DECISION SUPPORT FOR MAINTENANCE AND REFURBISHMENT PLANNING OF HYDROPOWER PLANTS

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Abstract: *The paper presents a concept for maintenance and refurbishment planning in hydropower systems. The concept consists of several modules that can be used separately, and in sum they provide very useful information for the task of ranking and timing maintenance and refurbishment projects. Both economical and qualitative values are considered within the concept. The calculation of production losses due to outages (caused by failures or preventive maintenance work) are done with the EOPS model, a model traditionally used for expansion planning and long to medium term generation scheduling in predominantly hydropower production systems. The qualitative elements are handled by the AHP method. The concept provides improved maintenance decisions and standardised documentation of the decision basis.*

1. Introduction

In the beginning of the 1990's the Norwegian power sector became deregulated. Both the electricity production and power network industries have gone through substantial changes since then. The sector has experienced a sharp decrease in the investment, maintenance and refurbishment of power plants and power networks. Thus, the average age of the components in the systems is increasing. This has led to increased focus on maintenance strategies for the components in both power plants and power networks. This is due to the need for reduction of the amount of reinvestments and thus extending component lifetimes.

The companies will often have a large number of maintenance projects in their project portfolio, and these projects must be ranked given some constraints (e.g. available economic resources, labour or time). When deciding which projects to run, there are other considerations to be taken besides the economic optimisation of investment and operational 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 concept for handling such complex planning problems.

2. Decision model overview

During the last decade, various decision support tools and methods for maintenance optimisation of hydropower plants have been developed in several projects run by SINTEF Energy Research in close cooperation with the Norwegian Electricity Industry Association (EBL) and a number of Norwegian power companies.

The project activities have addressed various topics related to maintenance as foundation for a more integrated decision concept for maintenance analyses and priorities. The work has resulted in a number of "stand alone" modules/tools dealing with parts of the problem. The output from each module are integrated within the concept described in this paper in order to optimise the ranking and timing of maintenance and refurbishment projects. The concept is outlined in Figure 1.

There are separate modules for

- estimation of failure probabilities,
- computation of economical losses due to failures,
- computation of economical losses due to refurbishments,
- handling qualitative utility value, and
- cost-benefit analysis.

All these parts will provide input to the module for optimal ranking and timing.

In order to be successful, the integrated model has to be closely linked to a company's project database. This will be achieved through a specified format for exchange of data between the decision support system and the project database.

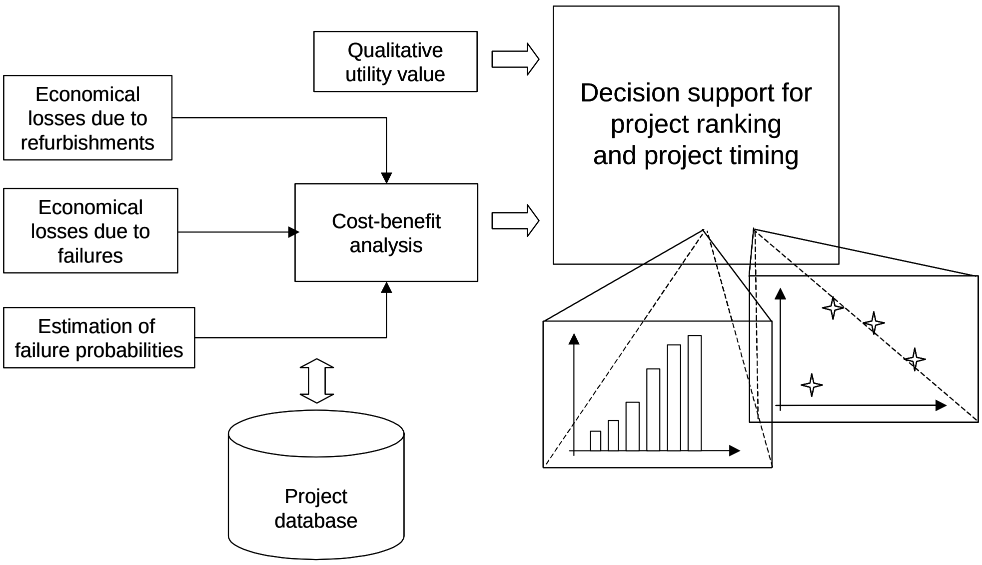

Figure 1 Integrated model for maintenance planning.

