Integrated tool for maintenance and refurbishment planning of hydropower plants

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ABSTRACT: Optimal investment in maintenance and refurbishment of hydropower plants is very complicated. This paper describes a new model currently under development. The model consists of several modules, each solving separate tasks and passing on necessary information to the other modules. There is a module for computation of losses from disrupted production caused by forced outages, a module for computation of production losses during maintenance, a module for specification of unit (i.e. turbine, generator and control system) failure probabilities as functions of time, a module for presentation and evaluation of qualitative criteria and finally a module for optimal timing of projects. The whole concept is adapted to decision makers who own many production units, although parts of the system may also be useful for smaller utilities.

1 INTRODUCTION

Due to increasing average age of existing hydropower plants in Norway there is a growing need for maintenance/upgrading and refurbishment in the Norwegian system. In this paper we will not distinguish between maintenance and refurbishment and will consequently use the term maintenance meaning maintenance, upgrading and refurbishment. Market based operation of the plants, i.e. more starts and stops, also increases the need for maintenance.

Optimal maintenance planning for hydropower systems is complicated for a number of reasons:

- The lifetime of the different components and the consequences (quantitative and qualitative) of failures are not known.
- Plant efficiency as a function of time of use is unknown.
- It is difficult to estimate probabilities of unit failure due to limited statistics or the applicability of available statistics.
- Loss of sales income due to plant failures or scheduled maintenance is dependent both on future market prices and inflow which are uncertain.
- In a hydropower system with several plants along a watercourse optimal maintenance for these plants may be related.
- There may be limited personnel and financial resources for maintenance in a given period.
- The goal of maintenance planning is a multi-criteria decision problem since both profit and HES (Health, Environment and Safety) are important factors.

During the last few years, several tools and methods for decision support in connection to maintenance of hydropower plants in Norway have been developed. These include:

- Methods and information needed to describe unit efficiency as a function of time.
- Methods and information needed to estimate probabilities of unit failures.
- Methods used to handle qualitative objectives such as health, environment, safety and negative publicity, Tangen 1996.
- A tool that can be used to compute economic losses of a given unit failure, Tangen et al. 1999.
- A tool that can be used to compute economic value of the production loss due to maintenance.

This paper summarises these methods and focuses on a new tool under development. The goal of this new system is to integrate the different models/tools into one decision support system that can solve the overall maintenance planning problem. Recent work has focused on different parts of the planning problem but there is yet not any tool available that can be used to solve the overall problem. The next chapter will describe the model concept, which consists of separate models that interact with each other.

