BEST PRACTICES IN HYDROPOWER PLANT MAINTENANCE

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SUMMARY

Hydropower companies have good technical competence and good knowledge of the plants, even though they still can utilize their knowledge more systematically. The improvement potential is high when it comes to apply new methods, tools, information about technical condition, operating history and indicators for continuous improvement of the maintenance function. Deterioration of hydropower components will increase due to new operation strategies and age, and hence increase the risk related to hydropower. Risk-based maintenance management must be implemented in order to meet these challenges. The *Optimal Maintenance Toolbox* described in the paper is developed for that purpose. The Toolbox with its *Failure model* constitutes a knowledge-based framework for continuous improvement of the maintenance management processes. Monitoring of risk and action needs indicators shall help the maintenance staff to identify unacceptable risk due to deterioration and to take appropriate actions. Maintenance management based on predefined failure models, systematic condition monitoring and assessment, risk analyses and monitoring of risk and action needs indicators represent best practice in any business. A roadmap to World Class Maintenance must include implementation and systematic utilisation of advanced risk-based maintenance management tools. This paper presents results from a Nordic R&D project organised by Norwegian Electricity Industry Association (EBL).

Key Words: Optimal maintenance, Failure model, Risk analysis, Indicators, Hydropower

1 INTRODUCTION

In latter years maintenance and renewal of power systems has changed from being a pure technical area into a new area with focus on cost reductions and market demands for availability. Many hydropower companies are implementing strategies and systems for risk based maintenance. The challenge ahead is to strengthen the ability of the maintenance function to provide better profitability and added values, among others by efficiently utilize best practice in terms of strategies, planning methods, implementation, condition monitoring, information handling, risk analysis, continuous improvement, etc.

The importance of balancing power from hydropower plants (hydropeaking) will increase as large scale non-regulated energy from onshore and offshore wind parks is growing rapidly in Europe. With 50 % of Europe's hydropower reservoir capacity, hydropower plants in Norway have to meet an increasing demand for regulated and peaking power in the future. This kind of operation will have adverse effects on machinery, hydraulic structures, dams and tunnels.

Hydropower companies in Norway and Sweden participate in a R&D project at SINTEF Energy Research called *Value adding maintenance in power production*. The objective is to develop and test methods, models and tools that can support maintenance planning and decision making according to best practice in hydropower plant maintenance. The project is organised by Norwegian Electricity Industry Association (EBL). This paper presents results from the project.

2 HYDROPOWER PLANT MAINTENANCE STATUS

An investigation was conducted in the hydropower sector to have an overview of the status and the best practices regarding the maintenance management. 15 hydropower companies participated in a survey about the maintenance practices, and 8 companies provided reports of indicators and tools that they use.

The general picture is that the hydropower companies are good at maintenance. They have staff with good technical competence and good knowledge of the plants, even though they still can utilize their knowledge more systematically. The improvement potential is high when it comes to apply new methods, tools, information about technical condition, operating history and indicators for continuous improvement of the maintenance function.

<u>Maintenance management processes</u>

The description of the maintenance status and the best practices in this paper are divided by the processes in the maintenance management loop (see Figure 1); *Objectives and strategies*, *Planning*, *Implementation*, *Reporting and analysis of results*, *Improvement*, *Modification* (not included in this paper) and *Resources*. Figure 1 is based on the figure *Maintenance management processes* from a draft European Standard, prepared by CEN / TC 319 / WG 8.

