# Handling maintenance priorities using multi criteria decision making

D. E. Nordgård, J. Heggset and E. Østgulen

*Abstract:* **This paper presents an analysing strategy for prioritising a power company's different types of maintenance projects. Qualitative criteria, such as for instance safety for personnel and effect on the environment, together with the economic figures, form the decision framework. The handling of qualitative criteria is assisted using the AHP (Analytic Hierarchy Process) method to structure the decision criteria and to obtain the relative weighting between different criteria. The analysing strategy is demonstrated by using case studies from maintenance decisions in hydropower plants.**

***Index terms: Maintenance planning, Multi Criteria Decision Making, Hydroelectric power generation, Power generation maintenance***

## I. Introduction

In the beginning of the 1990's the Norwegian power sector became deregulated. Both the electricity production and distribution industries have gone through substantial changes since then. The sector has experienced a sharp decrease in the development of new power stations and reinforcement of distribution systems. Thus, the average age of the components in the systems is increasing.

This has lead to increased focus on strategies for maintenance of the components in the production and distribution systems. This is due to the need to extend component lifetimes and thus reducing the amount of reinvestments.

When deciding which projects to run, there are other considerations to be taken besides the economic optimisation of investment and operation costs. These are often hard to quantify in monetary terms, however, they will inevitably appear within the decision frame. Aspects such as safety to personnel, working environment and environmental effects will play a part in the overall decision. This paper presents a methodology for handling such a complex optimisation problem. The method is demonstrated by the use of relevant examples from hydropower maintenance. Examples of methods dealing with these kinds of problems have also been developed in earlier research projects and PhD work, [1,2,3].

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Dag Eirik Nordgård and Jørn Heggset are with SINTEF Energy Research, N-7465 Trondheim, Norway. (E-mail: Dag.E.Nordgard@sintef.no, Jorn.Heggset@sintef.no)

Even Østgulen is with BKK Production, Bergen, Norway. (E-mail: Even.Ostgulen@bkk.no)

## II. Maintenance planning of hydro power stations

During the last few years, various decision support tools and methods for maintenance optimisation of hydropower plants have been developed in Norway. Each of these modules solves separate parts of the problem and the results from each module are integrated in order to optimise the timing of the maintenance projects.

Within this concept there is a module for computation of losses from disrupted production caused by outages, a module for computation of production losses during maintenance, a module for specification of unit (e.g. turbine, generator and control system) failure probabilities as functions of time, and a module for handling of qualitative criteria (which is the main focus of this paper). All these parts are supposed to provide input to the module for optimal timing of the maintenance projects (not yet developed). The concept is outlined in Fig. 1.

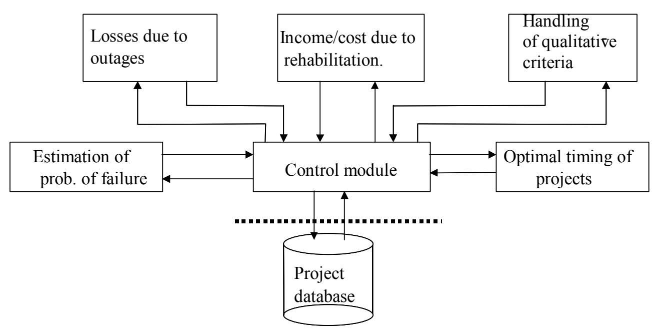


Fig. 1. Integrated model for maintenance planning

In order to be successful, the integrated model has to be closely linked to a company's project database. This is achieved through a (not yet) specified format for exchange of data between the control module and the project database.

The purpose of all the modules, except the module for handling of qualitative criteria, is to obtain data to be used in the economic analysis of the projects. The purpose of the module for handling of qualitative criteria is to substantiate important aspects that cannot easily be quantified in monetary terms. A way of combining the qualitative and economic analyses is presented in Fig. 4.

