Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

Wanwan Zhang

Condition-based Opportunistic Maintenance of Hydropower Stations

Master's thesis in RAMS (Reliability, Availability, Maintenance and Safety)
Supervisor: Yiliu Liu
Co-supervisor: Jiehong Kong, Hans Ivar Skjelbred
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SINTEF

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Preface

This thesis is a master project in TPK4950 as part of the study program RAMS (Reliability, Availability, Maintenance and Safety) at NTNU. The topic of this thesis is condition-based opportunistic maintenance of hydropower stations. The research is carried out with the company SINTEF during the spring semester of 2021. It gives an overview on short-term hydro scheduling, maintenance strategy and generator maintenance scheduling. A feasible condition-based opportunistic maintenance framework is proposed to fulfill the research gap between short-term hydro operation and maintenance scheduling. In the research process, SINTEF gives the model of cascaded hydropower system in their Python lab. Two supervisors from SINTEF, Jiehong Kong and Hans Ivar Skjelbred, provide research guide in operation management. Professor Yiliu Liu is responsible for the guidance and suggestions in RAMS area. The original idea of the project was brought up by SINTEF company which seeks an update of hydro model and wants to combine maintenance elements in their model. The maintenance part is discussed with Professor Liu and decided by the report author. The thesis can also be used as the reference for other hydro companies to adjust maintenance strategies. To read this thesis, readers are required to own the basic knowledge of operation and maintenance theory.

Trondheim, Norway

Wanwan Zhang

Acknowledgment

I would like to thank the following persons for their great help to my master thesis, Professor Yiliu Liu from RAMS group, Kiki Kong, Hans Ivar Skjelbred from SINTEF. With their professional and careful guidance, I felt motivated and confident to do the thesis. Since this thesis is in cooperation with SINTEF, Jiehong Kong and Hans Ivar's research is the basis and premise of my master thesis. Without their inspirational research foundation, it is not possible to complete my thesis. During my exploration for the research methods, Professor Liu gave me much encouragement, timely response, and useful advice to my research. Many mistakes I made in the thesis have been corrected by Professor Liu. It is a nice and positive experience to research under his supervise.

Except the supervisors, I also want to express my gratitude to my grandparents. My dearest grandpa is always my strongest supporter since my childhood and gives me much love, encouragement and consolation in the life. It is because of his unswerving support that I got the education chance, went to the university, stepped out of the village and came to Norway. My grandma also gives much care to me and tells me to seek what I want in the outer world, even she never attended a primary school. Their unconditional love is my forever backbone and motivation and helps me overcome difficulties with courage and confidence.

Many thanks is also given to my friends and roommates who help me a lot in the life. My friend Xuanchi Guo has accompanied me in the pandemic outbreak of Stockholm when I was in exchange. We supported each other as roommates, shared much joy and worries, successfully survived the crisis from spring to summer. I also need to thank my another friend Bingrong Huo who gives me great help in the exchange life. Her positive mind has consoled me a lot at that time. After I came back to Trondheim, the roommates in Voll also provide me much help and I appreciate them too.

Last but not least, I want to thank that NTNU gives me the chance to study here and experience the Norwegian life. Also I thank NTNU for funding me in my exchange to KTH and the gratitude also goes to all the teachers who provide high-quality courses. Education for me has always been a cruel battle. Now this battle is approaching the epilogue. There is bitterness but I also harvest happiness. All of these become the precious memories from which I learned patience, bravery and wisdom. I think this is the meaning of education for me, to learn to become a better person. I will carry these good virtues to play my role in the future life.

Wanwan Zhang

Trondheim, Norway

Abstract

The purpose of this thesis is to build a new condition-based opportunistic maintenance (CBOM) framework which combines short-term hydropower operation scheduling (STHS) and generator maintenance scheduling (GMS). It presents the challenges and limitations of current hydro maintenance research, the state-of-art of hydro generation and optimization in Norway. With the existing STHS framework, the CBOM framework supplements the requirements of building failure model and CBOM model. The generator PLANT004_G1 in the cascaded hydro system is used as the research example. The CBOM model finally schedules 9 maintenance activities in one year for the generator. The sensitivity analysis of the CBOM model shows that it has enough flexibility and can be adjusted according to the maintenance requirements. Among all the parameters, accident penalty and maintenance duration do not influence the maintenance results. The alert level and the upper OM threshold influence the number of maintenance activities. The latter also affects the value of accumulated profits. It is proved that the new CBOM strategy cancels or postpones many unnecessary maintenance activities and is more profitable than age-based maintenance and corrective maintenance.

Contents

List of Figures

List of Tables

Nomenclature

ABM	Age-based Maintenance
ACO	Ant Colony Optimization
CBM	Condition-based Maintenance
CBOM	Condition-based Opportunistic Maintenance
DA	Dynamic Programming
DDPM	Data-driven Predictive Maintenance
GENCOs	Generarion Companies
GMS	Generator Maintenance Scheduling
HGTU	Hydro Turbine Generator Units
HHPs	Hydro Power Plants
HMM	Hidden Markov Model
HPS	Hydro Maintenance Scheduling
IHA	International Hydropower Association
ISO	Independent System Operator
LHP	Large Hydro Plants
MINLP	Mixed Integer Nonlinear Programming
MIP	Mixed-integer Programming
MLE	Maximum Likelihood Estimation
MTFF	Mean Time to the First Failure
MW	MegaWatts
NVE	Norwegian Water Resources and Energy Directorate

OM	Opportunistic Maintenance
PBS	Profit-based Hydro Scheduling
RAMS	Reliability, Availability, Maintenance and Safety
RBD	Reliability Block Diagram
RCM	Reliability Centered Maintenance
RUL	Residual Useful Lifetime
S2ML	System Structure Modeling Language
SA	Successive Approximation
SBE	Stochastic Boolean Equation
STHS	Short-term Hydro Scheduling
TBM	Time-based Maintenance
WBS	Water-based Hydro Scheduling

Chapter 1

Introduction

This chapter has 4 sections. It starts with the background of hydroelectric power generation and maintenance in Norway. The maintenance scheduling problem is formulated based on the background, then 5 research goals are defined in detail for the maintenance problem. The final section gives a brief description of the thesis structure.

1.1 Background

Hydropower is the sum of kinetic energy and the potential energy stored in the running water. It is one of the renewable energies and frequently used to generate electricity. In the physical world, hydropower not only reduces the carbon emissions but also plays a crucial role in ensuring energy safety. One statistical investigation during the Covid-19 Pandamic period shows that hydropower is influenced relatively less than oil and gas and it makes a contribution to keeping steady electricity generation (IHA, 2020). The only premise for making hydropower exist is the water. The kinetic energy in the water can be converted from the potential energy. And the potential energy of water can naturally exist due to the gravity of the earth. This proves the reliability and resilience of hydropower in crisis.

In Norway, hydropower has been regarded as the backbone of its energy system because of this country's mountainous geography [1]. In 1991, the Norwegian electricity market was deregulated by the government (Royal Ministry of Petroleum and Energy, 1990). Since then, sellers have been allowed to supply electricity totally out of their own profits. The hydropower industry and electricity market grow and expand prosperously due to the free market policy. In 2014, the electricity supply from hydropower exceeded the supply from oil (see figure 1). According to the 2020 hydro status report (IHA, 2020), Norway's total hydro installed capacity has reached 32671 MW in 2019 and the annual hydropower generation is 125.77 TWh, which makes Norway become the top hydropower producer in Europe.