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 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 Figure 6 (Section 7).

3. Estimation of failure probabilities

In order to estimate the expected utility value or profitability of a preventive maintenance action we must know which effect the maintenance action has on the probability of forced outages. Therefore, failure probabilities must be estimated both with the assumption that the maintenance action is carried out, and that the action is *not* carried out.

Failure model

Figure 2 shows the elements of the failure model, which is used in the module for estimation of failure probabilities. The failure model has a maintenance approach more than a statistical approach. It is closely related to the failure mechanisms of the equipment, experiences and expert views regarding performance and reliability, and actual state information from inspections, condition monitoring etc. However, relevant failure statistics, if available, are also included in the estimation of failure probabilities.

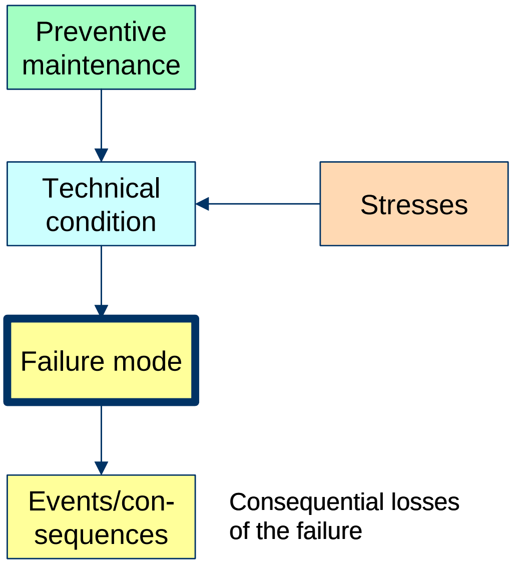

Figure 2 Failure model.

The main element of the failure model of a component, or a unit (e.g. stator winding), is the *Failure mode*. One unit may have more than one failure mode. Short circuit is one failure mode of a stator winding. The element *Technical condition* in Figure 2 represents the most relevant kinds of degradation of a unit, which may develop to the actual failure mode. Low insulation level due to degraded stator winding insulation is e.g. one technical condition of a stator winding. The failure model also represents how *Preventive maintenance* actions and (external) *Stresses* affect the technical conditions of units.

The last element of the failure model is *Events/consequences*. A failure mode may cause events with different kinds of consequences. Minor short circuits in stator windings may cause only limited damage, while an extensive short circuit may cause total breakdown of the stator and several months of production losses. The division between *Failure mode* and *Events/consequences* is an important feature of the failure model.

Technical condition

The technical condition of a unit (e.g. guide bearing) is characterised on a scale from 1 to 4 according to Table 1, i.e. the continuous degradation of a component is simplified by dividing it into four main states. A component as-good-as-new is in state 1. When the condition is characterised as critical, the state is 4 and maintenance actions must be taken immediately. If the level of degradation is characterised as 3, then some (preventive) maintenance actions must be taken sooner or later. States characterised as 2 are ‘normal’ and do not require any maintenance actions, but in some cases such components should be under observation during or after periods with extensive stresses.

Table 1 Technical condition states.

State	Description
1	No indication of degradation.
2	Some indication of degradation. The condition is noticeably worse than as new.
3	Serious degradation. The condition is considerably worse than as new.
4	The condition is critical.