## III. The Challenge

The production and distribution companies will normally have a relative larger number of maintenance projects in their project portfolio. These must be given priorities within given constraints. These constraints can be economical or they may be caused by limitations in other resources (labour and/or time). The projects will be of various sizes and types, and they may be launched for a number of different reasons. One reason will typically include economic benefits due to the project, however, the decision to initiate a project may also be based on conditions such as safety for personnel or public, working environment, environmental concerns, or any combination of these.

All the latter criteria are so-called “qualitative criteria”, and are characterised by the fact that the impact on each of them is hard to quantify, at least in monetary terms. Thus, a holistic evaluation scheme for the maintenance projects including all relevant criteria is not easily available.

The overall challenge described in this paper is to find ways to compare different projects, with respect to both economical and qualitative criteria, to gain a prioritised project list based on a set of strategically accepted company criteria. Multi Criteria Decision Making (MCDM) has been used as a framework for supporting this task.

## IV. Analysing Strategies

The approach described in this paper is based on two separate evaluation processes, one for qualitative criteria and one for economical criteria. By combining the results from these analyses one get a more complete basis for the decision.

### *A. Handling qualitative criteria*

To aid the inclusion of qualitative criteria into the decision process, MCDM-methods can be useful, and there exist a number of methods developed during the last decades supporting MCDM in different ways [6,7].

In the project activities described in this paper the *Analytic Hierarchy Process* (AHP) developed by Saaty [8] has been used to structure the qualitative criteria. The main reasons for choosing this method are that:

- It is intuitive, easily understandable and applicable.
- The user threshold for the method is low. This is important because one cannot expect the typical user to be an expert in MCDM tools.
- The results obtained from using the method corresponds with the user’s intuitive perception of the problem analysed.

### *B. Basics of the AHP method*

When the qualitative criteria to be used have been identified, the AHP method is used for pairwise comparison of these criteria.

For the comparison the numerical / verbal scale shown in Table I is used, [2,5,8].

Table I
The ratio scale for pairwise comparison of the AHP method

| **Numerical value** | **Description** |
|---|---|
| 1 | *Equal* |
| 3 | *Slightly preferred* |
| 5 | *Strongly preferred* |
| 7 | *Very strongly preferred* |
| 9 | *Extremely preferred* |

The comparisons are structured in an evaluation matrix, $A_C$, as illustrated in Table II.

Table II
Evaluation matrix, $A_C$, from pairwise comparison using the AHP-method

| ***Criteria*** | $C_1$ | $C_2$ | $C_3$ | .. | $C_n$ |
|---|---|---|---|---|---|
| $C_1$ | *1* | $p_{12}$ | $p_{13}$ | .. | $p_{1n}$ |
| $C_2$ | $p_{21}$ | *1* | $p_{12}$ | .. | $p_{2n}$ |
| $C_3$ | $p_{31}$ | $p_{32}$ | *1* | .. | $p_{3n}$ |
| .. | .. | .. | .. | *1* | .. |
| $C_n$ | $p_{n1}$ | $p_{n2}$ | $p_{n3}$ | .. | *1* |

where

- $p_{ij}$ = rating of criterion $i$ compared to criterion $j$ {1/9,9}
- $p_{ij} = 1/p_{ji}$
- $p_{ii} = 1$

The relative weight between the criteria is now calculated as the normalised eigenvector, w, of the evaluation matrix that corresponds to the largest eigenvalue, $\lambda_{max}$.

$$A_C \cdot w = \lambda_{max} \cdot w \tag{1}$$

The normalised eigenvector gives the relative percentage weight of each criterion, so that the sum of the weights of the criteria equals 100 %.

$$\sum_{i=1}^{n} w_i = 1 \tag{2}$$

For each criteria there must be established a scale that the projects can be measured by. These scales can be hard to quantify due to the nature of the criteria, and one will often have to use verbal descriptions instead of rigid defined quantities. The scales give the relation between the evaluated projects and their fulfilment of the criterion – from irrelevance (*score 0*) to full compliance (*score 1*) on the given criterion.

