Technico-economic modelling of maintenance cost for hydroelectric turbine runners

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Abstract Large utilities need to optimize investments to maintain their assets. For a utility like Hydro-Québec (37 GW of installed power) an important part of those investments is used to maintain their hydroelectric facilities. To minimize the maintenance costs, technico-economic model are essentials. They allow to propagate the uncertainties associated with the degradation processes for a given component. Therefore, we developed two technico-economic models for Francis hydroelectric turbine runners: one for crack propagation and one for cavitation. Since these are the main degradation mechanisms leading to failure of Francis runners, they enable us to study the effect of maintenance strategies on the maintenance cost. The models have been created using VME, an asset management software developed by EDF R&D (Électricité de France). VME uses Monte-Carlo simulations to generate stochastic failure dates and obtains probabilistic indicators of the net present value of a given management strategy. Using data based on a Hydro-Québec (Québec, Canada) facility, we illustrate the importance of the proper assessment of current and expected long-term reliability on maintenance cost.

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1 Introduction

Turbines are mostly designed based on their efficiency. Most of the operation and maintenance costs are often neglected. Our objective using technico-analysis is to get more information about the costs associated to maintenance and long-term operation. The assessment of an asset management strategy needs to be done by accounting for costs across the assets life cycle. Given a current reference strategy, other strategies can be proposed and then compared using financial indicator. The cost of a given strategy depends on the possible failures of the asset and the dates of the events. This introduces uncertainty according to probabilistic reliability methods. From these, one can compute risk indicators for a given asset management strategy to support efficient and robust decisions.

The repair of a turbine runner blade can cost a significant amount of money in terms of production losses. A common repair strategy is presented in Figure 1. This strategy can be described as follows: first, a time interval between inspections. Then each time this interval is reached, an inspection event occurs. An inspection can mean weeks of turbine downtime. The magnitudes of such inspection intervals are in number of years for turbine runner. At every inspection, if a crack is detected the turbine runner is automatically repaired, except if the age of the turbine is larger than a given number of years. We have used fifty years in this case. At that time, the facility is refurbished with a new runner. This is the strategy used in this study.

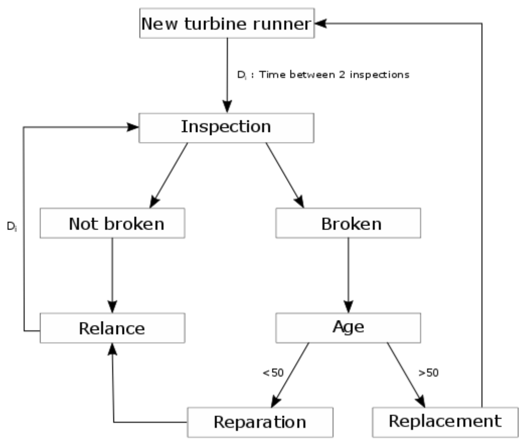

Figure 1 Current repairing strategy

VME, an asset management tool, was used to model the strategy. With VME, the first step is to build a graphic model with blocs such as ‘events’, ‘maintenance tasks’ or ‘resources’ of the chosen management strategy. Each bloc is filled with technical data - such as degradation laws and comportment after issues – and economic information. Then, the model is used for Monte-Carlo simulations which link the events and their probability to economic consequences. At the end, technical (like average number of failures or resources available…) and economic (like costs or value of production losses…) indicators are provided. Using these, the analyst can then give information to administrators help them during decision making. One of the main indicators used to evaluate the profitability of a strategy is the Net Present Value (NPV). The NPV is a classic indicator used in finance that sums the cash-flows (Figure 2), both positives ones (profits) and negative ones (investments) using the proper discount rate. A basic study, at Hydo-Quebec scale can easily results in millions of dollars benefits and this is why such calculations are so meaningful.

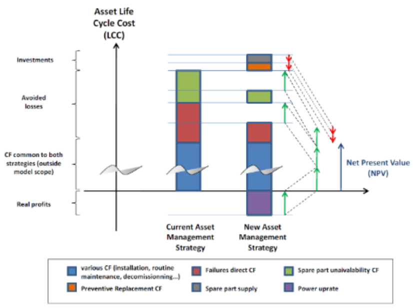

Figure 2 NPV Representation in asset management

The paper is structured as follows. First, we will have a look at the two-degradation process occurring in turbines runner: crack propagation and cavitation. Next, the study cases are presented to discuss the results obtained. Finally, we discuss the sensitivity of the assessment to uncertainties.

2 Crack propagation

Crack propagation consists in the propagation of an initial defect to a critical value due to stress cycles. In our case, the fatigue process is linked to two kinds of stresses. The first is related to the rotation of the turbine runner and hydraulic instabilities. These are considered part of high cycle fatigue (due to their high frequencies) while the second is linked to start-and-stop cycles that are part of low cycle fatigue (Gagnon *et al.*, 2012). Both have an impact on degradation process. The limit state used to determine when a stress cycle contributes to propagation is defined according to (Kitagawa, 1976). This limit state is a function of stress amplitude and defects size a, as shown in Figure 3. Then First Order Reliability Method (FORM) is used to obtain the probability of detecting a crack (Gagnon *et* *al.*, 2013). Once a crack is detected, it is automatically repaired due to the relative long inspection intervals.