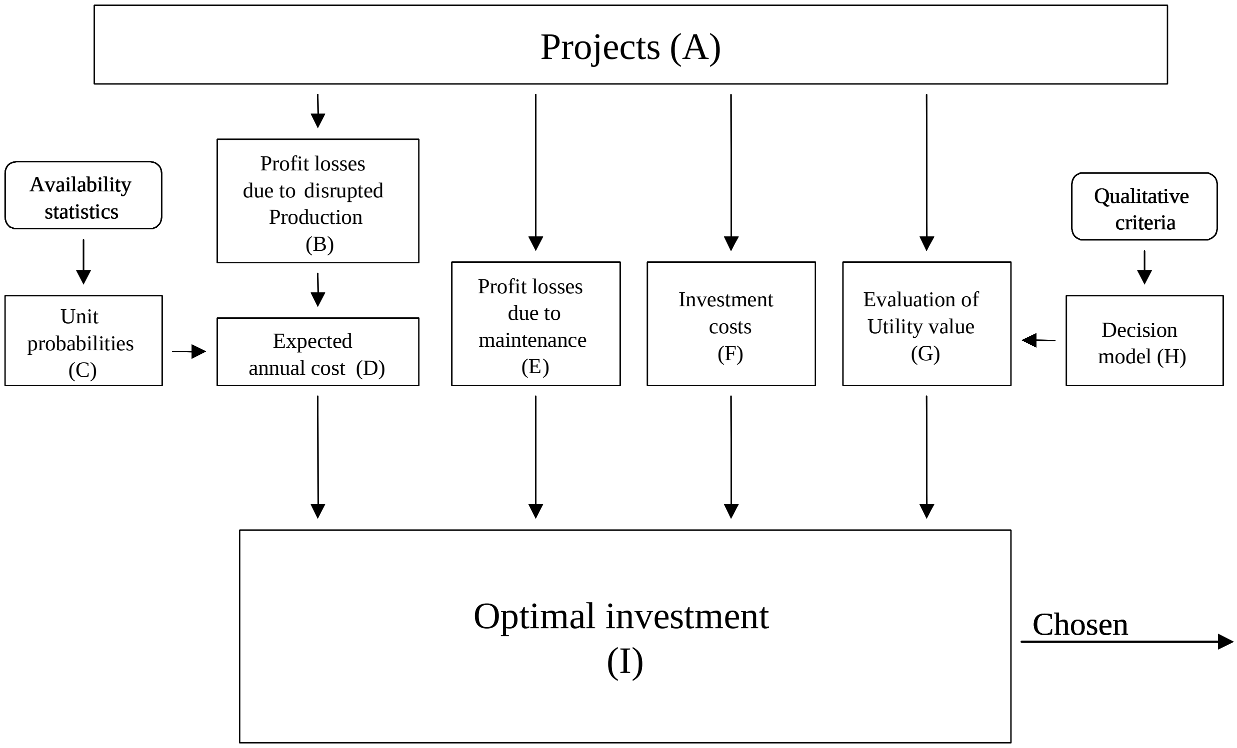

Figure 1. Integrated model for maintenance planning

2 DESCRIPTION OF INTEGRATED MODEL CONCEPT

Figure 1 illustrates the integrated model concept. As already mentioned, the concept consists of several modules that interact with each other, but that can be used separately.

Initially the decision maker considers a number of possible maintenance projects. These projects can go through a pre-screening process in order to reduce the number of projects. The reduced number of projects are input to the integrated model. In Figure 1 these projects are illustrated by module A 'Projects'. The output from this module is a list of possible maintenance projects. Projects that are obvious should be excluded from the list.

If there is no 'physical' connection between projects and no personnel or financial constraints, projects can be decided independently. In our integrated model these types of dependencies are treated differently. Physical dependencies have to be included in the list of possible projects. For instance if a hydro production system consists of two plants 1 and 2 which are physically connected, i.e. located along the same water course, the list of possible projects should consist of three projects, maintenance of plant 1, maintenance of plant 2 and simultaneous maintenance of both plant 1 and 2. Simultaneous maintenance of both has to be included in the project list. The optimization module (I) accounts for project dependencies due to personnel or financial constraints.

Module B in Figure 1 represents a model whose purpose is to compute the expected value of production loss due to unit failure. The model actually calculates a probability distribution for the production losses, where different price and inflow scenarios give the distribution. Only the expected value is output from the module since the goal of the model concept is to minimize expected costs.

Inputs to module B are unit number and downtime in addition to the physical description of the hydro system, inflow statistics and market description. The model is based on the EOPS (EFI's One area Power market Simulator) model, described by Flatabø et al. 1998 and Haugstad et al. 1997. This is described more fully in the section 4.

Module C represents collection of failure statistics and specification/computation of probabilities of failures for the different units. The statistics are limited and the user often must specify these numbers directly based on expert experience. However, in the future a more probabilistic based approach could be used. The output from this module is probabilities of unit failures as a function of time for all units.

Based on inputs from module B and C, module D calculates the expected annual costs due to disrupted production.

Module E represents a model that computes the value of the production losses due to preventive maintenance. These losses are part of the investment costs and very dependent on the time of year, market prices, storage capacity etc. The losses could be due to lost water or to increased production at lower prices. The EOPS model is also applied for this purpose, but run in a different mode. The model is further described in section 3.

