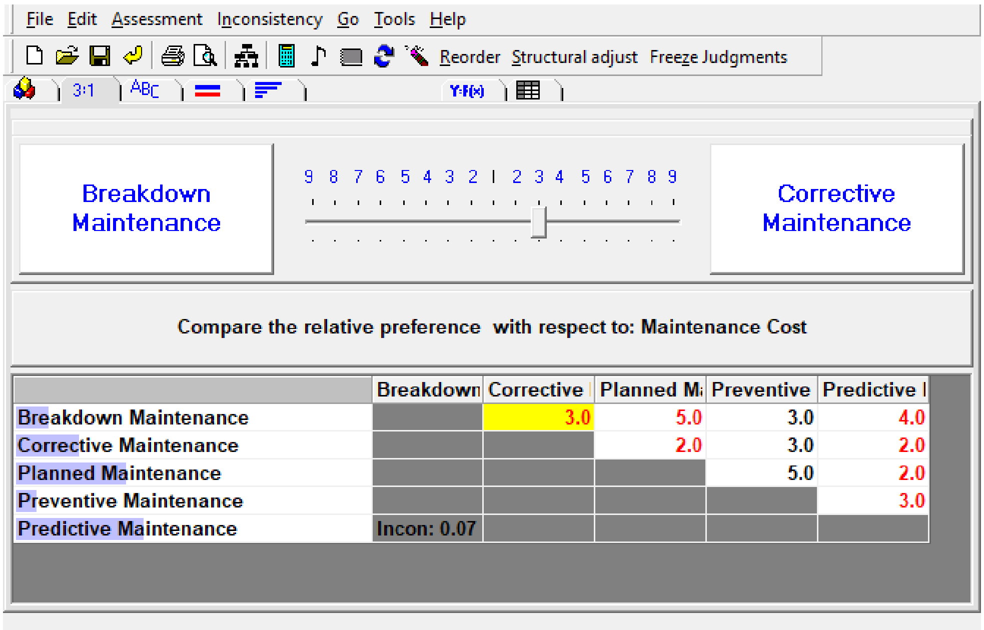


Fig. 13. Alternative comparison with respect to maintenance cost

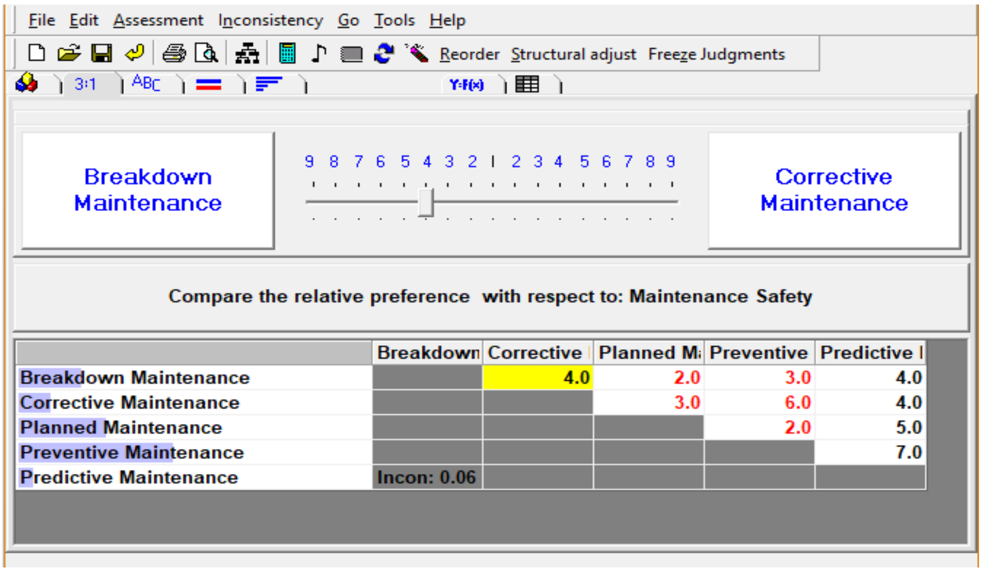


Fig. 14. Alternative comparison with respect to maintenance safety

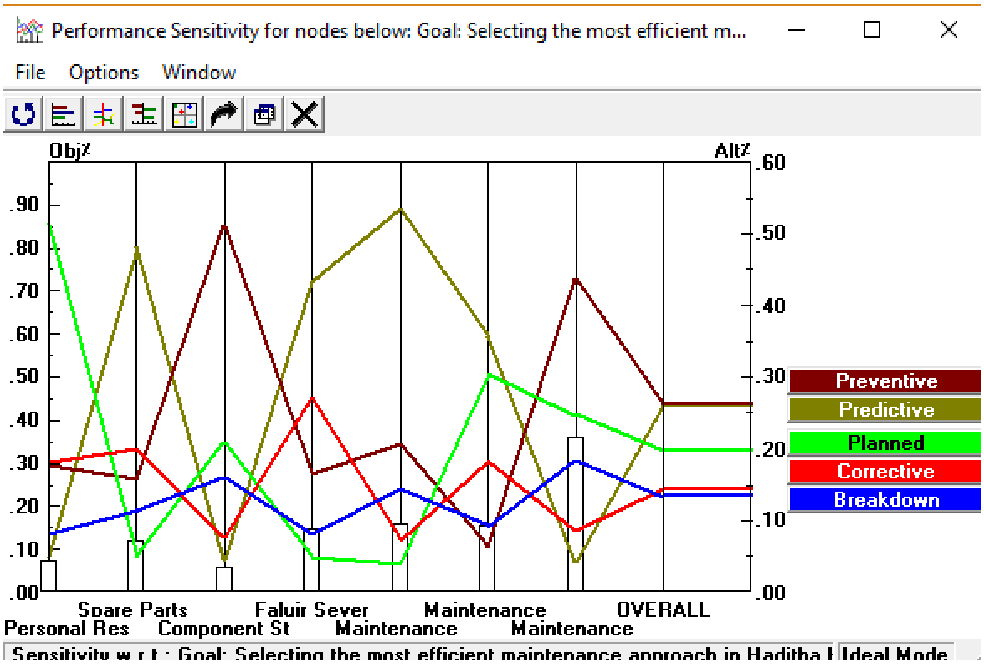


Fig. 15. Performance sensitivity

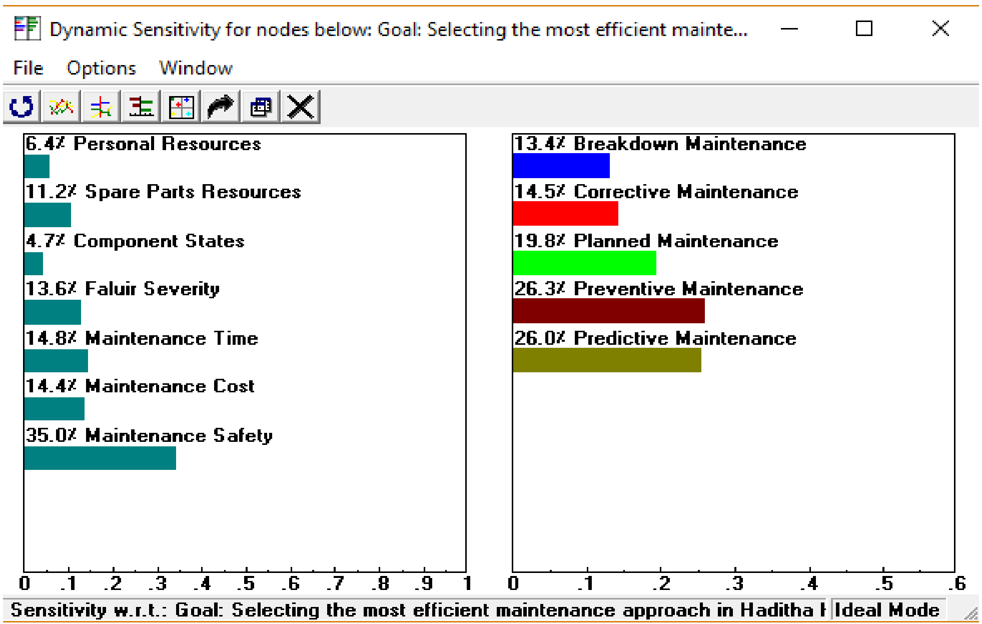


Fig. 16. Dynamic sensitivity