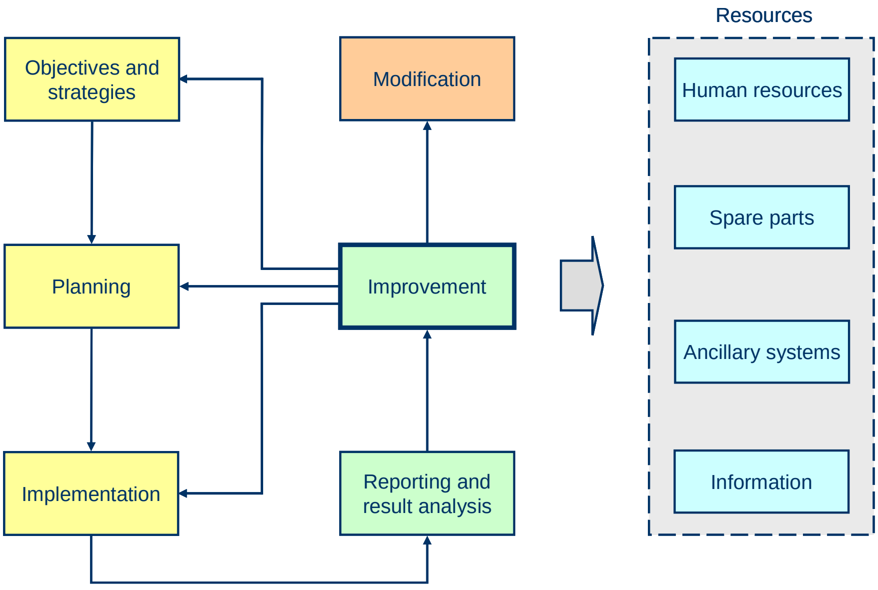

Figure 1. Maintenance Management Processes.

<u>Objectives and strategies</u>

Many hydropower companies have formulated maintenance objectives and target figures for availability, costs, HSE and external environment. They have prepared specific strategies to reach the objectives for the maintenance function. Indicators are used to report the status of the priority areas. 8 hydropower companies have together stated that they use 45 indicators. Many of these indicators almost deal with the same, but have different description and definitions. HSE-indicators *H1*, *H2*, *Lost time injury* (%), *Personal injuries* (number) and *Unwanted incidents* are examples of these kinds of indicators.

<u>Planning</u>

All the hydropower companies which reported about the maintenance status had established a preventive maintenance program. 73 % of the companies included all the equipment in this program. The rest limited the program to critical equipment or equipment with a high purchase price. Many companies have improved the preventive maintenance program by using Reliability Centered Maintenance (RCM) analysis during the last years. Most of the companies that participated in the survey had implemented a RCM analysis, and they stated an increase of the safety and effectiveness as the most important results.

<u>Implementation</u>

The indicator *Backlog* is used to measure the proportion of scheduled jobs (in hours or number of jobs) that are not carried out according to the plan over a measurement period. This is an important indicator of more and more hydropower companies with a view to control and increase the efficiency of the implementation. There are separate indicators for backlog preventive maintenance works and backlog regulatory actions. *Safe Job Analysis* (SJA) is a systematic and step by step review of all risk elements in advance of a job, so that measures can be taken to eliminate or control the identified risk factors during the implementation of the job. A SJA includes all the situations that may affect risk in terms of personnel, environmental and economic values. SJA is completely implemented by a few hydropower companies.

Reporting and analysis of results

Many hydropower companies registered 80-100 % of maintenance activities in the maintenance management system. It remains still much before the companies have an adequate reporting and quality assurance of information that is relevant to the *Improvement* process. Systematic analysis of results to identify and assess the improving actions is carried out primarily in connection with the RCM analysis and the benchmarking based on the VVO model (with weighted maintenance objects).

Improvement

There is little systematic follow up of results analysis with focus on continuous improvement of processes in the maintenance management loop. The survey gave 85 % of the companies that had followed up the results of RCM analysis in the daily maintenance. Participation in benchmarking (VVO) has led to increased cost-consciousness.

Resources

Human Resources

This includes the company's employees, organization, leadership, systematic training and continuing education, as well as actions to promote motivation and creativity. Maintenance organization is still practically oriented, but now developed more and more in the analytical way.

Spare Parts

The survey showed that 30 % of the companies experiences delays due to lack of spare parts. The most common reasons were old equipment, lack of spare parts management and expensive parts not in stock.