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[1] https://www.hydropower.org/country-profiles/norway

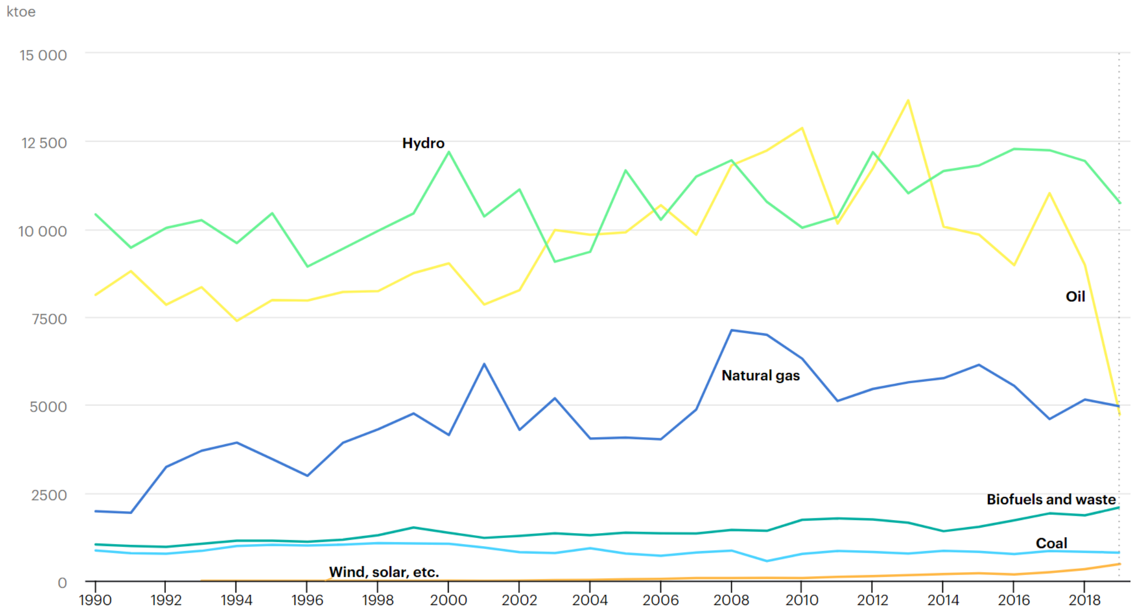

Figure 1: Total energy supply in Norway (IEA, 2020)

Hydropower stations can be classified into four categories in terms of the generation capacity. The table 1 presents the statistics about the composition of the hydropower system in Norway. The data is from Norwegian Water Resources and Energy Directorate(NVE) and updated till January of 2020. It shows that the production of large power plants (LHPs) with over 100 MW capacity accounts for 60.67 percent out of the overall hydropower generation, which suggests the production of LHPs has a significant impact on the hydropower supply of Norway.

Table 1: CBM methods for hydro units

Category	Quantity	Performance(MW)	Avergae annual production(TWh)
Under 1 MW	574	186	0.8
1-10 MW	737	2633	10.3
10-100 MW	257	9582	42.3
Over 100 MW	83	20270	82.4
In total	1651	32671	135.8

Moreover, multiple plants can be connected in parallel or series to form a large cascaded hydro system with greater capacity. The operation of cascaded hydro system is more complex than single plant because of the head-dependent relationship and heterogeneous maintenance conditions among plants. The maintenance activities inevitably halt the electricity production, which could affect the profit of plants. For large hydropower plant, the profit loss is high if the electricity can not be produced at the high market price.

However, if generators are not well maintained, the failure in generators will cause the plant outage and bring much more cost. If one accident happens, the production loss estimation per day is over 100 000 EUR for big power plant (Welte, 2008). The accident cost consists of the direct machine damage and human injury. It also can ruin the reputation for hydropower company and cause the loss of existing and potential customers. Therefore, it is important to conciliate the relationship between operation and maintenance in a scientific way.

1.2 Research problem formulation

Generator system is the key part of hydropower generation. The current maintenance strategy is the combination of preventive maintenance and corrective maintenance (Xu et al., 2019). The corrective maintenance is to repair the broken components after the failure appears. When there is no failure in the daily operation, hydro plants usually maintain the generator system in a periodic way. The intervals between two maintenance activities are mostly based on the failure history and expert's judgement.

With the development of industry 4.0, the physical items are connected to the internet and the real-time data can be transmitted by various sensors. Influenced by smart industry, the maintenance concept has evolved from traditional preventive maintenance to condition-based maintenance (CBM). Condition-based maintenance requires maintenance engineers to consider the real condition of objects and adjust maintenance intervals or strategies according to different conditions (Rastegari, 2017).

The commonly observed parameters include frequency, temperature, vibration, speed, partial discharge and cavitation etc. Based on the analysis of parameters, the generator condition can be determined and predicted. Relevant change in maintenance schedules can be made according to the condition. Compared with preventive maintenance, condition-based maintenance can avoid insufficient or unnecessary maintenance activities.

A trend from preventive maintenance to condition based maintenance appears in hydropower industry. However, this transition can not solely happen to the maintenance area. Because the operation of hydro plants need the three-party cooperation. The participants include maintenance experts, operation experts and independent system operators. Change in maintenance modeling will influence both the maintenance scheduling and operation plan for hydro plants.

For operation experts, the most common way to schedule the maintenance is to put maintenance tasks under the framework of operation optimization. When the operation expert schedules the optimal operation with maintenance tasks, the expert considers the maintenance tasks as the known constraints on electricity production. In most cases, maintenance tasks are scheduled on the fixed dates and only need to be added to the operation plan in advance.

However, the goals of maintenance engineers and operation experts are contradictory. The objective of operation experts is to make as much profit as possible, while the goal of maintenance engineer is to make the components as reliable as possible. In the production scheduling, the maintenance plan is regarded as the constraint on production. But scheduling maintenance does not necessarily consider the production unless the production has a significant impact on the failure characteristics.

To solve the conflict between production and maintenance, it is necessary to develop the new profit-oriented maintenance model. At the same time the new condition-based maintenance model for hydropower system is required. Hence, this thesis is to explore the possibility of combining the two requirements. The research problem is to discuss how to connect hydropower operation scheduling with generator maintenance scheduling by a new CBM model.

For operation scheduling model, there are long-term model, mid-term model and short-term model. The short-term model tends to be deterministic model and follows the results from long-term and mid-term plans (Fosso and Belsnes, 2004). It can provide more detailed production data than long-term or mid-term models. To clearly present the research result, this thesis chooses the short-term operation model as the research basis. Now the research scope is delimited to the maintenance scheduling in the short term. This research problem can be divided into the two sub-problems:

- How to consider the influence of electricity production in the condition-based maintenance model?
- How to integrate the new CBM model with generator maintenance scheduling?

This research problem combines the RAMS knowledge, hydrology knowledge and operation knowledge. Fulfilling the gap can shed some light on the potential development of CBM models in the hydropower industry. Since this research is in cooperation with SINTEF company, solving this problem can help SINTEF company to update their operation model which is designed for Norway's cascaded hydropower plants. The updated model can also become an available choice when the hydropower companies want to renew the maintenance scheduling methods.

1.3 Research objectives

The main objective is to construct a new framework of condition-based maintenance in the short term for hydropower plants so as to improve the technical availability and economic profits of hydro plants. Figure 2 shows the overlapped area that this research belongs to. The new CBM model needs to be developed with consideration of the three aspects. The new framework will satisfy both maintenance need and economic demand.

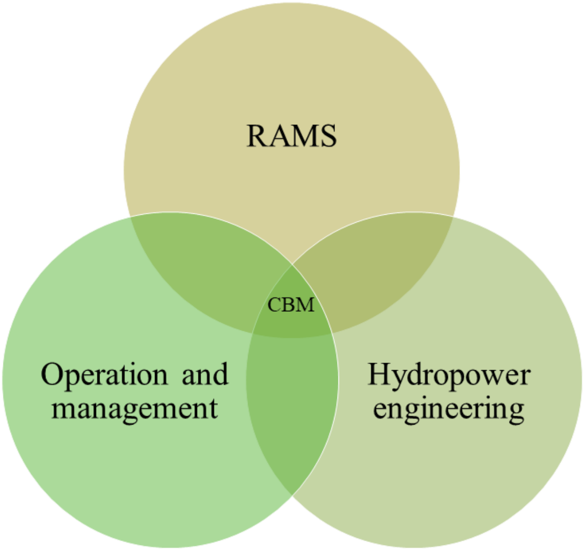

Figure 2: Research areas

To fulfill the main research objective, the following specific goals are put forward.

Goal 1: To identify the deterioration modeling of hydropower generators

The construction of degradation model should be reasonable and practical. For generators, the degradation model needs to reflect the characteristics of the inner structure and predict the trend of degradation. The suggestions about which types of data are to be collected and estimation methods of parameters should also be provided in the research.