The characterisation of technical condition in Table 1 is in accordance with the condition monitoring handbooks [1] from the Norwegian Electricity Industry Association (EBL). The handbooks cover all critical equipment in hydro power plants and are used by many power companies in Norway. It is therefore important that the failure model is based on the same technical condition characterisation already implemented by the power companies. The handbooks comprise specific criteria on unit level for the technical condition characterisation.

Residual lifetime

Figure 3 shows the duration of the four states concerning technical condition of a component (the length of the intervals are only examples). The technical condition axis (y-axis) indicates degradation level. The length of state 1 (TC_1), 2 (TC_2), 3 (TC_3) and 4 (TC_4) are T_1, T_2, T_3 and T_4 respectively [years]. If a unit is at the beginning of state 2 the expected residual lifetime of the unit is $T_2+T_3+T_4$ [years] from a degradation point of view. Some components may have states which are divided into 2 or 3 sub-states, if that is relevant, and criteria for a more precise fault condition estimation is available.

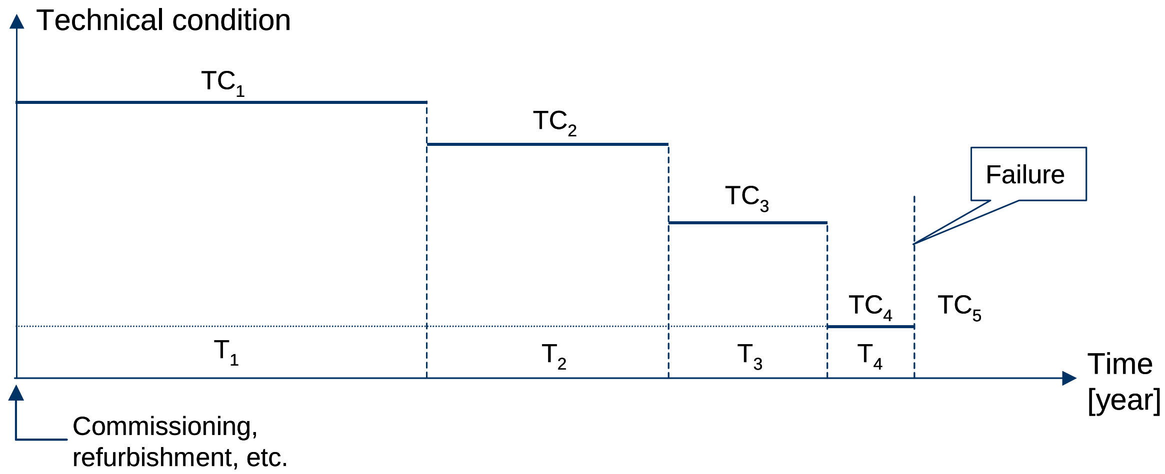

Figure 3 Residual lifetime vs technical condition levels (states).

As indicated in Figure 3, *failure* is denoted state 5. Failure is always assumed to occur from state 4. The length of each state may vary from 20-30 years (TC_1) to only a few years or months (TC_4). However the fault condition may change from e.g. state 2 (TC_2) to failure (TC_5) during a few weeks if a unit is exposed to extreme stresses.

Estimation of failure probabilities

Failure probabilities related to failure modes of units are estimated from the expected failure conditions and how the failure conditions are affected by maintenance actions and stresses (see Figure 2). The failure probabilities are estimated for each year within a period of time based on the expected time development of the technical conditions according to Figure 3. This is the main output from the failure probability estimation module.

As mentioned above, failure is always assumed to occur from state 4. Nevertheless, the failure probability will always be larger than zero even if the technical condition of the unit is estimated as state 1, 2 or 3. This is because the estimation of fault conditions has an element of uncertainty, which is represented by probability distributions in the failure model.

The estimation of fault conditions and the expected duration of each state is of course not only important for the estimation of failure probabilities, but also for the maintenance planning. Timing of inspections, condition monitoring and maintenance actions will be based on this information.