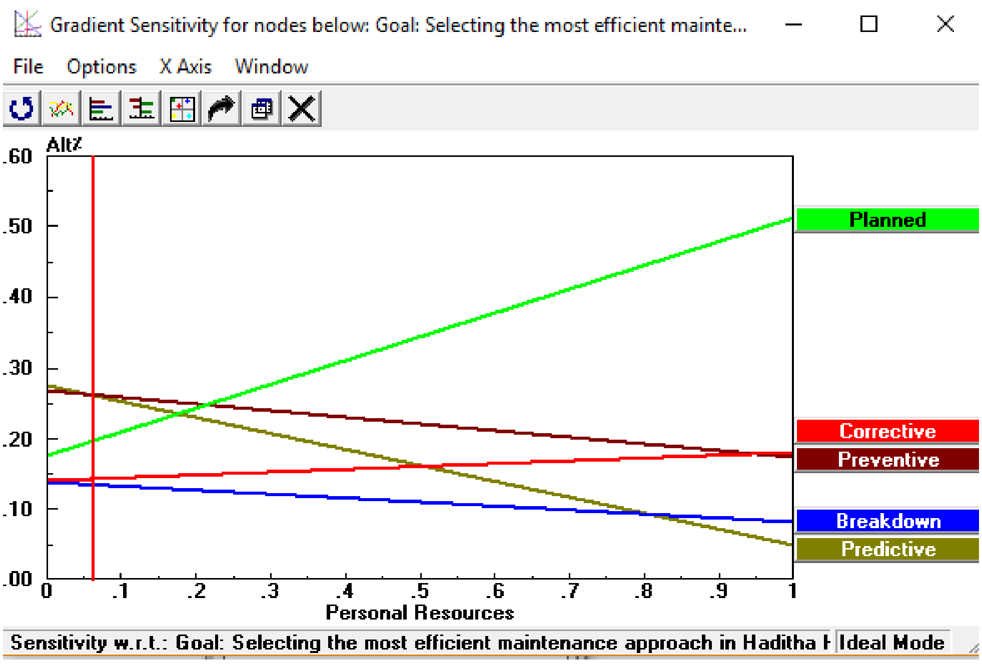


Fig. 17. Gradient sensitivity

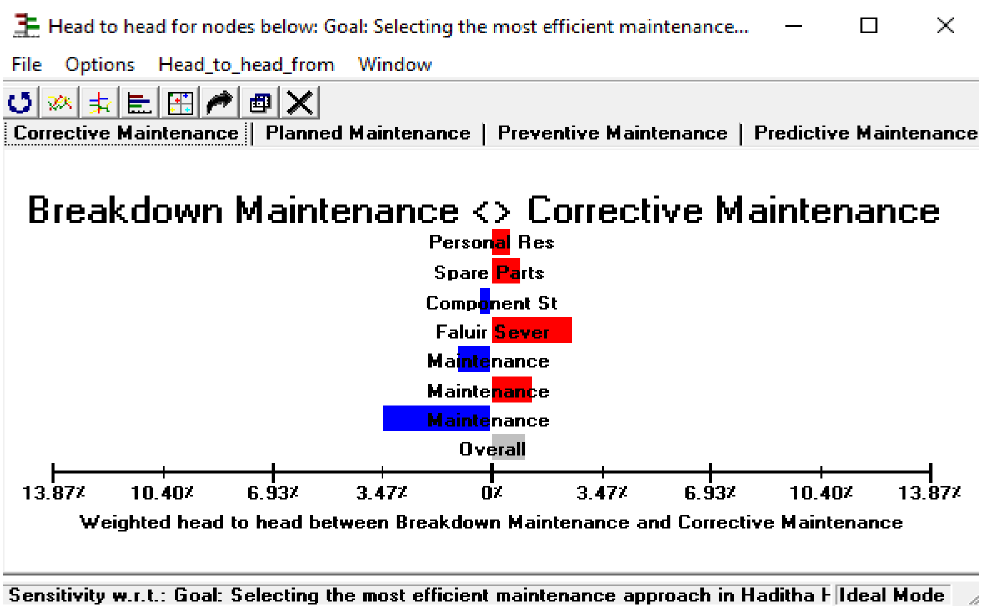


Fig. 18. Head to head

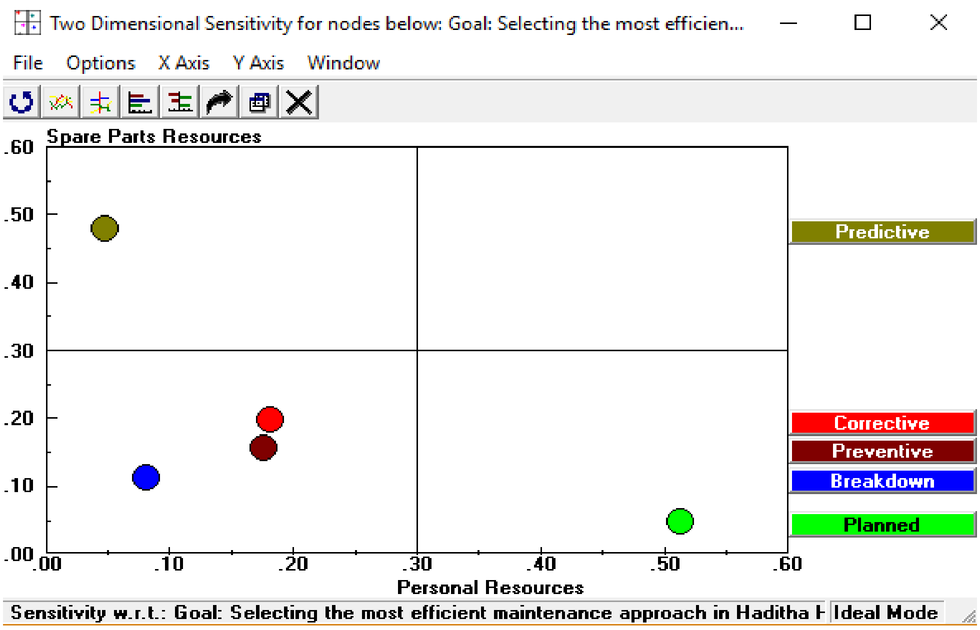


Fig. 19. Dimensional sensitivity

Sensitivity analyses indicate four types of results:

– The most compromise alternative with respect to the current relative importance of criteria.
– Rank Changes in alternatives if the relative importance of the main criteria has changed.
– Rearrange the alternatives with respect to only one selective kind of criteria.
– Comparing indications with respect to two certain criteria (head to head).

Accordingly, preventive maintenance is the most efficient type of maintenance when compared to the other four alternatives of maintenance performance types (Fig. 15). With respect to the personal resources criteria (which has about 6.4% of the overall criteria weight) (Fig. 16), the arrangement of the importance of alternatives shows that planned maintenance is the most important alternative (Fig. 17). In the same way, predictive maintenance is the best choice relative to personal criteria (Fig. 19).