Goal 2: To develop new CBM model based on the degradation and operation

The maintenance model is required to combine the degradation trend and the operation requirements. In this thesis, the operation research of cascaded hydropower system has been constructed by SINTEF. Both the results from degradation model and the operation model are the input data to maintenance model. The maintenance model finally needs to present a specific maintenance plan for a particular hydropower plant.

Goal 3: To identify a trade-off between economic goal and maintenance objective

From an economical perspective, the objective of operation is profit-driven and maintenance is purely an action which harms profits. The goal of maintenance is to extend the lifetime of generators and reduce failures. Maintenance engineers frequently need to make a trade-off between the maintenance and production in reality. The new CBM model should clearly describe the trade-off process.

Goal 4: To present the cost-efficient advantage of new CBM model

It has been proved from a policy perspective that CBM is more cost-efficient than TBM (Ahmad and Kamaruddin, 2012). However, the effectiveness in hydropower industry is still not certain and waits to be investigated. To present the cost-efficient advantage, the benefits of new CBM model should be visible and specific, including invisible safety cost and maintenance investment. The quantification of maintenance benefits is necessary and should be included in the objective function.

Goal 5: To provide evidence to practitioners by research examples

A example of how to apply the whole model should be provided. The results should be analyzed and well described in the thesis. The sensitivity of this model should be discussed. The advantages and limitations of this maintenance model is required to be presented to the stakeholders.

1.4 Thesis structure

This report contains six chapters. Chapter 1 introduces the background of hydropower industry in Norway and formulates the research problem and objectives. Chapter 2 gives a review of maintenance strategy, short-term hydro scheduling, and generator maintenance scheduling. Chapter 3 proposes the new framework. Chapter 4 uses a case study to illustrate the application of the proposed model. Chapter 5 discusses the sensitivity of new model towards the change of parameters. Finally, conclusions and future work is summarized in Chapter 6.

Chapter 2

Literature review

This chapter reviews the maintenance strategies, maintenance management, generator maintenance scheduling and short-term hydro scheduling. Limitations and implications obtained from the review are also described.

2.1 Typical classification of maintenance types

Based on European standards (CEN, 2012; BSI, 2010), maintenance can be classified into two main categories: corrective maintenance and preventive maintenance. Corrective maintenance is to repair or replace item to a brand new state after the failure happens, while preventive maintenance is conducted on the operating items before the failure happens (Trojan and Marçal, 2017). Here the preventive maintenance is an expansive term that indicates any maintenance measure before the accident happens. As Shin and Jun (2015) points out, condition-based maintenance can be classified as one kind of preventive maintenance based on the expansive definition. In figure 3, Preventive maintenance is spilt into time-based Maintenance (TBM) and condition-based Maintenance (CBM).

TBM and CBM have more differences than similarities. Both TBM and CBM can be scheduled on timetable, but CBM includes continuous monitoring. One obvious difference between TBM and CBM is that the maintenance action in CBM depends on the state of components. CBM does not require the maintenance to repair the component completely. However, in TBM the action is predetermined as repair or replacement and those actions always bring the component to as good as new state (Vaurio, 1997). Another significant difference is that the intervals between maintenance can be dynamic and vary with the condition of components in CBM, but TBM tends to use fixed predefined maintenance intervals.

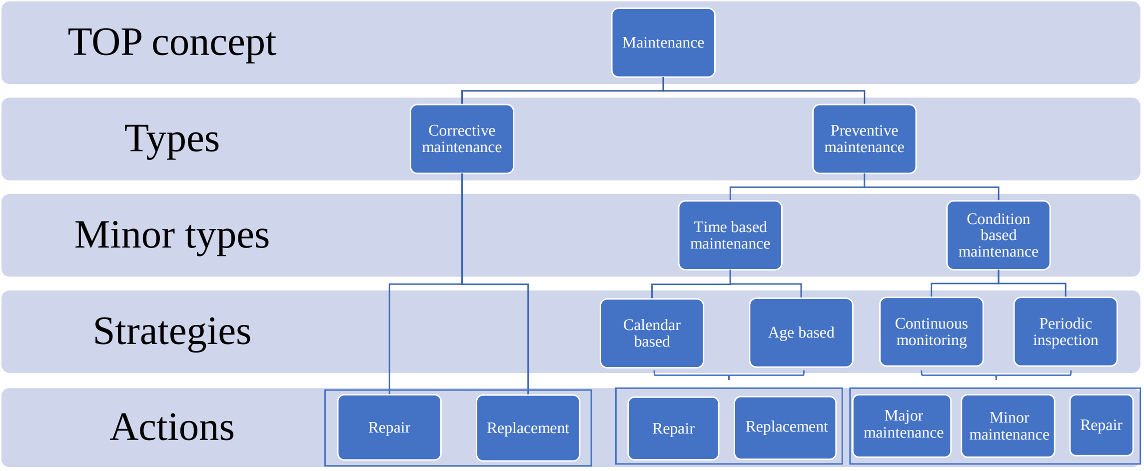

Figure 3: Classfication of maintenance

In addition, CBM works on an assumption that the deterioration of system takes time and the accident does not happen instantly. CBM focuses more on the modeling of deterioration and easily changes maintenance schedules according to the deterioration condition (Fu et al., 2004). In some sense CBM can be similar to age-based maintenance of TBM. In this thesis, the definition of age-based maintenance(ABM) refers to a specific group policy of maintenance activities and it is mainly used in the multi-component system. For example, Shafiee and Finkelstein (2015) uses this type of ABM: they decide to prioritize the maintenance of any component whose age exceeds the alert level. The decision of ABM is made only based on the age of components. Compared with ABM, CBM can consider more factors that are related with the components and not just focuses on the age.

For hydropower industry, the key component to be maintained is the hydro turbine-generator unit (HTGU), because it includes the core machines which can generate hydropower (Li et al., 2020). The maintenance of HTGU is a complex bureaucratic process and has the feature of high cost and long repair time (Xu et al., 2019). Generally, Hydropower plants (HPPs) adopt a combination of TBM and corrective maintenance to maintain HTGUs (Wang et al., 2016; Xu et al., 2019). The TBM method can be calendar-based maintenance or age-based maintenance.

For the calendar-based maintenance, it does not take the real age of components into account, which causes unsuitable maintenance activities. For the age-based maintenance, it only schedules the maintenance based on age and ignores the production condition, which is likely to bring profit loss. No matter whether it is calendar-based or age-based, the interval often relies on expert experience and failure statistics. It is frequently recommended by experts that HPPs should conduct frequent maintenance activities to avoid the high risk of failures (Yildirim et al., 2016a). This could lead to extra and unnecessary maintenance investment. To overcome these disadvantages, the maintenance of hydro power plants should be shifted to CBM.

2.2 Review of CBM on hydro units

This section is to review how CBM of hydro units is achieved in the physical world. As it is mentioned in the figure 3, traditional CBM strategies can be continuous monitoring or periodic inspection. Continuous monitoring is also named as online monitoring and relies on sensors to send the condition information, while periodic inspection is conducted by maintenance experts.

Some CBM researches are dedicated to the promotion of sensor-driven maintenance. For example, Selak et al. (2014) present condition monitoring and fault diagnostics (CMFD) system for the hydro turbine. This system has the function of acquiring the signals, transmitting data flow and diagnosing the condition by the support vector machine method. Yildirim et al. propose a two-module model which combines the sensor data analysis and mixed-integer programming (MIP) model in two papers (Yildirim et al., 2016a,b). In the first module, data collected by sensors is analyzed by Bayesian prognostic techniques to predict the residual useful lifetime (RUL) of generators. The second module is to integrate the analysis results into the MIP model and schedule the optimal maintenance dates in the 8 weeks. Basciftci et al. (2020) demonstrate a linear load-dependent degradation model to estimate RUL of generators by sensor. They also develop MIP model and decision-dependent simulation to calculate cost and failure frequency. The commonness in these researches is that the data from sensors needs to be analyzed to reveal the degradation level or used as the input of a deterioration model. After the condition is predicted, the maintenance plan is decided by the MIP model which minimizes the maintenance cost.