4. Economical losses due to failures

A key economic figure for maintenance decisions is the potential revenue loss if a project is postponed or cancelled and a major breakdown occurs. This is calculated by the EOPS (EFI's One area Power market Simulator) model [2]. The model was developed for expansion planning and long-term to medium-term generation scheduling in predominantly hydropower production systems. The optimal scheduling of hydro-resources is sought in relation to uncertain future inflow and market prices, taking into account specified constraints, contracts, demand and available thermal generation capacity. Both inflow and market price are stochastic variables in the model.

The EOPS model was originally designed to simulate system behaviour assuming a normal state of operation, including planned outages. The model has now been modified to simulate unplanned outages. A more detailed description is found in [3].

The timing of an outage has to be dealt with. One option is to simulate random outages. This would require simulation of a large number of scenarios, and also a decision about the probability and duration of an outage. However, this is not our approach. The strategy is to estimate the cost of an outage (in lost revenues) *if* one occurs, and then evaluate the probability of occurrence as a separate operation. In the chosen approach the timing and duration of an outage is specified for each simulation. Since the expected loss of revenues from an outage is likely to depend on the moment time, several analyses are conducted for each plant with outages placed at different times of year. Expected value of production loss due to a given unit failure is calculated by simulating the production system with and without the specified unit failure for possible price and inflow scenarios.

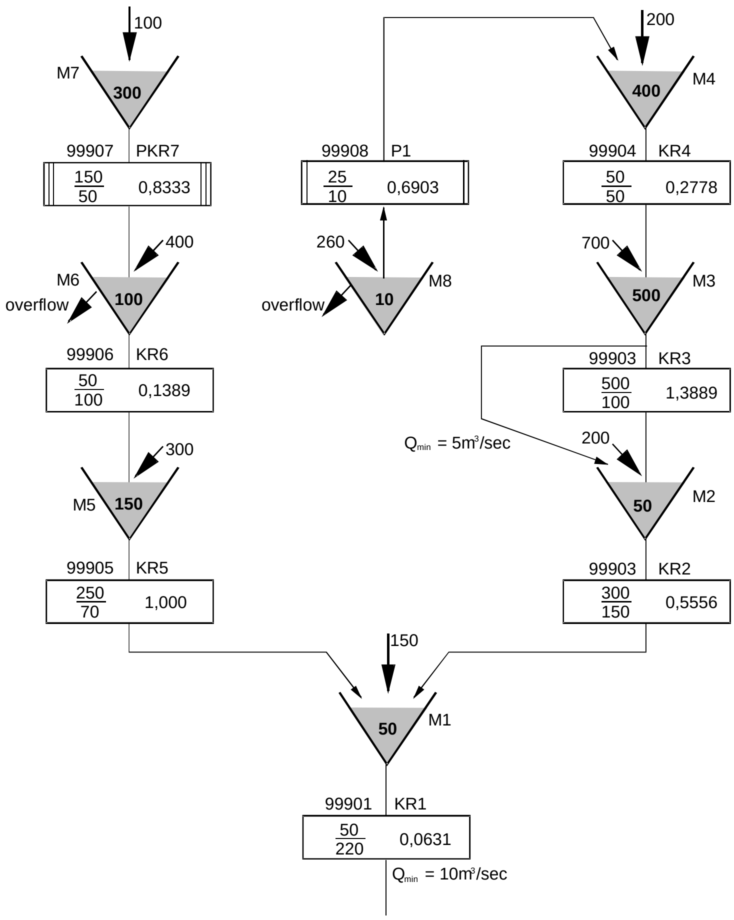

Figure 4 Example of hydropower system

Figure 4 shows an example of a hydropower system. The EOPS model is used for calculating the expected losses for disrupted production in plant KR4. This plant consists of one production unit with production capacity of 50 MW. We assume that the repair time for a failure will be nine weeks and calculate the expected losses caused by disrupted production for four different parts of the year. The results are shown in Table 2.