The F module is used to specify investment costs for each project.

The G module is used to evaluate and document the trade off between the qualitative values associated with a project. The outputs from this model are relative weights for each qualitative value, i.e. Health, Environment and Safety or other. The properties of this module are described in more detail in section 6.

As background for this evaluation module H contains the decision model for the trade-off between different qualitative criteria.

The I module is essential in the integrated concept. The module gets input from all the other modules and gives as a result a list of investments. The optimization part of this module is based on Dynamic Programming for a given set of possible maintenance decisions.

3 LOSSES CAUSED BY PREVENTIVE MAINTENANCE

During maintenance parts of the production system may be unavailable. This can result in lost water or profit losses because production has to be moved 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 good planning. Reservoir levels can be scheduled lower than 'normal' beforehand and maintenance could be timed to periods with expected low prices. Low prices are however generally correlated with high inflows.

The EOPS model was developed for expansion planning and long to medium-term generation scheduling in predominantly hydropower production systems. It is mainly used for local planning, since it is a single-area model with a single busbar and no grid. 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 long-term model consists of two parts:

1. A *strategy evaluation part* computes a decision table in the form of expected incremental water values for an aggregate model of the hydropower system. These calculations are based on use of a stochastic dynamic programming (SDP)-related algorithm.
2. A *simulation part* simulates optimal operational decisions for a number of corresponding inflow and price scenarios. Weekly generation is determined based on the incremental water value table calculated in the model's strategy part. Aggregate hydro generation is for each week distributed among available plants using a rule-based reservoir drawdown model containing a detailed description of the modelled hydro system.

Hydropower is represented in a fairly detailed manner, as indicated in Figure 2, based on use of standard plant/reservoir modules as shown in Figure 3. Flatabø et al. 1998 includes a detailed description of the properties that may be attached to each hydropower module.

The model may include thermal generation capacity, local demand, and other types of contracts for electricity sales or purchase, as indicated in Figure 2. For our analyses, however, only a spot market represents the market. This is modelled using a price forecast consisting of different scenarios for price development. Forecasts for market price are obtained by using models such as the EMPS model from SINTEF Energy Research, Haugstad & Ris-

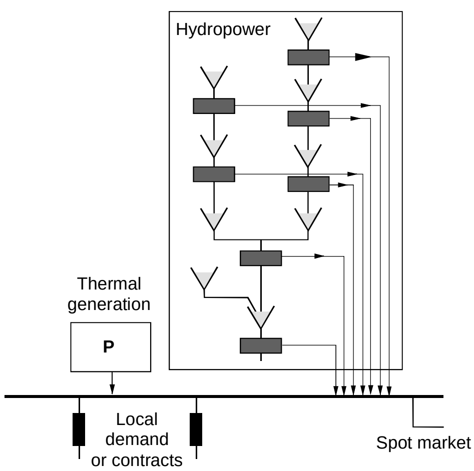

Figure 2. Modelling a producer's system in the EOPS model.

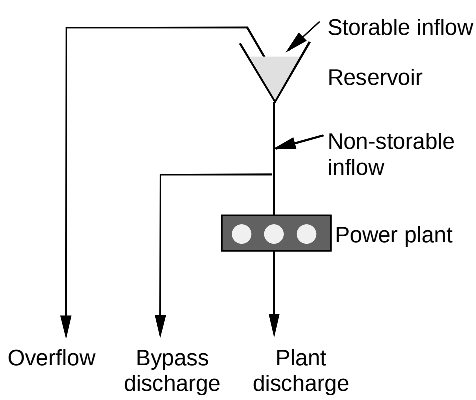

Figure 3. A hydropower system is modelled using standard plant/reservoir modules.

mark 1998. The system owner is considered to be a price taker, as it is assumed that short-term variations in generation do not influence the market price.