Similar to the sensor data, the data from periodic inspections can also be used to schedule maintenance. In the research of Welte et al. (2006), a Markov chain is applied to simulate the maintenance conditions of hydro units. The imperfect repair can be simulated by setting components to imperfect states or changing the transition rate between states. The length of inspection interval depends on the state of components in the previous inspection. Li et al. (2020) suggest a dynamic offline maintenance planning for HPPs. They use Hidden Markov Model (HMM), which is a model-based life cycle assessment (LCA) method, to analyze inspection data of hydro turbine runner cracks and gain the transition states probabilities. The analytical results are used to estimate the RUL of turbine runner and decide maintenance intervals. The two studies suggest that Markov model is a practicable method to schedule maintenance interval for offline CBM.

Except traditional CBM, the mixed maintenance strategy and predictive maintenance can also be a good reference. Kumar and Singal (2014) present a software package Reliability centered maintenance (RCM) which combines all the maintenance approaches such as run-to-failure, CBM and TBM etc, to obtain the best maintenance performance with the minimum maintenance cost. Wang et al. (2016) give a review of predictive maintenance and propose that maintenance should only be executed at the most appropriate time and maximizing the RUL of components without increasing failure risks. To achieve this goal, the intelligent big data analysis is the basis of maintenance. To avoid ambiguity of terms, these strategies are also regarded as CBM in this thesis, since all of them include the condition analysis of components.

The table 2 gives a summary of methods mentioned in the CBM review. In their research, the related software and packages are specially designed but there is no source codes attached in the papers. Therefore the software methods are not suggested. MILP and MIP refer to the mixed linear model. Constructing an linear objective function is the feasible way to realize the new CBM model. To build the linear model, the condition of components should be analyzed or given in the early stage.

Table 2: CBM methods for hydro units

CBM types	Methods	Reference
Continuous monitoring	condition monitoring and fault diagnostics (CMFD) software	Selak et al. (2014)
	Bayesian prognostic techniques and MILP model	Yildirim et al. (2016b)
	MIP model for sensor-driving degradation of generators	Basciftci et al. (2020)
Periodic inspection	Markov chain	Welte et al. (2006)
	Hidden markov diagram	Li et al. (2020)
Other model	RCM software package	Kumar and Singal (2014)

In summary, the development of CBM in hydro power industry is still in the initial stage. Online CBM relies on the sufficient sensor data and offline CBM mainly uses Markov Model. Both CBM strategies need reliable programming algorithms to find the best solution. The apparent drawback is that the current research of CBM does not consider the influence of electricity market. This makes it difficult to combine the STHS and CBM in maintenance practice. Because the downtime cost varies with the changing electricity price in the market (Qian and Wu, 2014). It enlightens that the range of condition in CBM should be expanded to include economic factors not just technical failure condition.

2.3 Management of maintenance schedules

In the management practice, the coordination between maintenance schedules and operation schedules is achieved by the Independent system operator (ISO). Generation companies (GENCOs) or plants submit their profit-oriented maintenance intervals to ISO and ISO decides whether it can realize the reliability and safety goal. If the plan satisfies all the objectives, it will be accepted and conducted, otherwise the plan will be resent to GENCOs to be modified (Dahal et al., 2015; Bahrami and Moazzami, 2019). GENCOs desire to get the maximum profits while ISO want to ensure the reliability of power generation. From GENCOs' perspective, the maintenance cost should be as minimum as possible. For ISO, the maintenance should enhance the reliability to a certain desired level (Mukerji et al., 1991). In most cases, the two objectives are difficult to be harmonized.

It is worthwhile to point out the difference of reliability concept in energy engineering and maintenance research. The reliability in energy study refers to the reliability capacity which is the difference between available generation capacity and electricity demand. However, reliability is defined as "the ability of a system or component to perform its required functions under stated conditions for a specified period of time" in the standard ISO/IEC and IEEE (2010). It is usually denoted by mean time to the first failure (MTFF) in RAMS analysis and is an important parameter of failure (Sherwin et al., 1995). What the ISO want to improve is not the failure-tolerant ability of the targeted system but the generation capacity.

The limitation in the maintenance management of power industry is that both GENCOs and ISO ignore the failure principle and characteristics of generators. They only arrange maintenance activities from the economic and management point of view. Their common goal is to satisfy the electricity demand or reach the maximum power generation. The engineering features of generators are omitted or idealized in their plans. It is possible that most of the maintenance activities are unnecessary or conducted in the wrong time. In addition, the negative effect of industrial accidents, such as the potential safety cost and reputation damage, are ignored. This kind of maintenance schedule could bring more potential cost in the long run. Therefore, it is important to integrate the CBM strategy into current hydro maintenance management.

2.4 Generator maintenance scheduling

Generator plays a critical role in any power generation area due to its power conversion function. In terms of its importance, there is a vast amount of literature in generator maintenance scheduling (GMS). GMS research is different from the maintenance research in RAMS area but more close to the optimization research. The goal of GMS is to arrange generator's maintenance activities by an objective function to schedule an optimal timetable under some constraints. The objective can be economic-driven goal (e.g. maximizing profits), or reliability-centered goal, such as maximizing reliability.

For hydropower industry, GMS has a crucial impact on power generation and capital expenditure of HPPs. GMS is to arrange maintenance dates in an optimization way. On the one hand, the inactive state of generators in maintenance interval decreases the amount of power output. On the other hand, the life span of generator is extended by maintenance and the purchase of backup generators can be postponed (Volkanovski et al., 2008). Different from other industries, GMS in hydropower generation must consider the features of hydro environment, for instance, nonlinearity of hydropower production function, the uncertainty of water flows and interdependence of hydro variables (Rodríguez et al., 2021) as well as the impact of maintenance on profits.

However, most literature studies the thermal generator and only a few focuses on the hydroelectric generator. The time horizon is generally preferred to be one year with weekly time units (Ilseven and Göl, 2020). For example, Foong et al. (2008) use Ant colony optimization (ACO) to schedule a five-station hydropower system. Their objective is to maximize the reliability of power system which is the sum of squares of reserve capacity. Canto (2008) consider three types of power plant and construct an objective function to minimize the sum of production cost, start-up cost and maintenance cost under maintenance, economic and commitment constraints. Benders decomposition is used to optimize maintenance schedules.

Similarly, Helseth et al. (2018) apply the Benders decomposition to coordinate the maintenance scheduling with mid-term hydro operation for a Norwegian watercourse. Their goal is to maximize the expected revenue of energy production. Rodriguez et al. (2018) propose a MILP model to address the GMS problem in HPPs. They maximize the difference between the net profit of power generation with maintenance decisions and the maintenance cost. They consider the hydro variables of a Canadian hydropower plant and basic maintenance constraints such as the maximum number of outages, the completion of predetermined maintenance tasks and the number of active generators. After two years, Rodríguez et al. (2021) extend the MILP to two-stage stochastic program. The objective function is still the difference between expected profit and maintenance cost. The table 3 summarizes the hydro GMS researches.

Table 3: Hydro GMS researches

Reference	Objective function	Constraints	Approach	Time	Case study
Canto (2008)	Minimize the sum of cost	Maintenance constranits Economic and unit commitment Power generation	Bender's decomposition	One year	75 Spanish power plants(50 thermal, 20 hyroelectric and 5 nuclear)
Foong et al. (2008)	Maximize the sum of squares of reserve capacity	Maintenance windows Load constraints Resource constraints Precedence constraints Reliability constraints	Ant colony optimization	One year	5-station Tasmania hydro plant. 14 maintenance tasks
Helseth et al. (2018)	Maximize the expected revenue	Hydro constraints Maintenance window	Bender's decomposition C++ with Gurobi 7.5 library	Two years	A Norwegian watercourse with 7 reservoirs
Rodriguez et al. (2018)	Maximize the net benefit	Power generation Maintenance activity Hydro constraints	MILP	One month	A Canadian cascaded power plants. 18 maintenance tasks
Rodríguez et al. (2021)	Maximize the net benefit	Maintenanc activity Hydro constaints Power generation	Bender's decomposition	15 days	A four-plant system. 8 maintenance tasks

The common maintenance constraints include the maintenance window, precedence constraint, number constraints etc.