Ancillary Systems

All the companies surveyed had computerized maintenance management system (CMMS). In general, there is lack of integration between the maintenance, documentation, and especially economics. Most require/want full integration. Power companies that work with 5S are all in the initial phase. 5S is a practical tool to Sort, Set in order, Shine, Standardize and Sustain that will contribute to increase productivity, quality and security at work. Introduction of 5S will improve the maintenance function in a hydropower company.

Information

The introduction of computerized maintenance management systems has led to a significant improvement in the data base in terms of plant data and maintenance history. On the other hand, the reporting of failures/faults and technical condition states are sporadic and insufficient.

3 BEST PRACTICES

Maintenance Best Practice (MBP) is defined by the companies that at any time use the best methods in the maintenance management loop in order to achieve the company objectives. In order to apply MBP, it requires to be updated about the maintenance performance in other companies - both the same kind of industry and others - and measure their own maintenance performance up against the best.

Some examples of maintenance best practice in Norwegian hydropower companies:

- They have maintenance objectives and strategies to achieve the company objectives.
- They have maintenance indicators that support the maintenance objectives.
- Analyses are conducted to estimate the maintenance requirements.
- There is a preventive maintenance program that is improved continuously (for example yearly).
- Safety Job Analysis is performed for all the maintenance work.
- 5S is introduced to make effective the implementation of maintenance.
- They benchmark the maintenance function against other hydropower companies.
- Quality audits are conducted regularly and improvement actions are identified and applied.
- Improvement actions have a deadline and actions are performed within this deadline.
- There is sufficient integration between the CMMS system and the economy system.

- Condition monitoring and reporting of condition states are according to the EBL handbooks [2].
- Individual competence development plan exists for all employees, based on a survey of skills needed.
- They have a development plan for the maintenance functions as a whole.

For some of the maintenance management processes, the status in the hydropower industry is compared with other businesses. Results from a survey of maintenance status and availability in the Norwegian industry in 2002 were used for comparison. Hydropower companies are both worse and better than the rest of the Norwegian industry. Developments in recent years denote that the differences between these two industries have been reduced.

4 OPTIMAL MAINTENANCE TOOLBOX

SINTEF Energy Research has over the years developed an *Optimal Maintenance Toolbox* with various calculation tools, methods, models, handbooks, specifications, recommendations and educational material. The toolbox contains results from R&D projects for Norwegian Electricity Industry Association (EBL), mainly carried out at SINTEF Energy Research.

The tools are:

- Failure model with predefined failure mechanisms, failures, risk indicators, condition states criteria and lifecurves.
- Tool for estimation of failure probability based on knowledge of a component’s technical condition [1].
- Tool for calculation of profitability (net present value) of maintenance projects. [1].
- Tool for calculation of qualitative utility value of maintenance projects based on qualitative evaluation of HSE etc. [1].
- Tool for calculation of start-up costs for hydropower plants.
- Tool for identification and documentation of operational pattern for hydropower plants.
- Condition monitoring handbooks [2].
- Framework for planning of shut down maintenance with elements from pit stop.
- Assessment model for key performance and risk indicators.
- Maintenance cost model.
- Terminology.
- Post-graduate educational material on Master and Bachelor level.

5 FAILURE MODEL

The *Failure model* describes elements and relations between them that are significant for the lifetime evolution (deterioration) of a component. Figure 2 shows the main elements and the relationship between them. The model is professionally well-founded and with assured quality. It is theoretically in accordance with recognized methodology for lifetime analysis and estimation of probability of failure. The model is at the same time practical-oriented in terms of risk-based maintenance management, by applying an established classification system for technical condition in the Norwegian hydropower industry [2].

The maintenance assets are described in terms of failure mechanisms and their criteria for the classification of deterioration states. The physical design, material variants, insulation level, manufacturing, etc will often be decisive for whether a failure mechanism is significant for a give component. The arrow in Figure 2 from *Design solution* to *Failure mechanisms* illustrates that. Two in principle identical components can have different failure mechanisms as a result of differences, for example, regarding the materials.

The technical condition of a component will deteriorate over time. Various physical/external and operational stresses influence the deterioration process and the lifetime. Operational stresses include overload and part-load operation, frequent start-ups, operating temperature, etc. The relationship between *Stresses* and *Technical condition* is shown in the figure.