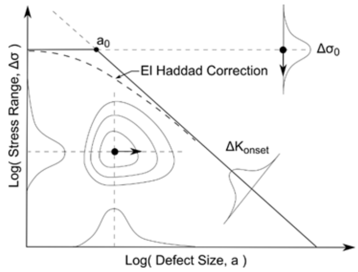

Figure 3 Kitagawa diagram and propagation threshold

2.1 Degradation types

The degradation is composed with three components (Figure 4). At the beginning there is a high probability of failure because of the lack of knowledge due to inspection methods which cannot confirm the absence of defects (dead on arrival). In this case, we cannot be sure that the turbine will survive until the first inspection. After the first inspection, if the turbine is not in a failed state, only at that time, we have the knowledge that the crack probability is null. In parallel there is also a degradation component which is a function of time. Finally, there is an uncertainty component which was not included in our model.

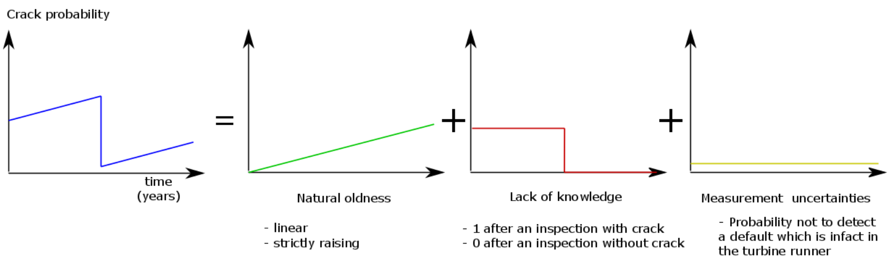

Figure 4 Components of degradation

Because we consider that repaired turbines have worst mechanical characteristics, an increased rate due to aging is expected. Furthermore, in our model, after a repair, the lack of knowledge probability is also expected to be higher. In fact, the runner blade reliability has three states: the initial state, the repaired state and zero after inspections without failure. The combination of these values leads to the results in Figure 5.

While in Figure 5 left, we show results from typical values, we have used significantly higher degradation values in Figure 5 right to highlights the correlation between the two phenomena. If natural degradation is high the percentage of new runners rises and then the proportion of death on arrival also rises. Then, when many runners are replaced, the contribution of the natural degradation decreases due to the increased percentage of new turbines.

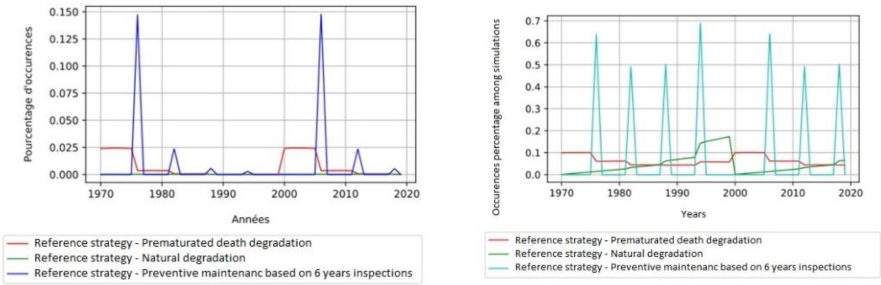

Figure 5 Technical results from crack propagation model (200 000 iterations)

2.2 Turbine runner economic model

The turbine runner modelled in this study has 13 blades. Also, we consider the runner in failed state if at least one blades has failed. To model properly the reliability, the 13 blades are modelled in series rather than the runner as a single unit. As shown in Figure 6, since each blade is independent, and it has its own influence on the turbine this allows a better precision. This should lead to more realistic behaviour and results (Figure 7).

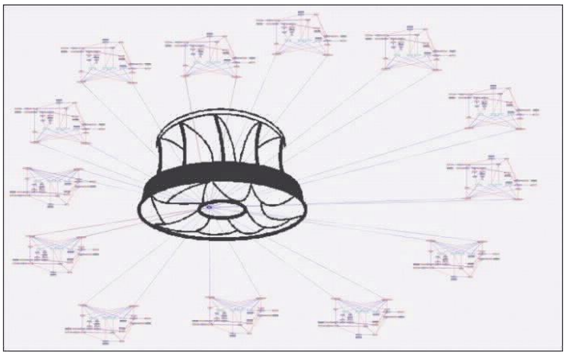

Figure 6 View of the VME crack model

In the case shown Figure 7, the reference strategy results are linked to corrective maintenance and penalties of non-inspection. The evaluated strategy corresponds to preventive maintenance and inspection costs. With time the observed steps in the evolution of cost are smaller and smaller due to actualisation. Here the evaluated strategy is less expensive which explains a positive NPV.