5. CONCLUSIONS AND SUGGESTIONS

Based on the analysis of the research results, it was found that there is no clear, predominating solution among the four alternatives. It seems that the two kinds of (predictive and preventive) maintenance have to be more converged of about 26% of the total percentage. Planned maintenance seems to be more accepted in the case of emphasis on personal resources criteria. The inconsistency numbers for the six matrixes are (0.08, 0.07, and 0.06) that means the comparison process was rational as much as possible. In order not to be confused, the number of matrixes for all the processes could be indicated as follows:

$$\text{Number of Matrixes} = A + B + C$$

where: A is number of criteria, B is number of sub-criteria groups and C is SUM (sub-criteria units + criteria units that have no sub-criteria). EC software gives the facility the ability to amend the DM solution in case of any change or update to the criteria ranking.

Maintenance, like any other operations management entity, requires its decisions to be made in a multi-criteria environment. It needs coordination between various functional groups like production and maintenance, since it is a support function for production activity. In the present paper, this follows a case study at Haditha hydropower station.

Maintenance costs are a significant part of the total operating expenses of all manufacturing or production plants, therefore the most efficient maintenance approach is predictive maintenance. To follow the principles of predictive maintenance we should apply condition monitoring in our plant (Haditha hydropower station).

For long-term research regarding maintenance, it's advocated to place other variables under consideration in order to be able to develop much better measurement criteria that may be an alternative solution concept in hydropower plant maintenance.

LITERATURE

Arifin, A.Z. (2011). The analytical hierarchy process (AHP) method for stocks rank. In *Proc. Cambrige Business & Economics Conference*, 1-26.

Belton, V., Stewart, T. (2002). *Multiple criteria decision analysis: an integrated approach.* Springer Science & Business Media.

Beria, P., Maltese, I., Mariotti, I. (2012). Multicriteria versus Cost Benefit Analysis: a comparative perspective in the assessment of sustainable mobility. *European Transport Research Review*, 4(3), 137-152.

Bhushan, N., Rai, K. (2007). *Strategic decision making: applying the analytic hierarchy process*. Springer Science & Business Media.

Borris, S. (2006). *Total productive maintenance.* New York: McGraw-Hill.

Boulding, W., Moore, M.C., Staelin, R., Corfman, K.P., Dickson, P.R., Fitzsimons, G., Weitz, B.A. (1994). Understanding managers' strategic decision-making process. *Marketing Letters*, 5(4), 413-426.

Cheng, J.H., Lee, C.M., Tang, C.H. (2009). An application of fuzzy Delphi and fuzzy AHP on evaluating wafer supplier in semiconductor industry. *WSEAS Transactions on Information Science and Applications*, 6(5), 756-767.

Dezert, J., Tacnet, J.M., Batton-Hubert, M., Smarandache, F. (2010). *Multi-criteria decision making based on DSmT-AHP. In BELIEF 2010: Workshop on the Theory of Belief Functions*. Belief Functions and Applications Society (BFAS), 8-p.

Dulmin, R., Mininno, V. (2003). Supplier selection using a multi-criteria decision aid method. *Journal of Purchasing and Supply Management*, 9(4), 177-187.

Eti, M.C., Ogaji, S.O.T., Probert, S.D. (2007). Integrating reliability, availability, maintainability and supportability with risk analysis for improved operation of the Afam thermal power-station. *Applied Energy,* 84(2), 202-221.

Gulati, R., Smith, R. (2009). *Maintenance and reliability best practices.* Industrial Press.

Herrera, F., Herrera-Viedma, E. (2000). Linguistic decision analysis: steps for solving decision problems under linguistic information. *Fuzzy Sets and Systems*, 115(1), 67-82.

Ishizaka, A., Labib, A. (2009). Analytic hierarchy process and expert choice: Benefits and limitations. *Or Insight*, 22(4), 201-220.

Lai, L.L. (2003). Power utility deregulation – what is its future? Sixth International Conference on Advances in Power System Control. *Operation and Management ASDCOM 2003* (Conf. Publ. No. 497), 2003, DOI: 10.1049/cp:20030556, 7-19.

Lenahan, T. (2006). *Turnaround, shutdown and outage management: Effective planning and step-by-step execution of planned maintenance operations.* Elsevier.