The probability of failure increases as the technical condition deteriorates. When a component fails the consequences depends on the barriers or the consequence reducing measures (protection, physical barriers, etc). Although there are established barriers to prevent or limit the consequences of failures, there are ‘holes in the fence’ that can lead to unwanted consequences caused by the failure. This is illustrated in Figure 2.

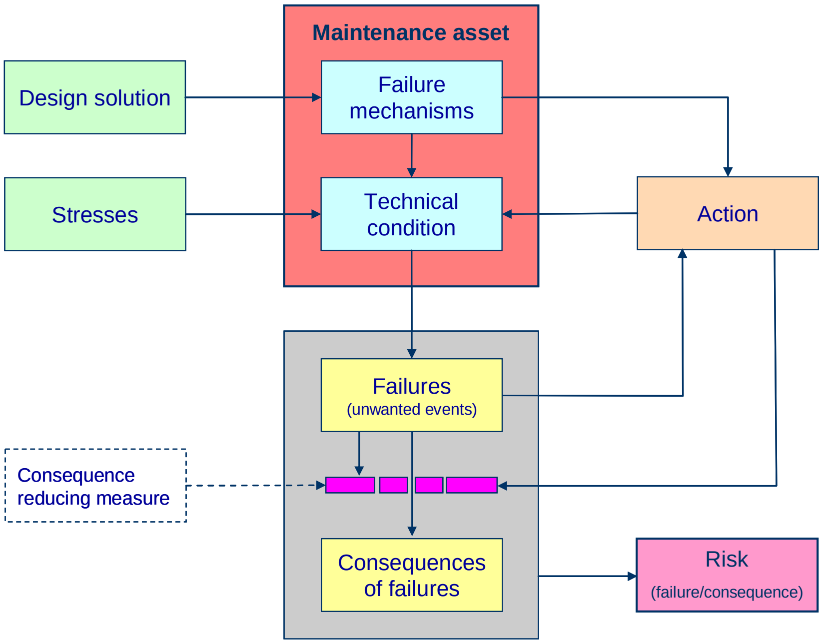

Figure 2. Failure model.

The consequences of a failure can be more or less serious. The probability that a very serious event or accident happens is normally less than the probability of less serious consequences. A failure can have consequences in terms of costs, poor quality, personal injury, environmental damages, loss of reputation, etc. The associated risk of a failure (unwanted event) is the combination of the probability and the consequence of the failure.

Actions include both preventive maintenance actions to mitigate wear-out, corrective maintenance actions (repairing faults) and renewing. The actions can also be in form of barriers.

Experts have specified relationships between *Design solutions* and *Failure mechanisms*, and between *Stresses* and *Technical condition* for the most critical hydropower components [3]. For every failure mechanism there is also specified a failure and the corresponding consequences.

The deterioration from ‘as good as new’ to the fault state is divided into 5 discrete states as shown in Table 1. The state classification system is according to EBL’s Contidion monitoring handbooks [2]. For every failure mechanism there are specified criteria that describe the transition between the 5 states.

Table 1. Technical condition states [2].

State	Description
1	No indication of deterioration ('as good as new').
2	Some indication of deterioration. The condition is noticeably worse than 'as good as new'.
3	Serious deterioration. The condition is considerably worse than 'as good as new'.
4	The condition is critical.
5	Fault state.

The *Failure model* includes lifecurves as shown in Figure 3 that are divided into the same discrete states as Table 1. The sojourn times T_1, T_2, T_3 and T_4 correspond to the technical condition states 1 to 4 (TC_1, TC_2, TC_3 and TC_4 in Figure 3). A lifecurve is defined for a given failure mechanism. Sojourn times is specified for a certain level of physical/external and operational stresses. Experts have specified lifecurves for some hydropower and grid components.