*Example of scale for the criterion Safety:*
The following scale can be used when evaluating projects that may have impact on safety for personnel or public:

- *0 - No impact on safety*
- *0,1 – Little impact on safety*
- *0,4 – Some impact on safety*
- *0,9 – Significant impact on safety*
- *1,0 – Very large impact on safety*

Prior to using this rather informal scale, the company should consider performing a risk evaluation, to analyse and classify the project's impact on the given criterion.

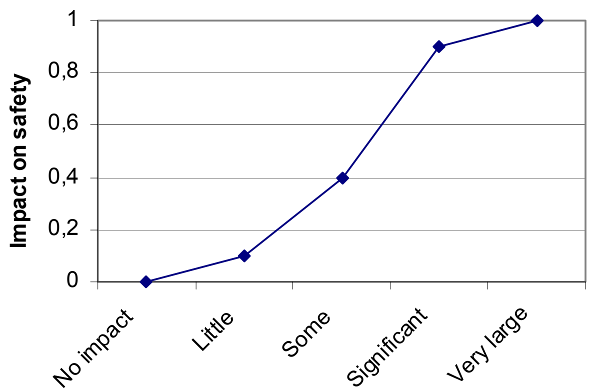


Fig. 2. Example: Scale for a project's impact on safety

*C. Stages in structuring the handling of qualitative criteria*

The process of identifying and weighting the qualitative criteria for evaluation of project proposals can be summarised in three main steps:

- Identification of which decision criteria to include in the model.
- Establishing the relative weights between the criteria, using the AHP method.
- Establishing scores/scales for each criterion.

These steps lead to *the decision model*, which can be used to evaluate different projects. Fig. 3 shows the schematic structure of a model handling qualitative criteria. The model has $n$ criteria with their respective weight, $w_n$, and a scale established for each criterion.

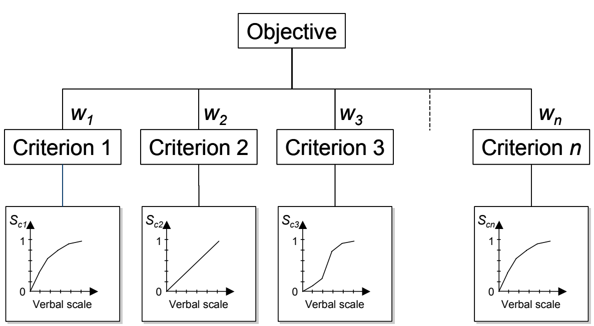


Fig. 3. Structure of model for handling of qualitative criteria

The qualitative utility value, QUV, for a project evaluated using this model can now be expressed as:

$$Qualitative\ \ utility\ \ value = \sum_{i=1}^{n} S_{Ci} \cdot w_i \qquad (3)$$

where

- $S_{Ci}$ is the project's score on criterion $i$
- $w_i$ is the weight of criterion $i$

*D. Economic calculations*

The net present value (NPV) of the project is obviously important when evaluating a project. The NPV could be treated as one of the criterions handled by the AHP method, where the NPV is given a relative weight compared with other criteria. However, in our approach we have not included the economical criteria when using the AHP method. In our opinion, it is better to do two separate analyses and thereafter combine the economic and qualitative figures (as outlined in section E).

An economic analysis of a maintenance project is often performed with a minimum cost approach. We have chosen a different strategy: In order to focus on the profitability of the projects we treat every positive economic effect of a project as an income, including a reduction in failure probability due to the accomplishment of the project. In such a case the income is calculated as the difference in failure probability if the project is carried out or not, multiplied with the expected loss if a failure should occur. Deferment of investments is also regarded as income in our approach.