(1) Maintenance windows

Maintenance window defines where the specific generators should start and finish maintenance in this duration. It can be expressed as equation 1. T_m is the starting time sets for maintenance activity m, which should be between the earliest starting time Ear_m and latest ending starting time Lat_m (Foong et al., 2008; Rodriguez et al., 2018). It is assumed that any maintenance activity should be completed during the time horizon $T_{horizon}$, so the ending time of the latest activity should not exceed $T_{horizon}$ as equation 2. Dur_m is the duration of maintenance activity m.

$$\mathrm{T_m = \{t \in T_{plan} | Ear_m \leq t \leq Lat_m\}} \tag{1}$$

$$\mathrm{Ear_m \leq Lat_m \leq T_{horizon} - Dur_m + 1} \tag{2}$$

(2) Precedence constraint

Precedence constraint defines the local sequence of maintenance activities. If the activity n is prior to the activity m, then they should satisfy the equation 3. Sat_n is the starting time of maintenance activity n (see reference Canto (2008)).

$$\mathrm{T_m = \{t \in T_{plan} | Sat_n + Dur_n - 1 \leq t \leq Lat_m\}} \tag{3}$$

(3) Number constraint

Maintenance decision variable is expressed as the binary variable $y_{m,t,c}$. It denotes whether maintenance activity m is conducted at the plant c at the time t. The total number of activities for plant c is predetermined as β_c and the sum of conducted activities should not be larger than β_c (Rodriguez et al., 2018).

$$\mathrm{y_{m,t,c}} = \begin{cases} 0 & \text{maintenance is conducted} \\ 1 & \text{no maintenance} \end{cases} \tag{4}$$

$$\sum \mathrm{y_{m,t,c}} \leq \beta_\mathrm{c} \tag{5}$$

2.5 Review on short-term hydro scheduling

This review is to summarize the practical engineering properties of hydro power scheduling problem. Figure 4 shows the number of articles about SHTS from 1992 to 2019. It is obtained by searching key word"short-term hydro scheduling" on Web of science. The researches' number increases greatly since 2004 and keeps stable in recent 3 years, which suggests STHS was a hot research area and currently reaches its bottleneck. This is because the progress in objective function research is not as much as in the programming algorithm for STHS. When the programming method is strong enough to solve the complex objective function. The research focus is transferred to update the structure of the objective function. However, the function update needs the radical development in the principles of hydropower operation, which is a difficult research area.

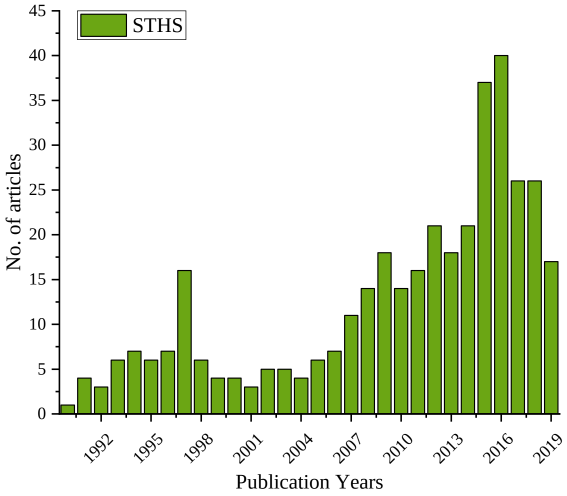

Figure 4: The number of articles by publication year

The appendix A gives the summary of constraints of STHS study. Based on literature in appendix A, the objective of STHS functions can be divided into two categories, profit-based hydro scheduling (PBS) and water-based hydro scheduling (WBS). The two scheduling methods have many differences. PBS aims at maximizing the profit of hydropower sales in the electricity market, whereas the goal of WBS is to minimize the water consumption under the premise of meeting the electricity demand. In addition to different objectives, the two methods considers different constraints to optimize the operation of plants.

For PBS, there are two typical profit functions. The traditional net benefit function equals the total revenue plus stored water value minus generation costs. Generation costs mainly refer to the start-up and shut-down costs or other penalties. When the costs are too small and can be ignored, the net benefit function becomes the total income function. The only difference between the two kinds of functions is the generation costs. Due to the complex hydro environment, the construction of profit function also keeps developing towards a more complicated direction and the two basic profit functions can be altered to adapt to the specific hydro scheduling problem.

Most researches directly use the total income or the real revenue as the objective function and use different programming methods to obtain the optimization solution. The possible methods include nonlinear programming (Mariano et al., 2007; Wang, 2009; Pérez-Díaz et al., 2010b), particle swarm optimization and chance-constrained Programming (Jiekang et al., 2008), dynamic programming model (Pérez-Díaz et al., 2010a; Feng et al., 2017), quadratic programming (Kladnik et al., 2011), aggregation-decomposition method (Shayesteh et al., 2016), two point estimate method (Sharma and Abhyankar, 2017), successive approximation (Ge et al., 2018) etc. Some researches directly use the net benefits as the objective function. Lagrange relaxation (Cong et al., 2002), Mixed-integer linear programming (Borghetti et al., 2008) can also be used to solve the maximum problem.

In regulated market and vertical linked plants, the maximum profit goal of PBS can be converted as the maximum of power generation. when the hydro electricity price has little fluctuation under the government regulation (Ge et al., 2014; Guo et al., 2020). Immune algorithm and data mining technique can be applied to maximize the total hydropower generation under hydro environmental and technical constraints (Fu et al., 2011; Ma et al., 2013; Bai et al., 2017). With electricity demand, the maximum production goal can be changed into the min-max objective. For example, Wang et al. propose an min-max objective function in 2017 to schedule hydro power operation by minimizing the gap between generated electricity and electricity demand.

The power output can be degraded to the potential energy stored by the water in reservoirs. The PBS objective can be further changed into the maximum water volume in reservoirs or the largest power generation efficient of HPPs. Ak et al. (2017) review all the operating policies for the single reservoir hydro system and propose to maximize the average annual revenue or the average power output. Guedes et al. (2017) describe an unit-based algorithm which maximizes the final water storage with the highest power generation efficiency on the unit level, given the hydro constraints. Bensalem et al. (2007) design a novel discrete maximum method to schedule the hydro power plant. They maximize the potential energy of stored water by dividing the time horizon into small time periods.

WBS focuses more on generation costs. The costs may not be monetary but closely linked with the hydro condition of HPPs. For example, Naresh and Sharma (2002) suggest that the goal can be set to minimize the sum of energy cost which represents the gap between energy demand and generated power. Cristian Finardi and Reolon Scuzziato (2013) use the discharged outflow to determine the water consumption and try to minimize the necessary flow and satisfy the electricity demand under hydro technical constraints. Lu et al. (2015) have a goal function to minimize water consumption of cascade system with start-up and shut-down costs and optimize it by a new bee colony algorithm. Mo et al. also develop an objective function to minimize the water consumption and meet the electricity generation demand meanwhile. Hidalgo et al. (2015) switch to focus on minimizing the daily water release to save water and reduce the number of start-ups and shut-downs of generator units. Zhong et al. (2020) minimize the deviation of power output with the expected load because the hydropower plant system is operated as a supplement to thermal coal plants.

Sometimes, PBS and WBS can be combined to schedule hydro operation. Li et al. (2015) study two objective functions by a heuristic algorithm. One objective is to minimize the water consumption and another is to maximize the power generation. Marchand et al. (2019) provide a global objective function with 4 criteria of satisfying bounds of flow and generation units, reaching maximum system efficiency, minimizing load difference and the number of start-up and shutdowns. With the fast progress in the programming techniques, the complicated objective function of PBS and WBS can be solved by suitable algorithms.

It can be noted that STHS studies rarely consider the influence of maintenance and concentrate on the hydro characteristics. The electricity price is the driver of STHS operation. Second, STHS seeks for high time resolution, for example, hourly generation. Much efforts are made to improve the programming technique not modify the function and constraints.

In the current STHS research, the results from generator maintenance scheduling are regarded as one type of hydro technical constraints. GMS can be profit-oriented and reliability-oriented, but STHS only considers the profit and cost. It is possible to combine GMS and STHS, but the integration of GMS and STHS faces the special challenges such as overcoming the objective conflicts, harmonizing the difference among constraints, time resolution and optimization methods.