The EOPS model can include specified maintenance periods for specified units, but the model does not find the optimal timing of maintenance projects. In the current version of the model this has to be done by running the model for different maintenance timing and comparing the economic results. Production losses due to maintenance are given by the difference between the sales income for a run 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 reservoirs levels are much above normal, it may be that maintenance should be delayed.

In the I module forecasted maintenance costs for the current year and for all the other years in the planning period are needed. The current state of the system may effect the system for about three years in the Norwegian hydropower system. For the following years we assume that the production system is stable and that it is only necessary to compute maintenance costs for the third and for the last year in the planning period. This simplification is done in order to reduce computation time. Maintenance costs for the intervening years are found by linearization. Even if forecasted market prices are time varying, this will usually be a reasonable simplification.

We have not included an example of computation of maintenance costs with the module because these calculations and types of results are identical to what is shown in the next section. Only the running mode of the model is different; maintenance is seen in advance and the hydro schedule is adapted to the maintenance plan.

4 LOSSES CAUSED BY DISRUPTED PRODUCTION

A key economic figure for maintenance selection is the potential revenue loss if a project is postponed or cancelled and a major breakdown occurs. Usually, power plants in waterways with low storage capacity (compared to inflow) are more sensitive to halts in operation than power plants in waterways with large reservoirs able to store inflow for longer periods. The EOPS model has been adapted to and applied to estimate the potential energy and revenue losses related to unplanned outages. A more detailed description of this module is found in Tangen et al. 1999.

The EOPS model is designed to simulate system behaviour assuming a *normal* state of operation, including planned outages. The model has been modified to simulate *unplanned* outages, so that the operational strategy is not adapted to the future outage being analysed. In practice this module is the same as described in the previous section, but the model is run in a different mode.

The timing of an outage has to be decided. One option is to simulate random outages. This would require simulation of a great number of scenarios, and also a decision about the probability and duration of a breakdown. At this stage, however, this is not what we are looking for. Our strategy is to find out how much an outage is likely to cost (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 to the model for each simulation. Since the expected loss of revenues from an outage is likely to depend on the time of year, several analyses are conducted for each plant with outages placed at different times of year. Simultaneous outages of several plants in the same watercourse have not been considered. This is a reasonable simplification, considering the high reliability of a hydropower plant. 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.

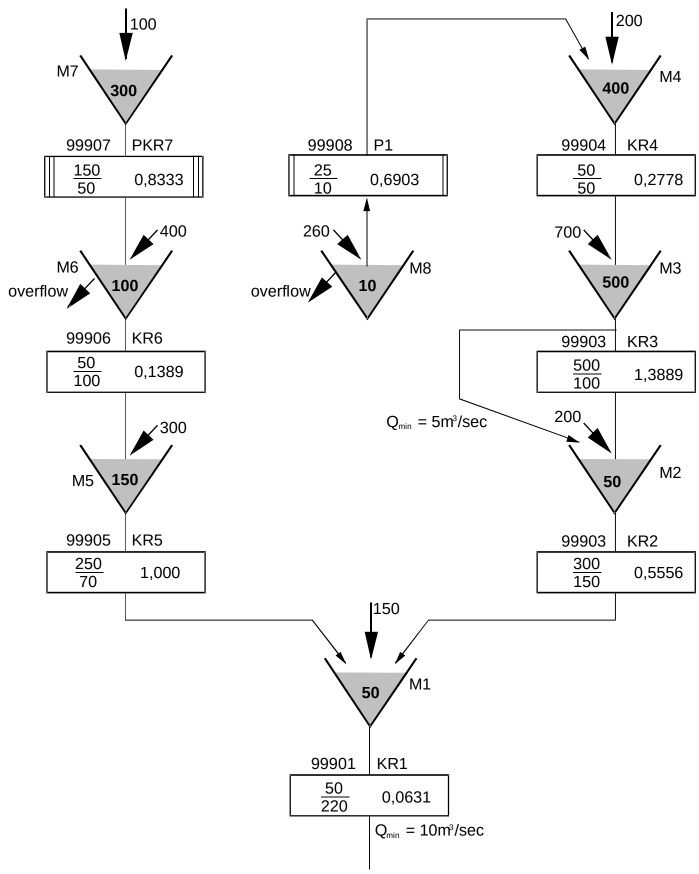

Figure 4. Example of hydro production system

Figure 4 shows an example of a hydro production system. The system consists of 6 hydropower plants, one pump (P1) and one pump storage (PKR7). The numbers in the figure show expected inflow