From this analysing strategy the following cost elements should be taken into account:

- Ressources (labour, spare parts, transport, etc.).
- Unavailability costs during the project.
- Maintenance introduced faults.
- Other costs.

The income side comprises the following elements:

- Increased power efficiency.
- Increased availability (reduced failure probability).
- Deferment of future investments.
- Other incomes.

All these values, some of them being annual, are discounted to the present time and the NPV are calculated.

*E. Combining qualitative and economic analyses*

The overall project evaluation strategy can be illustrated as shown in Fig. 4.

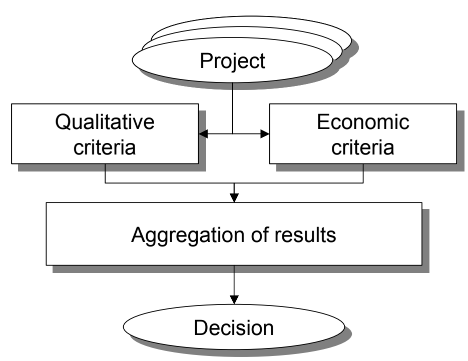


Fig. 4. Structure of project evaluation taking both economic and qualitative criteria into account

Again, the approach chosen involves two separate analyses. The results from the analysis of the qualitative criteria and the economical criteria are combined to achieve a more holistic decision basis for project evaluation. One way of combing the results is to present them in a plot. The Net Present Value and the Qualitative Utility value for the different projects can be plotted, as indicated in figure 5 and shown in figure 7. The most favourable locations in this plot are in the upper right region (+), while the least are in the lower left (÷). Along the other axis indicated in the figure, a choice has to be made between projects with high profitability / low qualitative utility and projects with low profitability / high qualitative utility.

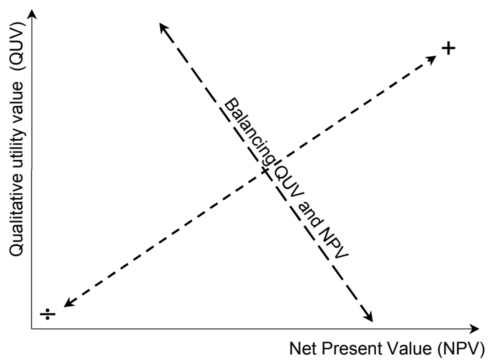


Fig. 5. Sketch of plotting results from qualitative and economic analysis

## V. Example using MCDM methods for maintenance planning

The approach illustrated in Fig. 4 has been tested by a group of five Norwegian power companies. Prior to the testing the companie representatives got a brief introduction to the method. Each company established the criteria to be used, and performed pairwise comparison for these using the AHP-method. Descriptive scales and scores were established, and the method was tested in real project evaluations.

### *A. Establishing the decision model*

The overall goal has been to develop a method/tool that can help power companies' to prioritise their project portfolios. An example of an established decision model from one of the five power producers is shown in Fig. 6..

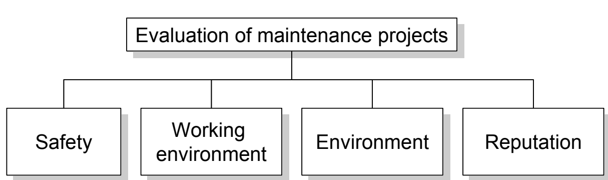


Fig. 6. Decision model for maintenance project evaluation

The pairwise comparison resulted in the evaluation matrix shown in Table III.

TABLE III
EVALUATION MATRIX FROM PAIRWISE COMPARISON USING THE AHP-METHOD

| **Criteria** | **Safety** | **Working env.** | **Environment** | **Reputation** |
|---|---|---|---|---|
| **Safety** | *1* | *7* | *3* | *7* |
| **Working env.** | *1/7* | *1* | *1/3* | *3* |
| **Environment** | *1/3* | *3* | *1* | *3* |
| **Reputation** | *1/7* | *1/3* | *1/3* | *1* |

The eigenvector of this matrix and hence the relative weight of these criteria w is calculated as:

$$w = \begin{cases} 0{,}60 \\ 0{,}11 \\ 0{,}23 \\ 0{,}06 \end{cases} \tag{4}$$

Table IV gives an example on how the results from an evaluation of five projects can be performed. (The scales are not explicitly shown for each criterion in this paper, but the numerical values are used in Table IV).