2.6 Limitations and implications

There are some implications after reviewing CBM, GMS and STHS. The maintenance intervals and activities are always fixed and predetermined in Hydro GMS researches, which suggests TBM occupies the dominant place in HPP maintenance. Besides, the minimal unit time horizon is day or week, which is different from the hourly unit time in STHS. Since GMS and STHS can share a similar maximum profit goal, it is possible to combine the two researches. To conquer the operation and maintenance problem, some specific limitations of current researches are identified and summarized as follows.

- The hydro power industry currently adopts time-based maintenance and it brings much extra cost in maintenance expenditure. The shift to condition-based maintenance is necessary but still facing many problems, such as the requirement of sufficient sensor data and advanced programming algorithms.
- The condition-based maintenance research does not consider the condition of economic factors and mainly focuses on technically failures and influence, which makes it difficult to combine CBM and STHS.
- The operation management tends to ignore the failure principle and influence of components. It is only subject to electricity demand requirement or profit goal. It is likely that the schedule that meets those economic and management demand but cannot fulfill the technical reliability demand. This may bring large failure cost in the future.
- There is only a few papers on generator maintenance Scheduling in hydropower industry and they only use TBM intervals. The research on the integration of CBM in GMS is still blank. Likewise, the combination method of GMS and STHS needs to be explored, especially on adjusting the different time horizons and constraints of the two researches.

Since there is a research gap among CBM, GMS and STHS, this research aims to propose a framework which can accomplish the integration of the three research models. To combine the GMS and STHS, there are two steps to take. The first step is to replace TBM in GMS by CBM. It requires a new CBM strategy for hydropower plant. To adapt CBM to hydro GMS, the fixed maintenance interval should be changed to be dynamic and condition of generators is the analytical base. The second step is to combine the updated GMS with STHS. The difference in time horizon should be adjusted to the same. Time resolution and the constraints need to be selected. The calculation of maintenance cost should count the influence of electricity price in the downtime. Accomplishing the two steps can achieve a new CBM scheduling model under the framework of STHS.

Chapter 3

Methodology

This chapter explains the methods to solve the maintenance problem. The first section presents the framework of STHS that has been developed by Sintef, which is the premise of the research problem. The second section describes the programming language and possible mathematical failure models. The third section proposes condition based opportunistic maintenance strategy. The final overview of work is provided and described.

3.1 Optimization of hydropower production

In Norway, researchers take a maximum profit objective function with hydro environment constraints and use various programming methods to optimize it under different backgrounds (Belsnes et al., 2016; Kong et al., 2020; Skjelbred et al., 2020). In this thesis, SINTEF company provides its own operation framework of short-term hydropower optimization. Figure 5 gives the details of current hydro optimization framework from SINTEF. This research model is achieved by the SHOP module in Python.

The electricity price is determined by the energy supply and demand. The forecast of electricity prices is fundamental study and the basis of operation scheduling. Generally the prediction of electricity price is done in the long term and gives support to short-term operation study. To forecast prices, essentially is to predict the total demand and the total supply in the market. The prediction of hydropower supply needs to model the bidding behaviours and capacities of all the participants (Ilseven and Göl, 2020), while the energy demand is predicted by the electricity consumption.

The forecast of hourly prices is from a macro perspective and considers all the participants in the market. However, a single participant can only accept the electricity price and cannot influence it. Since the operation researcher observes the electricity market from a single participant's perspective, the hourly electricity prices are always predetermined. The study perspective is transferred from a macro market view to a micro participant's view. Now the problem becomes how to optimize the generation of hydropower plants under the given prices.

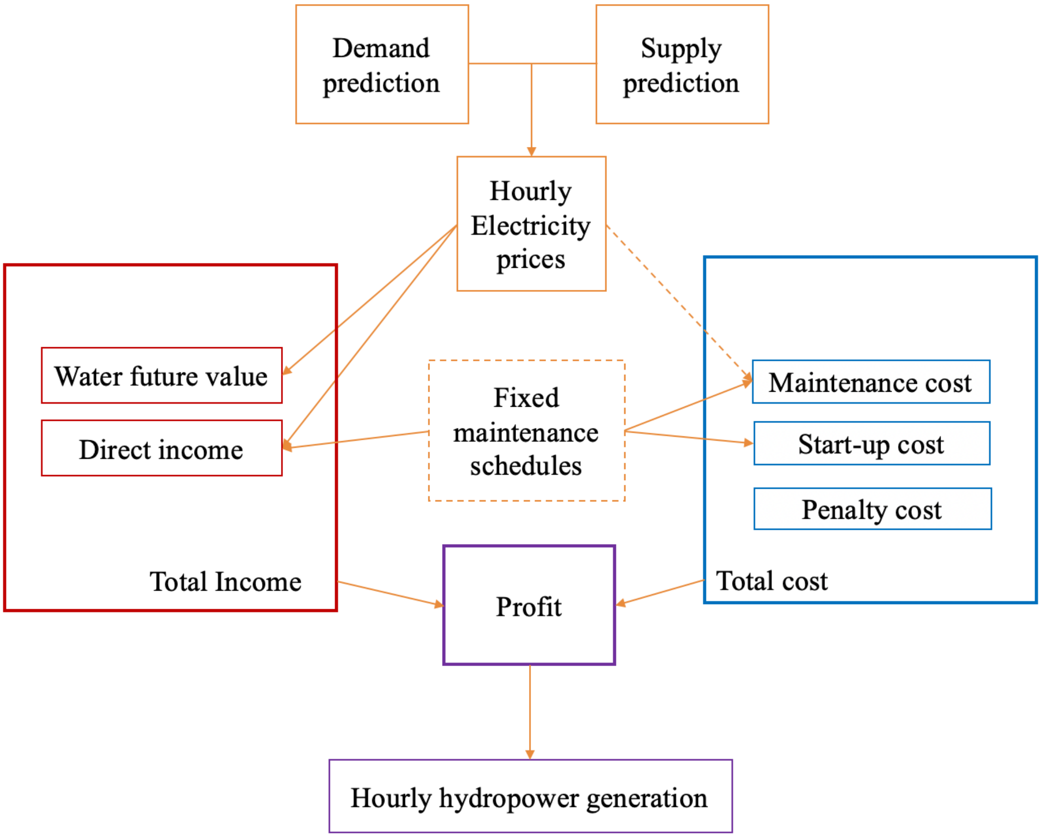

Figure 5: Traditional STHS framework from Sintef

The fixed hourly electricity prices determine the total income of plants which is the sum of water's future value and power sale's income. The electricity prices influence the opportunity cost of generators when the generators are being repaired. The fixed maintenance schedules can be entered or not entered. The schedules directly influence the income from power generation, start-up cost and the total maintenance cost. Finally, the hourly hydropower production is optimized by maximizing the net profit. In the next chapter, a cascaded hydropower example will be given to show how this framework works without fixed maintenance schedules.

3.2 Mathematical failure models

The failure characteristics of the single component can be modeled by classical mathematical models (Sherwin et al., 1995). The mostly used two distributions to model failure are Weibull distribution and Gamma distribution. Because they can present different shape under different parameters. For Weibul distribution, the cumulative and probability density function of failure probability is given in the formula 7 and 8 separately. Here reliability $R(t)$ is defined as the probability that the component do not experience any failure until the end of its lifetime T. $F(t)$ is the failure probability and its probability density function follows the Weibull distribution. For Gamma distribution, the probability density function is given in the formula 9. The parameters can be obtained from the past literature or estimated by maximum likelihood estimation (MLE).

$$\mathrm{R(t) = p(t < T)} \tag{6}$$

$$\mathrm{F(t) = p(t \geq T) = 1 - e}^{(\frac{t}{\alpha})^{\beta}} \tag{7}$$

$$\mathrm{f(t)} = \begin{cases} \frac{\beta}{\alpha}(\frac{t}{\alpha})^{\beta-1} e^{(\frac{t}{\alpha})^{\beta}} & t \geq 0 \\ 0 & t < 0 \end{cases} \tag{8}$$

$$\mathrm{f(t)} = \frac{\lambda}{\Gamma\,\mathrm{(k)}}\,(\lambda \mathrm{t})^{\mathrm{k}-1}\,\mathrm{e}^{-\lambda \mathrm{t}} \tag{9}$$

The failure characteristics of a system are more complex than the single component but still based on the condition of single components. The existing CBM methods have been reviewed in the chapter 2. However, they are not suitable for solving the maintenance problem when the real-time data is lacked. In this thesis, the model for the system failure is based on the Boolean models which are reliability block diagram and quantification part of fault tree analysis. To simulate the system, the internal structure of the system should be analyzed. The state of system is dependent on every single component and the interrelationship between components. Traditional reliability block diagram only has the series or parallel structure. It ignores the complex connection and the multiple outputs from components. The fault tree often tends to focus on the breakdown of top event and lose the deep analysis of structures.