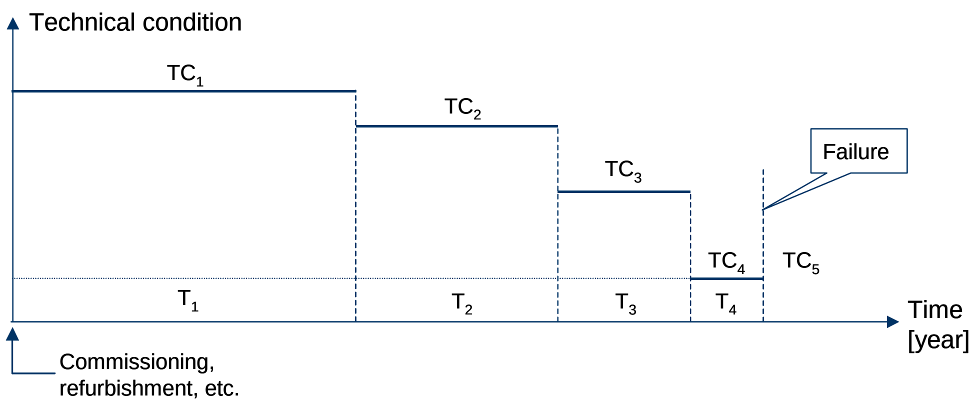

Figure 3. Lifecurve with sojourn times T_1, T_2, T_3 and T_4.

It has been developed an Excel/MATLAB tool that can estimate the annual and cumulative probability of failure based on lifecurves. The user must set the current state of the component being considered.

Instead of setting the technical condition related to a defined lifecurve, the user can specify directly the Mean Residual Life (MRL) with a 10th percentile. The tool adapts these two values to a gamma distribution with define parameters, and uses this distribution as the basis for calculating the annual and cumulative probability of failure.

Estimating the probability of failure and its consequences is a two step process as shown in Figure 4. The annual and cumulative probability of failure is estimated as mentioned above based on lifecurves or MRL with 10th percentile. This is the first step in the process. The step 2 is to calculate the probability of the associated consequences of failures. For this, it is appropriate to model the course from the failure to the end events with the help of an event tree analysis as shown in Figure 4.