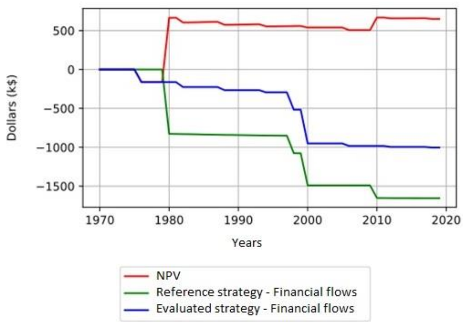

Figure 7 Evolution of the costs between two strategies given the model

2.3 Verification

To validate these results, we used the Kaplan-Meyer method. First, we defined that a single blade was in the repaired state, while keeping the other in the initial state. By increasing the number of repaired blades in turbines, we verified that the degradation increased to ensure the proper behaviour of the model. Notice that an issue related to VME is that we cannot account for the time between a failure (crack) and an inspection. Since this time interval is correlated with the repair costs this might induce some unrealistic behaviour in our study.

3 Cavitation phenomenon

Cavitation is a completely different type of degradation. Cavitation occurs due to water's change of phase. While usually water gets to boiling point with a temperature increase, in cavitation changes to gas with a pressure decrease for a constant temperature (Figure 8).

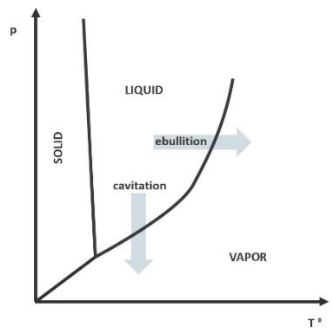

Figure 8 Water state diagram

In turbines, due to pressure changes small vapour bubbles appear. When these bubbles explode on the blade, they erode the surface of the turbine runner blades. First mechanical stresses appear leading to a hardening followed by a tearing of material. These two stages of degradation were modelled as shown in figure 9.

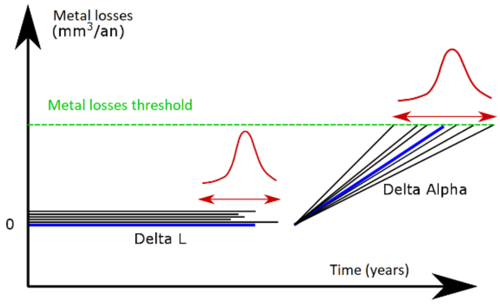

Figure 9 Schematic representation of the cavitation phenomenon

Both stages have uncertainties (Figure 9): the first one is the delay before erosion starts and the second one is the speed rate of the erosion. The loss of material will change from an inspection to another one as a function of those uncertain parameters. A variable threshold is usually set by cavitation experts in function of the use case to decide if a turbine runner need repair.

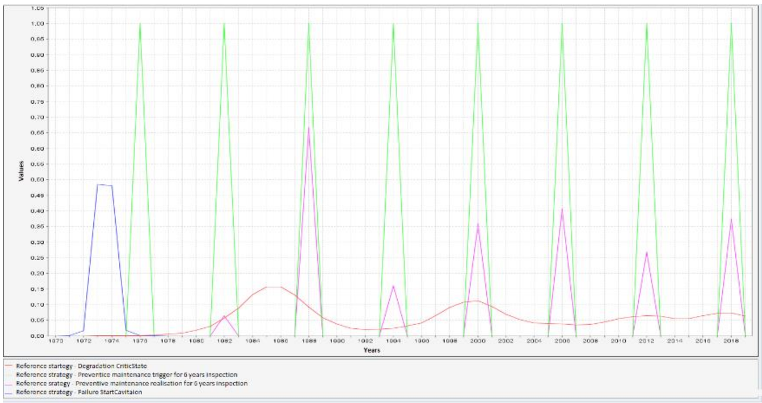

Figure 10 Technical results from the cavitation model (200 000 simulations)

Figure 10 shows the result obtained for such model. The proportion of turbines needing repair changes in a periodic manner depending on the erosion rate. We noticed in this cased that the results converge after around 200 000 Monte Carlo simulations. The results taken from our first use case are very encouraging and the use of such a tool (VME) might be scalable to much bigger situations.

4 Conclusion

To get a better idea of turbines life cycle, we were able to build technico-economic model for fatigue and cavitation analysis of hydroelectric turbine runner. We made some simplifications and assumptions so that the model obtained enable us to get economic indicators based on technical knowledge. The VME software proved to be able to account for most of our degradation process even if we noticed that it cannot properly account for the time between failure and inspection. Our results show that by modifying maintenance strategies, the model helps to understand the impacts of maintenance's strategies and chose the most financially advantageous. By combining the two degradation models, future studies will be able to model and understand the financial value of different strategies using more realistic degradation process. Later on this will be converted into considerable profits for the company.

Acknowledgement

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