To overcome this disadvantage, this thesis adopts the objected-oriented programming language to model the system rather than use the traditional FTA tools to calculate. The selected programming language is S2ML+SBE (Rauzy, 2020). It is object-oriented language and very flexible to achieve any versatile structure that users want. The corresponding calculation plant form is XFTA that is inserted in the software AltaRica Wizard. It is a calculation platform which is developed by Professor Antoine B. Rauzy from the RAMS group at NTNU. It can be used to build fault trees and related physical or functional models. With these useful tools, it is possible to model the failure condition without enough real-time data.

3.3 Selection of maintenance strategy

To simplify the research problem and give a concrete example, the question of the thesis is changed to schedule the maintenance for single generator system in one plant of the cascaded system, not schedule all the generators at the same time. Because the scheduling for the whole cascaded system is impractical and contains huge workload. Hence, this research only approaches the maintenance question in a small step and try to design a maintenance strategy for the single generator system. Nevertheless, the designed maintenance strategy can be applied to other generators in different plants.

There are two basic assumptions for maintenance before the strategy for hydropower plant is selected. The first assumption is that the occurrence of accidents is an accumulative process not an instant event without signs. This gives a basis to encourage CBM not the corrective maintenance. The second assumption is that the maintenance type is perfect maintenance which can recover the components back to "as good as new" state.

The maintenance strategy makes references to the concept of "Opportunistic Maintenance(OM)". There is no international standard for the definition of OM. In literature OM refers to performing maintenance at the right time (Thomas et al., 2008). OM stresses the rightness of time and the environment influence should be reflected in the maintenance schedules. In other words, OM is to find the best opportunity of conducting maintenance. The definition of opportunity varies with different environment. Similarly, the environment is an expansive concept. It not only refers to the hydro environment but also the production condition.

In this thesis, the proposed maintenance strategy can be classified as Condition-based Opportunistic Maintenance (CBOM) in the expansive definition. The concept of CBOM appears in several literature and is used to solve the maintenance problem for multi-component system (Zhao et al., 2019; Koochaki et al., 2012), but it is narrowly defined as the grouping and prioritizing of components. This thesis does not take the grouping definition and use the expansive definition which indicates the right time to do CBM. The figure 6 shows the CBOM strategy.

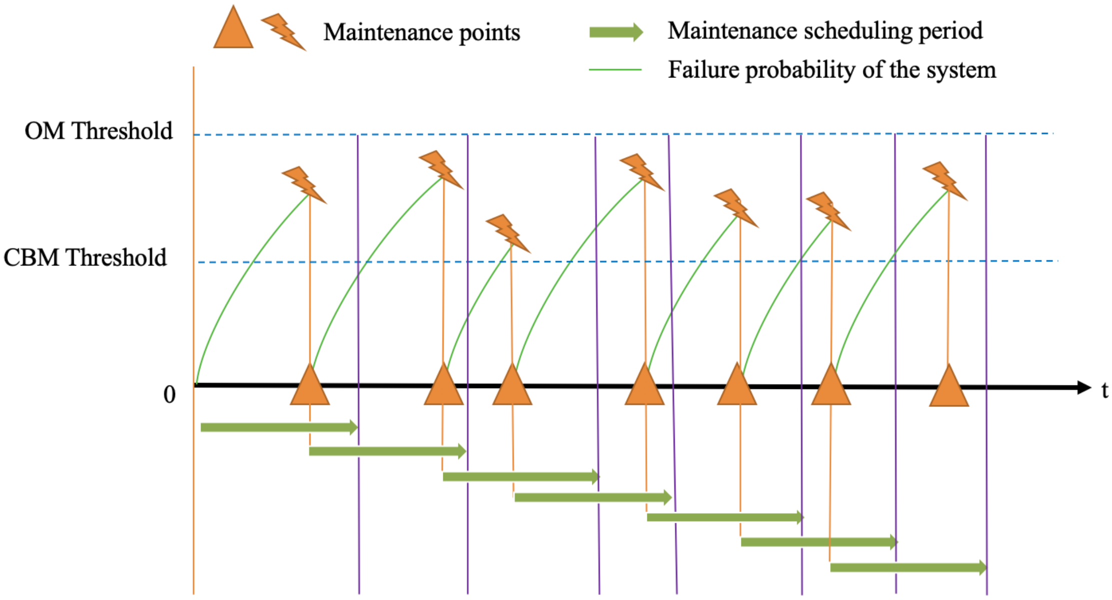

Figure 6: The CBOM strategy

To conduct the CBOM, there are two thresholds for maintenance in the research. One is the CBM threshold and another is the OM threshold. In the chapter 4, the CBM threshold is equal to alert level and the OM threshold is the upper limit. When the failure probability does not reach the CBM threshold, maintenance activities are not scheduled. Once the failure probability exceeds the CBM threshold, the schedules must be made before the failure probability reaches the OM threshold.

The brown triangles are the maintenance points. The length of green arrows represent the duration of the small maintenance scheduling periods. All the green arrows have the same length and always start at the time when the failure probability is zero. It indicates that the small scheduling periods for optimization have the same length. The green curve shows the increase of failure probability over time. Every time the maintenance activity is conducted at the location of brown triangles, the failure probability will be set back to zero.

These small scheduling periods (green arrows) moves forward on the time axle. Once the system is maintained, the starting point of green arrow will be set to the maintenance points. It is different from the static division of time horizon. CBOM only stops until the end of last green arrow touches the limit of research time (e.g. 8760 hour). It suggests that the research time is covered by these small scheduling periods. CBOM in this thesis is a dynamic and short-term optimization over the small periods. The objective is to find the maintenance date with the maximum profit during each small scheduling period.

3.4 The overview of methodology

The figure 7 illustrates the modified framework for conducting the CBOM in the hydro system. There are three models in the framework, STHS model, failure model, and the CBOM model. This framework can be enlightening for similar hydro maintenance research, because the three models the framework can have multiple specific forms.

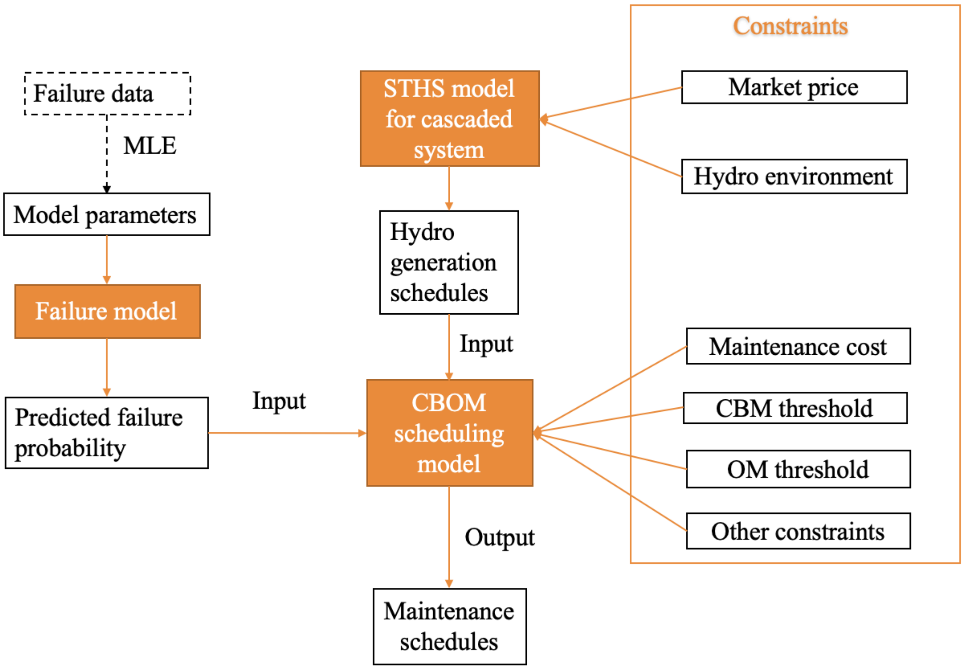

Figure 7: The adjusted framework for CBOM in hydro system

In this thsis, Sintef already achieves the STHS model in the SHOP module and the hydro production data is available. The methods for constructing the failure model and CBOM model are already proposed in this chapter. The two important inputs for CBOM model are the failure probability and production. The constraints limit the processing speed of the model and assist to reflect the maintenance strategy. In the end, the maintenance schedules for a specific generator system should be given by the CBOM model.