TABLE IV
EXAMPLE – PROJECT EVALUATION FOR 5 MAINTENANCE PROJECTS

| Projects | Safety | Working environment. | Environment | Reputation | Qualitative utility value | Net present value, [kNOK] |
|---|---|---|---|---|---|---|
| | Weight | | | | | |
| | 0,60 | 0,11 | 0,23 | 0,06 | | |
| 1 - Aggregate | 0 | 0,4 | 0,4 | 0,4 | 0,16 | -30 |
| 2 - Hatch rehab. | 1 | 0,7 | 0,7 | 1 | 0,90 | 1500 |
| 3 - Water level measurement | 0,4 | 0,4 | 0,1 | 0,4 | 0,33 | 40 |
| 4 - Turbine rehab. | 0,9 | 0,1 | 0 | 0 | 0,55 | 2000 |
| 5 - Dam rehab. | 0,9 | 0,7 | 0,4 | 1 | 0,77 | -1000 |

1 € ≈ 7,5 NOK

### *B. Aggregation of results*

Fig. 7 shows a way of presenting results, from both economic and qualitative analyses, forming a perspicuous basis for interpretation of the results.

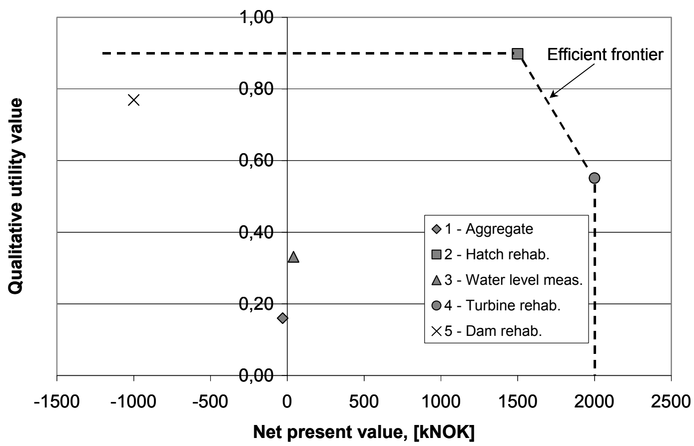


Fig. 7. Example - Presentation of project evaluation results

In Fig. 7 projects 2 and 4 stands out. Project 2 outranks projects 1,3 and 5 due to both higher NPV and higher QUV, i.e. project 2 *dominates* the latter projects. Equally Project 4 dominates projects 1 and 3. The projects, not dominated by any other, form the *efficient frontier* of the set of projects. The most favourable project is among the ones forming this frontier.

The consequence of choosing project 2 instead of 4 is a reduced NVP of -500 kNOK, and an increased QUV of +0,35. The cost per unit QUV is thus 1428 kNOK/Unit QUV. The management responsible for prioritising among the maintenance projects will have to rank these two projects based on this information. If the cost of 1428 kNOK/Unit QUV is too high, then project 4 is the preferred project. However, if the cost is acceptable project 2 should be chosen.

We would like to point out that, in general, all projects with positive NPV should be chosen. However, limited resources can make it necessary to make priorities among these projects as well.

## VI. What can power companies gain from using MCDM?

Choosing the right projects, and initiating the projects at the right time, is essential in order to get the most out of each NOK spent.

All other aspects equal, a power company would prioritise the projects with the highest NPV first. However, in addition to the economic side of each project there are usually other aspects present that will, and should, influence the decision of which projects to initiate.