The results show that production losses are very dependent on when production is disrupted. In our example, the reservoir above the plant (M4) has relatively large storage capacity compared with the expected annual inflow. In this case plant failure during the winter period is much more expensive than the other periods of the year.

Table 2 Expected losses caused by disrupted production in plant KR4 for four different time periods.

	Week 6-14	Week 21-29	Week 31-39	Week 42-50
Expected losses (1000 NOK)	7848	65	952	992

1 € ≈ 8 NOK

The values in Table 2 are the expected values for 60 different inflow and price scenarios, which are assumed to have equal probability. Figure 5 shows simulated losses for each scenario, assuming plant failure from week number 6 to 14, and the expected loss as a straight line. The figure shows that the losses are very dependent on future market price and inflow, i.e. the scenario number. These values correspond to column one in Table 2.

In our integrated model only the expected cost of a given unit failure is used as input to the economical calculations. However, it is possible for the user to check detailed results for a given plant failure. Detailed results include simulated reservoir operation, production, overflow etc. for all price and inflow scenarios. These are the same type of results that are available when the model is used to calculate the production losses for a given maintenance outage (see next section).

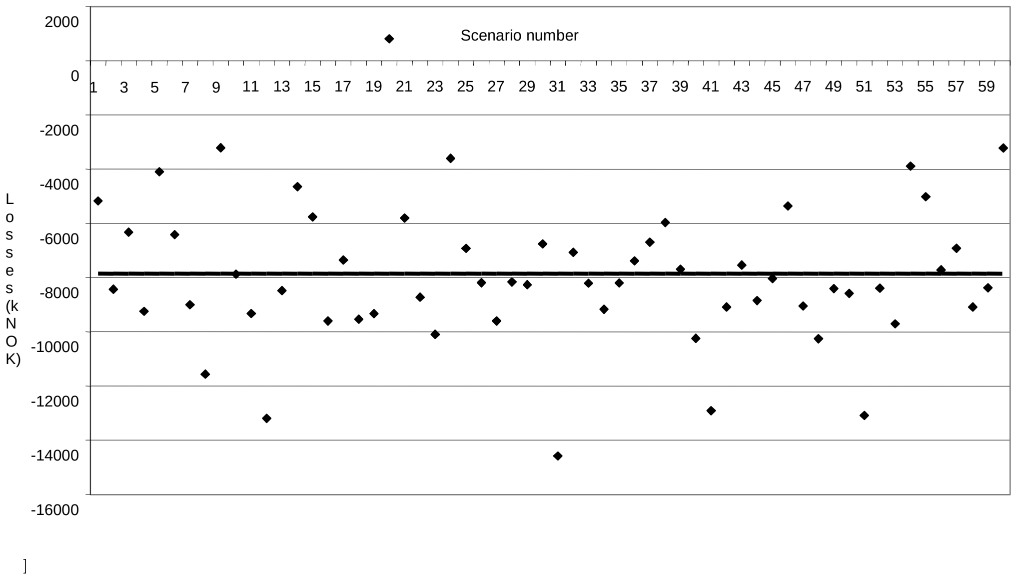

Figure 5 Simulated production losses for different inflow and price scenarios

The output from this module is the expected loss *if* an outage occurs. We are, however, interested in the expected *annual* costs due to failures. Thus, the output from the module is multiplied with the corresponding failure probability (as described in Section 3).

5. Economical losses due to refurbishments

During refurbishment parts of the production system may be unavailable. This can result in water and profit losses because production may have to be postponed to periods with lower prices. These losses are an important part of the total maintenance cost. However, it is possible to reduce these costs with adequate planning. Reservoir levels can be scheduled lower than 'normal' beforehand and maintenance could be placed in periods with expected low prices. Low prices are however generally correlated with high inflows.