(Mm^3/year), maximum discharge (m^3/s), corresponding production (MW) and maximum storage capacity (Mm^3). We have used the EOPS model to calculate the expected losses for disrupted production in plant KR4. This plant consists of one production unit with production capacity of 50MW. 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 1. If we assume that the probability of a unit failure is independent of the time of the year we can estimate the expected loss due to plant failure by taking the average of the four values in Table 1.

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 to expected yearly inflow. In this case plant failure during the winter period is much more costly than for the other periods of the year.

Table 1. Expected losses caused by disrupted production in plant KRV4 for four different parts of the year.

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

The values in Table 1 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 1. The figure shows a simulated profit (about 1.0 mill NOK) for scenario 20 if production is disrupted. This is because this scenario is a extreme low price scenario with normal local inflow. In this case we are able to store the inflow in the reservoir and were lucky to produce later at higher prices. This might happen also in real operation. Scenario number 31 is an extreme high price scenario with inflow a bit above normal resulting in large losses if the production is disrupted.

Since our integrated model does not include risk aversion, only the expected cost of a given unit failure is passed on to the I module. However, it is possible for the user of the B module 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.

5 STATISTICAL MODELLING OF FAILURES

The output from module B, described in the previous section, is the expected loss *if* an outage occurs. We are, however, interested in the expected *annual* costs due to forced outages. Thus, the output from module B must be multiplied with the corresponding failure probability. To achieve this, statistical models for failures in individual components in the power plant are needed. Registration of failures