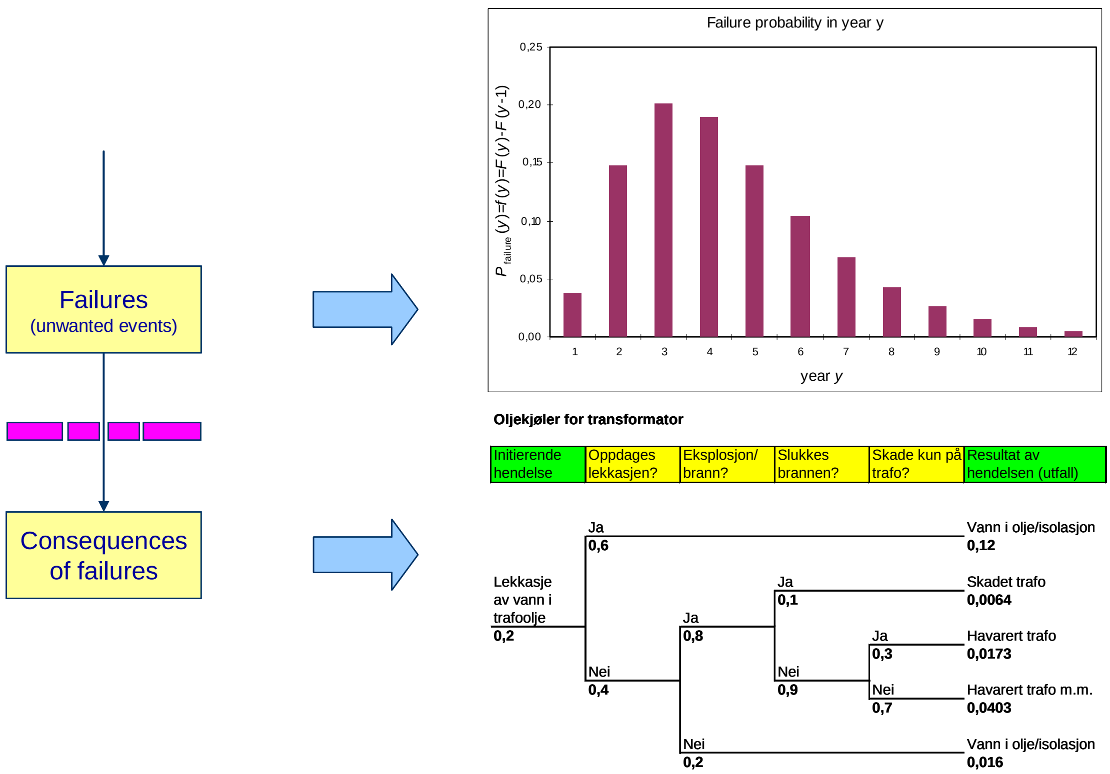

Figure 4. Estimation of failure probability and corresponding consequences.

6 PILOT IMPLEMENTATION AND TESTING

Tools from the *Optimal Maintenance Toolbox* are being implemented and tested on a pilot basis in hydropower companies participating in the R&D project *Value adding maintenance in power production*. **Agder Energi Produksjon** and **Statkraft Energi** are pilot companies when the implementation and testing of the *Failure model* (Figure 2) and the *Failure probability estimation* tool starts in November 2009. The main purpose here is systematic monitoring of *risk indicators* derived from the reporting of technical condition and the condition assessments based on that data. The indicators shall help the maintenance staff to identify unacceptable risk due to degradation and to take appropriate actions, as for example to perform more detailed condition monitoring. Cost-benefit based *action needs indicators* may identify needs for more detailed profitability analyses of condition improvement and risk reduction projects. Monitoring of risk and action needs indicators may be performed periodically or initiated by certain events.

Implementation and testing of the *Failure model* with risk and profitability analyses based on technical condition address the maintenance management process *Reporting and analysis of results* (see Figure 1). Risk based continuous improvement of maintenance functions and strategies will be based on these tools. The risk analyses are not limited to economic risk. Risk indicators shall also cover safety of personnel (occupational safety), environmental damages and public reputation. Relevant tools for the other maintenance management processes in Figure 1 are also subject to pilot implementation and testing.

The pilot companies have performed Reliability Centered Maintenance (RCM) analyses that are useful sources for their implementation of the *Failure model*. It is appropriate to start with critical maintenance objects and failure mechanisms from the RCM analyses. Only failure mechanisms relevant for the actual design solutions of the objects should be included. The decision of which condition parameters/data that shall be reported and analysed must be based on what can be provided with reasonable quality and use of resources. The reporting of technical condition must be in accordance to the discrete states in Table 1.

The *Failure model* requires predefined failures and consequences. The RCM analyses have identified critical failures. Specification of economic consequences and probabilities related to the selected failures will involve use of event trees (see Figure 2). Only a few lifecurves are available at the present time. More lifecurves for the selected failure mechanisms must be specified during the pilot implementation. These lifecurves will be preliminary ones until they are verified by experts. The strategy is to start with such preliminary lifecurves and then improve them when that is possible.

Monitoring of cost-benefit based action needs indicators requires predefined preventive maintenance and renewal options. The specification of these options must define how much these actions improve the technical condition (e.g. to state 1 or 2). Action cost and economic life will also be specified for each option.

Table 2 shows an example of monitoring economic risk indicators for failure mechanisms (*FailMech*) and failures in a hydropower plant. The columns *Plant*, *Unit*, *FailMech* and *Failure* contain code numbers. *TC* is technical condition state and *MRL* is Mean Residual Life. *MRL* is calculated when a lifecurve is specified for that failure mechanism, or specified together with a 10th percentile when lifecurves are not available.

Table 2. Example of monitoring economic risk indicators. Costs are in kNOK.