The EOPS model can include specified maintenance periods for specified units, but the model does not find the optimal timing of maintenance projects. This is supposed to be done in other modules of the decision support system. In the EOPS model this has to be done by running the model for different maintenance periods and then comparing the economic results. Production losses due to maintenance are the difference between the sales income for a calculation with no scheduled maintenance and the sales income with maintenance included. These costs may depend on the current state (market price, reservoir levels) of the system. For example, if the current reservoir levels are much higher than normal, it may be reasonable to postpone maintenance to periods with lower reservoirs.

6. Cost-benefit analysis

An economic analysis of a maintenance or refurbishment project is often performed with a cost minimisation 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 occurs. Deferment of investments is also regarded as income in the approach.

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

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

The income comprises the following elements:

- Increased power production 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 net present value (NPV) is calculated.

7. Qualitative utility value

When deciding the project ranking there are other aspects to consider in addition to the economic optimisation of investment and operation costs. Aspects such as safety to personnel, working environment and environmental effects (so-called *qualitative criteria*) will inevitably appear as important elements of the overall decision. Common for these are the fact that they are hard to quantify in monetary terms. One way of dealing with such problems is using methods of multi criteria decision making (MCDM).

The MCDM approach applied

Several methods have been developed during the last decades which all represent ways to handle multiple criteria which typically are conflicting or hard to quantify. In the project activities we have chosen an approach where the qualitative criteria – after being identified – are being weighted using the *Analytic Hierarchy Process* (AHP) method developed by Saaty [4]. The method results in relative weights, w_i, of each criterion (in percentages – summing up to 100 %). The main reason for choosing this method is that it is easily understandable and applicable. The user threshold for the method is also low, which is an important aspect because one cannot expect the typical user to be an expert in MCDM tools. The results obtained from using the method have shown to be in accordance with the user's intuitive perception of the problem analysed.

For a closer description of properties and use of the method, we refer to [4, 5].

Process / stages in using MCDM-tools

When applying the AHP-method for aiding the selection of maintenance projects there are three different phases of usage:

- Establishing the decision model (Phase A)
- Using the model for project evaluation (Phase B)
- Aggregation and presentation of results (Phase C)

<u>A. Establishing the model</u>

The first phase of establishing the decision model includes the identification of the decision maker(s). Further the qualitative criteria, which are important for the company, shall be discussed and structured in a decision model. The first phase concludes with establishing the relative weighing of the criteria using the AHP-method, and stating an appropriate scale for each of the criteria. We have used a direct scale when each project is analysed independently of the other proposed projects. The first phase is ideally a 'one-time' job, and the established model will be used unchanged for evaluation of different projects. The concept of the decision model is shown in Figure 6.