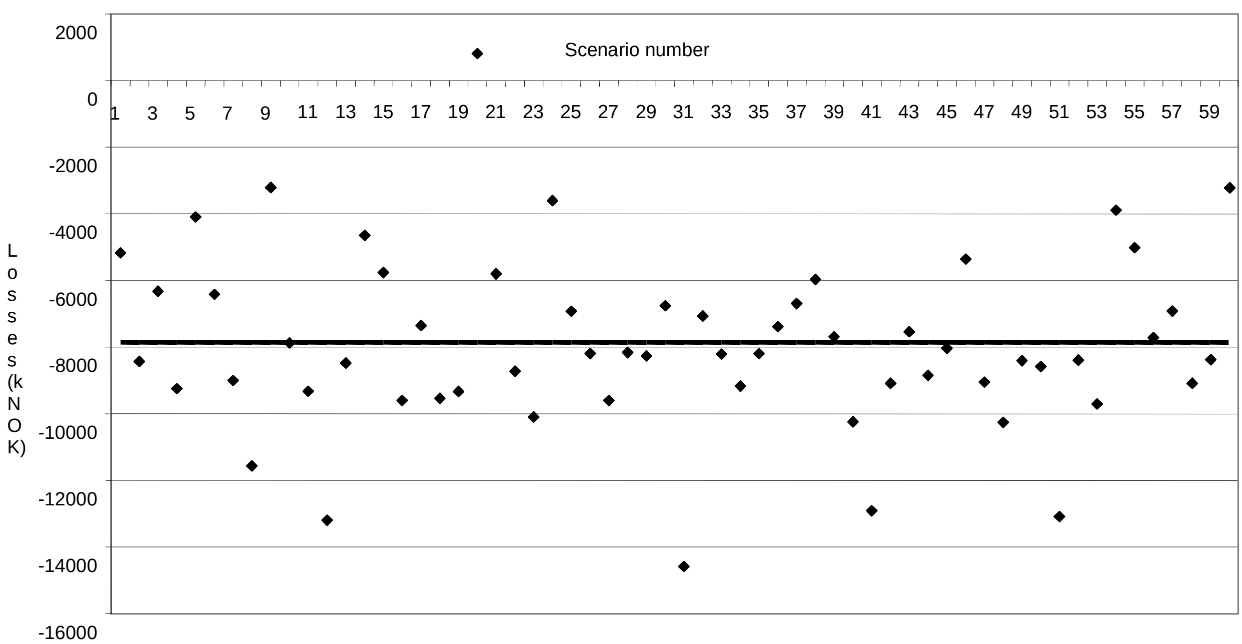

Figure 5. Simulated production losses for different inflow and price scenarios

in existing power plants will be used as input to the probability distributions. To provide the necessary data basis an extension of the FASIT reliability data collection system (Heggset & Kjølle 2000) has been developed to suite maintenance purposes. This system specifies formats for registration of failures, inventories, maintenance parameters and relevant external conditions for various components. Data from the system will be used to develop probability distributions for failures in a given power plant. However, this requires flexibility in the software so that a user may be able to calibrate the models for specific projects. The calibration will depend on the relevant external conditions, maintenance actions, incidents and operational patterns.

The tool we are developing focuses on the unit level, i.e. the module calculating the losses caused by disrupted production will only consider failures that lead to disrupted or reduced output from the plant. This means that failures with other consequences will be neglected in the model. Due to this we must perform a Failure Modes, Effect and Criticality Analysis (FMECA) for the plant and use only the failures that cause disrupted production in the further analysis.

After mapping all possible failures, the probability distribution for each relevant failure must be estimated. These distributions will be used as a basis for calculating the resulting failure probability distribution for the whole plant. Module C will help the user to choose or estimate the probability distributions that will be used together with the results from module B to calculate expected annual costs due to disrupted production. These costs will be compared with the costs associated with relevant maintenance actions performed to reduce the probability of the failure in question. This optimization will be performed in module I (Figure 1).

6 EVALUATION OF QUALITATIVE CRITERIA

When evaluating projects, also non-economic (qualitative) criteria should be considered. Examples of such criteria may be a project's impact on safety and environment. Several methods have been developed for handling qualitative criteria in a structured manner; among these are the Multi Criteria Decision Making (MCDM) methods. Tangen 1996 describes the theoretical fundament for MCDM and practical implementation of such methods are discussed.

MCDM is made for formalizing the decision process using decision models and value functions to describe a project's impact on predefined criteria.

By using such methods the decision process is improved in several ways. Examples of improvements are:

- Standardized procedures for evaluating the project's qualitative utility value
- Objectivity and consistency when comparing projects
- Establishment of a systematic information basis
- Improved documentation of decisions

MCDM is included in the integrated model in addition to economic analyses in the evaluation of projects. This is illustrated by module (G) in Figure 1.

Based on the identified criteria applicable for the company, a decision model is established. Furthermore an evaluation is performed where the criteria's importance compared to each other is decided.

The resulting model contains numerical weights of the criteria and also scales suitable for each criterion for the projects in question.

When combining the decision model with information from each project, a project specific utility value is computed.

An example of the structure of a decision model is shown in Figure 6.

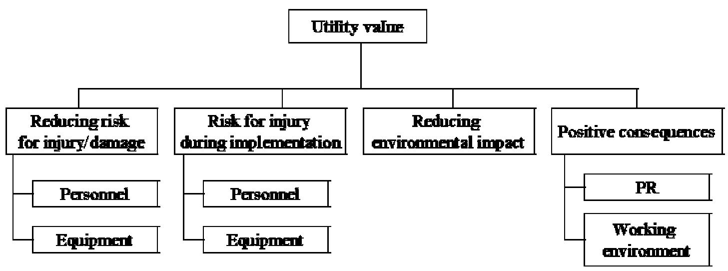

Figure 6. Example of decision model

Figure 7 shows an example of how results from a MCDM-analysis can be presented.