Majumder, M. (2015). *Multi criteria decision making. In Impact of urbanization on water shortage in face of climatic aberrations*. Springer Singapore, 35-47.

Malczewski, J. (2006). GIS-based multicriteria decision analysis: a survey of the literature. *International Journal of Geographical Information Science*, 20(7), 703-726.

Mobley, R.K. (2002). *An introduction to predictive maintenance.* Butterworth-Heinemann.

Petkov, D., Petkova, O., Andrew, T., Nepal, T. (2007). Mixing multiple criteria decision making with soft systems thinking techniques for decision support in complex situations. *Decision Support Systems*, 43(4), 1615-1629.

Revoledu, http://www.people.revoledu.com/kardi/tutorial/AHP/index.html.

Saaty, T.L. (2008). Decision making with the analytic hierarchy process. *International journal of services sciences*, 1(1), 83-98.

Schinas, O.D. (2005). *Application of multi criteria decision making techniques in finance: the case of the Greek coastal shipping companies* (Doctor-al dissertation, Doctoral Dissertation, Division of Ship Design and Maritime Transport, School of Naval Architecture & Marine Engineering, National Technical University of Athens).

Scribd, http://www.s.scribd.com/doc/2908406/Modul-6-Analytic-Hierarchy-Process/21 June 2009.

Shahriar, K., Bakhtavar, E., Saeedi, G., Akbarpour, S. (2007). A new numerical method and AHP for mining method selection. In *Proc. 4th Int. Symp, on 'High performance mine production'.* Aachen, Germany, May, International Mining Symposia, 289-306.

Taylor III, Bernard W. (2002). *Management Science* (seven edition). New Jersey: Pearson Prentice-Hall.

Vandagriff, R. (2001). *Practical guide to industrial boiler systems.* CRC Press.

Woo, H.H., Lu, S.C. (1981). *Worldwide assessment of steam-generator problems in pressurized-water-reactor nuclear power plants (No. UCRL-53032).* Lawrence Livermore National Lab., CA (USA).

Xi, X., Qin, Q. (2013). Product quality evaluation system based on AHP fuzzy comprehensive evaluation. *Journal of Industrial Engineering and Management*, 6(1), 356.
Zionts, S. (2012). *Multiple criteria decision making. In Multiple Criteria Decision Making Theory and Application: Proceedings of the Third Conference Hagen/Königswinter, West Germany*, August 20-24, 1979, 177, Springer Science & Business Media, 150

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WYBÓR NAJBARDZIEJ EFEKTYWNEJ STRATEGII UTRZYMANIA W ELEKTROWNI WODNEJ HADITHA Z WYKORZYSTANIEM WIELOKRYTERIALNEJ METODY WSPOMAGANIA DECYZJI AHP

Elektrownie wodne mają kluczowe znaczenie dla społeczeństwa. Konserwacja staje się niezbędna w zapobieganiu nieprzewidzianym przestojom i całkowitemu uszkodzeniu maszyn w elektrowni wodnej. Pogorszenie stanu tych zasobów i optymalna alokacja ograniczonego budżetu na ich utrzymanie odpowiadają najważniejszym wyzwaniom dla zarządców zakładów energetyki wodnej. Decydenci powinni być wspierani optymalnymi rozwiązaniami, aby wybrać najlepszą strategię obsługi. W artykule opisano najbardziej popularne metody konserwacji, a następnie dokonano ich oceny wykorzystując wielokryterialną metodę wspomagania decyzji (MCDM). Analityczny proces hierarchiczny (AHP), to skuteczna metoda, która może rozwiązać problem podejmowania decyzji, na którą ma wpływ wiele składowych. Zaproponowano wprowadzenie tej metody do wyboru sposobu obsługi elektrowni wodnych w celu uzyskania naukowego i obiektywnego harmonogramu konserwacji.

Słowa kluczowe: utrzymanie, metody wielokryterialne, podejmowanie decyzji, AHP