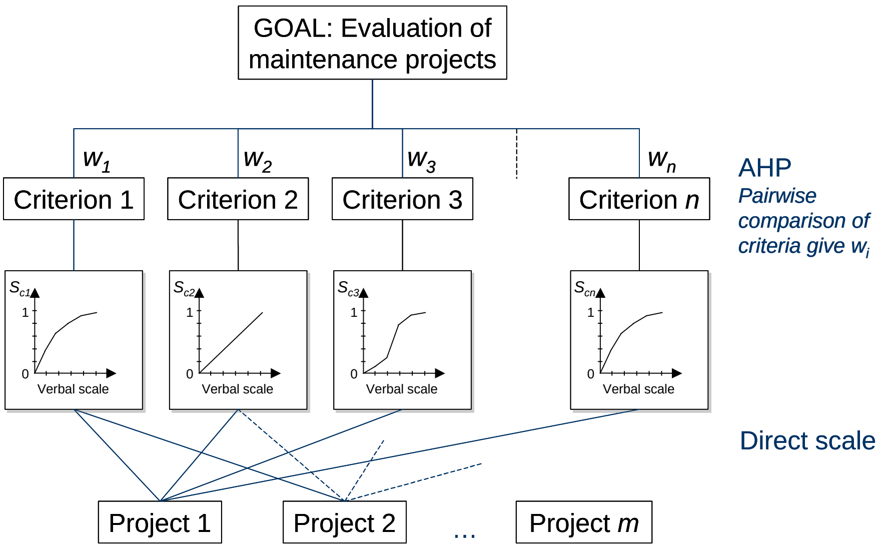

Figure 6 Evaluating qualitative criteria of projects using a MDCM-model

B. Using the model

The decision model containing the chosen qualitative criteria with their weights and their scales can now be used for evaluating projects.

For each project a qualitative utility value (QUV) is calculated. The QUV represents a quantification of the project's score on the chosen qualitative criteria, and will be a number between 0 and 1.

The qualitative utility value, QUV, for a project evaluated can be expressed as:

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

where

- S_{Ci} is the project's score on criterion *i* [0-100%]
- w_i is the weight of criterion *i* [0-100%]

The QUVs for the different projects can be compared to find which project(s) are preferred with regards to the qualitative criteria.

C. Aggregation / presentation of results

To make a holistic decision basis for priorities, the economical aspects also need to be included in the same decision frame.

The results from NPVs and QUVs for the relevant projects can be combined as shown in the example in Figure 7.

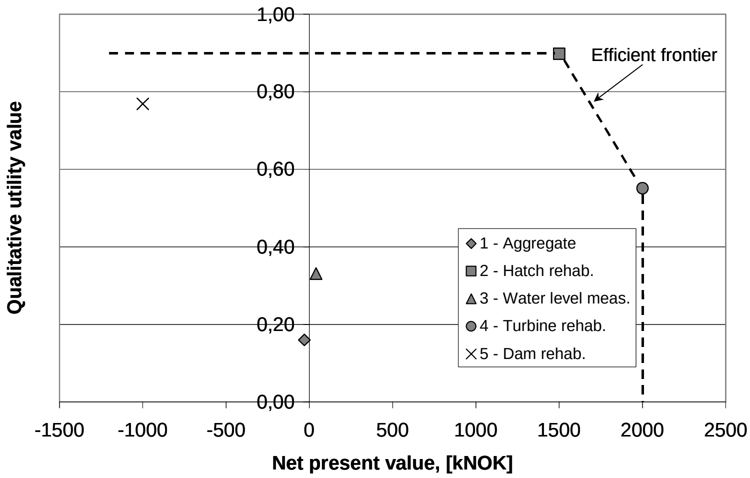

Figure 7 Example: Aggregation of results from project evaluation - NPV and QUV

In the figure the project(s) not outranked by any other will form the efficient frontier of the set of projects. The most favourable project will be found among those that form the frontier.

8. Project ranking and timing

When the projects have been ranked, the task of placing the projects in time still remains due to possible company restrictions in performing several projects simultaneously. Limiting factors can for example be available labour, project management of multiple projects, or economic resources. When considering the sequence of projects in time, the criticality of the projects must be taken into account. Some projects are motivated from critical conditions, which may – if postponed – have severe consequences, while others can wait a year or two without running unacceptable risk.

In general the placing of projects in time is a multi-objective optimisation problem. In the project activities this has not been fully addressed so far, but a more pragmatic approach have been chosen where focus have been on presentation and visualisation of possible conflicts in time regarding the chosen projects.

9. Conclusions

The companies will often have a large number of maintenance projects in their project portfolio. The paper presents a concept that provides decision support for ranking and timing of maintenance and refurbishment projects. Several modules are integrated within the concept and thus giving the decision maker an improved decision basis. Experiences from Norwegian hydropower companies show that the development and integration of the modules, including a company's project database, form a holistic framework for handling the challenging task of maintenance and refurbishment planning in hydropower systems. The module handling qualitative criteria is providing a new perception through its systematising and documentation of elements that decision makers seem to find useful.

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