Plant	Unit	FailMech	TC	MRL	Failure	$P(T_R \leq 5yr)$	$P(T_R \leq 10yr)$	FailCost	FailCost_5yr	FailCost_10yr
107	421.100.131	350	4	9	3200	0,0332	0,2843	840,0	113,4	611,9
107	421.100.131	357	3	13	3600	0,0838	0,1321	1.360,0	452,1	938,7
107	421.100.131	368	3							
107	421.100.132	415	3	18	1150	0,0184	0,0971	630,0	48,4	211,5
107	421.100.133	210	3	14	890	0,0289	0,1121	750,0	78,3	345,6

$P(T_R \leq 5yr)$ is the cumulative failure probability for the first 5 years, while $P(T_R \leq 10yr)$ is the cumulative failure probability for the first 10 years. Both are useful indicators. Predefined actions or follow-ups may be attached to certain probability criteria (levels). Such criteria will depend on the kind of risk. Monitoring safety of personnel risk may have lower action levels than monitoring risk regarding environmental damages and public reputation.

FailCost is total cost caused by a failure, i.e. repair cost and cost of unavailability (production loss). *FailCost_5yr* and *FailCost_10yr* are total present value of annual expected failure costs for the first 5 and 10 years respectively. Annual expected failure cost is calculated by multiplying *FailCost* with annual failure probability. *FailCost_5yr* and *FailCost_10yr* are economic risk indicators adding more information to the maintenance staff than the cumulative failure probabilities $P(T_R \leq 5yr)$ and $P(T_R \leq 10yr)$.

Table 3 shows an example of monitoring cost-benefit based action needs indicators for predefined preventive maintenance and renewal actions. The column *Action* contains code numbers. The column *FailMech* shows which failure mechanisms that are affected by the action, i.e. which technical conditions that are improved.

Table 3. Example of monitoring cost-benefit based action needs indicators. Costs and profit are in kNOK.

Plant	Unit	Action	FailMech	ActCost_5yr	FailCost_5yr	TotalCost_5yr	RefCost_5yr	Profit	Total/Ref
107	421.100.131	4278	350	498,4	143,7	642,1	389,0	-253,1	1,651
107	421.100.131	4298	357, 368	86,4	112,8	199,2	253,9	54,7	0,785
107	421.100.411	3211	278	213,5	322,8	536,3	389,4	-146,9	1,377
107	421.100.423	3560	422	170,8	532,8	703,6	409,4	-294,2	1,719
107	421.100.431	1351	432	322,8	187,4	510,2	678,4	168,2	0,752

ActCost_5yr in Table 3 is the action cost within a 5 year period of analysis, i.e. the total action cost is reduced by the present value of the remaining value at the end of the period of analysis. *FailCost_5yr* is the same as *FailCost_5yr* in Table 2, but here *FailCost_5yr* is with the action implemented in the beginning of the 5 year period of analysis. *RefCost_5yr* is equal to *FailCost_5yr* in Table 2, i.e. without the action. *TotalCost_5yr = ActCost_5yr + FailCost_5yr* and *Profit = RefCost_5yr – TotalCost_5yr*. *Total/Ref = TotalCost_5yr* divided by *RefCost_5yr*.

The implementation of the action is profitable when *RefCost_5yr* > *TotalCost_5yr*, i.e. when *Profit* > 0 and *Total/Ref* < *0*. *Profit* and *Total/Ref* are cost-benefit based action needs indicators that help the maintenance staff to monitor when it is time for preventive maintenance or renewal due to degradation.

7 CONCLUSIONS

Deterioration of hydropower components will increase due to new operation strategies and age, and hence increase the risk related to hydropower. Risk-based maintenance management must be implemented in order to meet these challenges. The *Optimal Maintenance Toolbox* described in the paper is developed for that purpose. The *Failure model* and the tools constitute a knowledge-based framework for continuous improvement of the maintenance management processes. Monitoring of risk and action needs indicators shall help the maintenance staff to identify unacceptable risk due to deterioration and to take appropriate actions.

Maintenance management based on predefined failure models, systematic condition monitoring and assessment, risk analyses and monitoring of risk and action needs indicators represent best practice in any business. A roadmap to *World Class Maintenance* must include implementation and systematic utilisation of advanced risk-based maintenance management tools.

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