We believe that MCDM will be a useful tool in helping to take these aspects into account in a systematic and consistent manner. Typically safety, environment and the company's reputation must be taken into account.

We believe that MCDM is an analytic tool that will make it easier to get a complete overview of the criteria involved for each project. The use of MCDM will help compare the projects in the company's project portfolio with respect to all relevant aspects. By using the method we believe that the project analysis will be more consistent, perspicuous, complete and realistic. This will reduce the likelihood of making inexpedient decisions.

The main reasons why MCDM is a preferable method are that:

- The qualitative criteria that have effect on the analysis of a project are given explicit attention.
- It requires a clarification of which aspects to be taken into account when prioritising the company's project portfolio.
- It makes it possible to give a perspicuous representation of both the economic and the qualitative aspects of the projects.
- The results from the project analysis can be systematically documented and the choices that have been made will be lucid and easy to re-examine.

The results from the project analysis will be more consistent, even if the company uses a number of different caseworkers.

Implementing the use of MCDM requires that the decision makers in the company clarify which criteria to be taken into account when prioritising the project portfolio and how the criteria should be weighted. This is the hard part, however, it is quite useful because it helps identify the core elements of the decision problem. Once it is done, it relatively easy to find the QUV for each of the projects in the portfolio.

Again, once the company's MCDM model has been established, one can find the QUV for each project in the portfolio. Because the QUV is built from the score on each criterion, the details underlying the overall QUV can easily be extracted and presented. Furthermore, one can easily do a sensitivity analysis to see how changes in the score on the different criteria will affect the overall QUV.

When the QUV and the calculated NPV of each project are presented in the same plot or list, the decision maker gets a good indication of which projects should be initiated first.

The MDCM model can also be used to compare several alternative solutions for the same project. It will then be easier for the decision maker to see which solution that stands out when both NPV and the QUV for the alternatives have been considered.

## VII. Conclusions

The paper presents a way of evaluating maintenance and reinforcement projects, taking both economic and qualitative values into account. Such projects are generally initiated for a number of different reasons, some of them being qualitative in nature (safety, environment, company reputation, etc.). The approach described in this paper is based on using the AHP method (Analytic Hierarchy Process) when dealing with the qualitative evaluation of projects. This is a method for structuring and weighting different decision criteria. The method seems to be very promising for the purpose of evaluating maintenance projects, at least related to hydropower stations. The main reason for this is that the method makes it possible for a decision maker to treat qualitative elements objectively and systematically.

By using such a method, the qualitative objectives are evaluated in a standardized way. This increases the probability of consistent project evaluation even if different caseworkers and decision makers have evaluated the various projects. This, together with the calculation of all relevant costs and incomes related to the projects, gives the decision maker a more complete basis for prioritising the company's project portfolio.

It must be emphasised that the MCDM method cannot make the decision for the decision maker. However, it is a useful tool to help establish a better basis for complex decisions.

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## IX. Biographies

**Dag Eirik Nordgård**, was born on December 18 1971 in Steinkjer, Norway. He received his MSc degree in electrical engineering from the Norwegian Institute of Technology (NTH), Trondheim, Norway in 1994. He is a research scientist at SINTEF Energy Research, Department of Energy Systems.

**Jørn Heggset** was born on May 11 1962 in Molde, Norway. He received his MSc degree in electrical engineering from the Norwegian University of Science and Technology (NTNU), Trondheim, Norway in 1987. He is a research scientist at SINTEF Energy Research, Department of Energy Systems.

**Even Østgulen** was born on July 27 1965 in Drammen, Norway. He received his BSc degree in electrical engineering from the Iowa State University, USA in 1991 and he completed a Foundation Program in Business Administration at the Norwegian School of Economics and Business Administration, Bergen, Norway in 2000. He is a Spesial Adviser within the field of maintainance at the powercompany BKK Produksjon AS, Bergen, Norway.