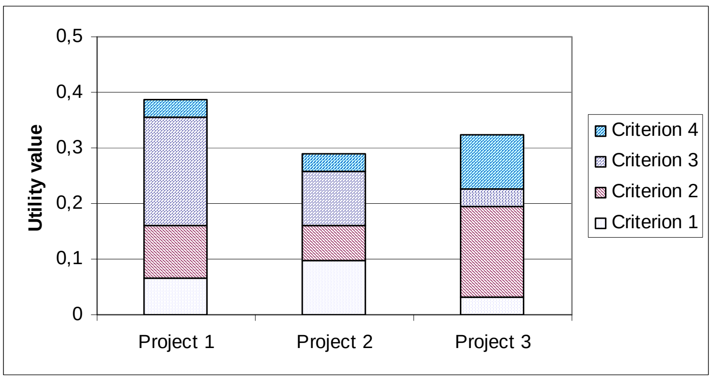

Figure 7. Presentation of utility value results

7 OPTIMAL PLANNING

The purpose of the essential module (I) of the concept is to calculate optimal maintenance plans. The result is a list of projects to be carried out in the current year and a maintenance schedule for the rest of the years in the planning period. An example of how this could be presented is shown in Figure 8.

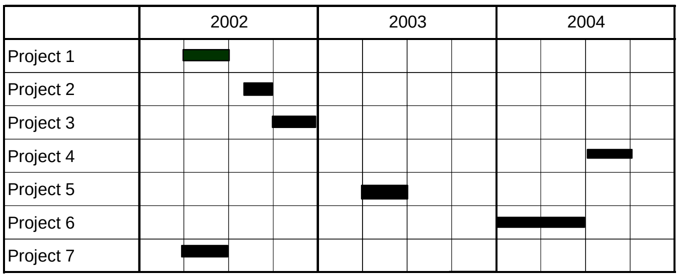

Figure 8. Example of optimal maintenance schedule

The optimization will be based on dynamic programming and take into account financial and personnel constraints defined by the user of the model. This optimization module has a yearly time resolution.

The objective function is to minimize the total present value of sum relevant costs over the planning period. The relevant costs include:

- Investment costs
- Lost production due to maintenance
- Expected costs of disrupted production
- Decrease in production due to reduced efficiency

Qualitative utility values will not be included in the optimisation but be part of the presentation for the optimal projects.

Input to this module is a list of possible projects with corresponding investment costs and HES values as indicated in Table 2.

Table 2. Example of project description

	Project description	Investment cost	Public relations	Environment	Safety
		mill NOK	scale 1-4	scale 1-4	scale 1-4
Project 1	New runner plant C	5	1	2	1
Project 2	Turbine maint. plant B	4	1	3	2
Project 3	Generator maint. plant D, unit 2	17	2	4	1
Project 4	Generator maint. plant D unit 1	15	1	3	2
Project 5	New hatchet plant C	3.5	2	2	3
Project 6	New runner plant A	4.5	1	1	2
Project 7	New runner plant D	6	1	2	2

The state variable in the optimisation is a number that describes the state of the whole production system for a given year. Transition from one state to another in a time period implies maintenance in one or more units in that period. Many transitions are not possible, or obviously not optimal to do. Table 3 shows an example of the connection between state variable and project investments. For example, going from system state 1 to system state 2 represents investment in project 2, project 1 is already done. In order to cover all possible combinations the number of rows in the table can be very large even for a limited number of projects. It is therefore important to use relevant information to reduce the number of system states. Expected costs due to production losses during the maintenance period and changes in expected losses due to plant failures are as mentioned before calculated for each possible state transition by the B and E modules.

Table 3. Possible specification of system state in Dynamic Programming approach

System	Project number						
state	1	2	3	4	5	6	7
1	x						
2		x					
3			x				
4				x			
5					x		
6						x	
7							x
8	x	x					
9		x	x				
10	x			x			
11		x	x	x			
12				x	x	x	
13				x	x		x
14		x	x	x	x		
…							

8 FURTHER WORK

Further development of the integrated concept will be split into two phases:

In phase one we will develop the model as shown in the Figure 1, but the model will not include optimisation of the maintenance schedule. The model only calculates sum profit and qualitative utility values (eg HES) for a given maintenance schedule. The system will be user friendly and the user will be able to calculate and compare sum profits and check personnel and investment constraints for many different maintenance schedules in a relative short time. The results will also include a graph that shows profit and qualitative utility values.

In phase two we will include optimisation of the timing problem. This development phase includes a further development of the interaction between the modules.

This two-phase development will allow us to deliver a useful tool at an early stage. Also, utilities with only a few plants may not need the optimisation of the timing.

The B and E modules in Figure 1 have already been delivered to several utilities and are used in current maintenance planning. These modules only need minor changes in order to fit into the integrated concept.

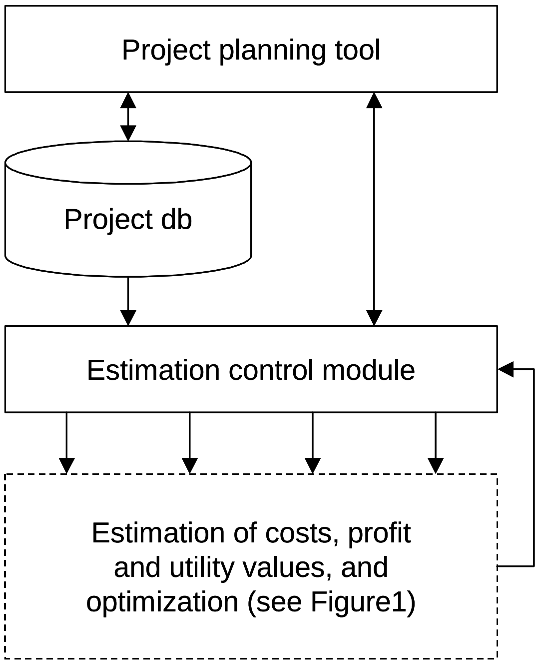

Figure 9. Integration with project planning

Module A in Figure 1 represents the maintenance projects, which are the basis for the calculation of optimal maintenance plans. Relevant information about the projects is normally managed by the utility's project planning tool and stored in a project database (see Figure 9). The estimation and optimisation model in Figure 1 will be a module, that will support the project planning tool with complex analyses when that is needed. Figure 9 illustrates one solution of integration with the project planning tool and the project database. In addition to the model in Figure 1 we will develop a control module (see Figure 9), whose purpose is to communicate with the project planning tool and the project database as well as control the estimation and optimisation processes, including the data flow.

We believe that the pre-screening process in order to reduce the number of projects for detailed analyses, as mentioned in Section 2, should be handled by the control module. This solution is favorable regarding a 'standard' interface with various project planning tools.

One utility has already established a ‘manual' interface between its project planning tool and the modules B and C in Figure 1. The interface in terms of manual routines, specifies how to apply the two modules in maintenance planning. Estimation of profit losses is performed based on i.a. data from the project database, and estimated cost figures are then stored in the same database. All data entries are carried out manually. The control module will improve this interface and the whole planning process. The manual operations will be automated as far as it is appropriate from the users point of view.

Utilities use various kinds of project planning software. We will therefore specify an interface with our control module, which is flexible with regard to this problem.

9 CONCLUSIONS

This paper presents a new tool for maintenance and refurbishment planning that is currently under development. The tool consists of several modules that may be run separately. The concept introduces several improvements to current practice. The model includes evaluation of both economic and qualitative values. Physical connections and financial or personnel limitation which have implications for the project prioritising are included in the model. The model calculates automatically the optimal maintenance schedule and thus reduces the manual work necessary.

The model should give improved maintenance decisions and documentation of why the decisions were taken. It will also provide for a uniform documentation of all possible maintenance projects.

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