Chapter 4

CBOM of Generator in the cascaded hydro system

This chapter investigates the failure condition of Generator G1 in the Plant004 and schedules maintenance activities in one year by the methods proposed in the chapter 3. Both the failure model and CBOM model will be designed. Failure data, production data and the value of parameters are provided to generate the maintenance results.

4.1 Research example

A cascaded hydro system is modeled, with 9 reservoirs and 7 plants. The time horizon is set to be one year from January 1st, 2017 to January 1st, 2018.

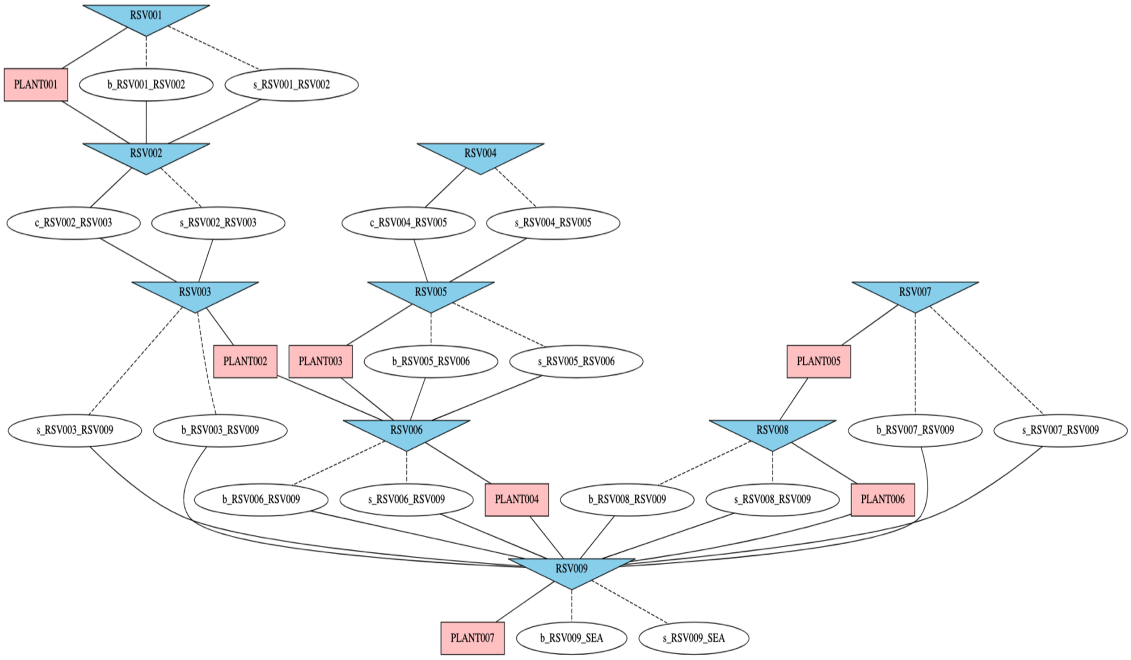

Figure 8: Topology of hydropower production in SHOP

The figure 8 shows the topology of the cascaded hydropower system. The water from the reservoir can flow through one plant to reach the next reservoir. When the whole plant is on maintenance, the reservoir needs to flow through the bypasses reservoirs to reach the next reservoir. For example, the water flows downstream from the reservoir RSV001, goes through the PLANT001 and arrives at RSV002. When PLANT001 is under maintenance, the water needs to flow into the bypass reservoir or the spillway reservoir. All the reservoirs between reservoirs are bypass channels. They does not consume the hydropower that the water stores. The hydropower is only utilized when the water flows into the hydropower plants.

Skjelbred et al. from SINTEF develop a MILP algorithm to optimize the operation of the cascaded hydropower system in the short term. This algorithm is achieved by the SHOP module in Python. SINTEF developed SHOP module 30 years ago and it is a programming tool to solve the short-term use of hydropower resources [1]. The original objective inserted in SHOP module is to minimize the target function. Here it represents the maximum profit objective function due to the use of negative signs. The objective function that Skjelbred et al. formulate is shown in the equation 10:

$$\mathrm{Max} \sum_{t \in T} M_t^{SELL} \cdot \Delta T \cdot p_t^{SELL} + \sum_{k \in K} W_{k,\bar{t}}^{END} \cdot E_s \cdot v_{k,\bar{t}} - \sum_{t \in T} \sum_{s \in S} \sum_{i \in I_s} C_{i,s} \cdot \mu_{i,s,t} \tag{10}$$

The first item is the income for selling energy and the second one is future income. The third part is the start-up cost of each unit. There also exists a invisible penalty cost when the stored water exceeds the upper water level or is below the lower water level. However, this objective function is optimized under hydro constraints without any maintenance element.

The figure 9 shows the original distribution of sale and buy price for the electricity in Nord pool. The two prices will decide the final electricity price in the market. The final electricity price is one of the input data to the STHS model.

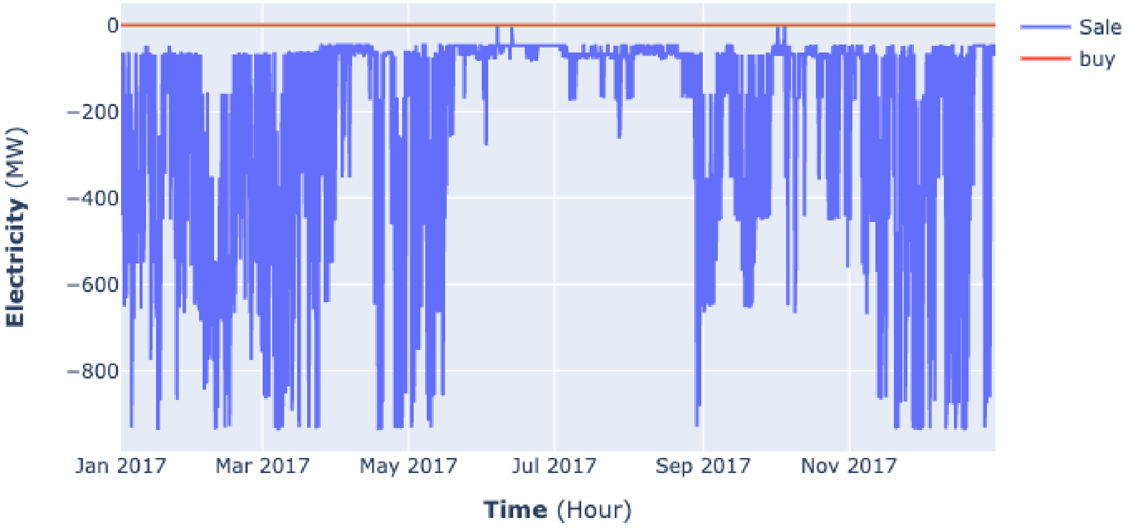

Figure 9: Sale and buy of electricity from SHOP

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[1] https://www.sintef.no/programvare/shop/

Except the electricity price, there are several types of input data for SHOP model. They are inflow data, water value, turbine efficiency data and reservoir characteristics (see appendix B). The figure 10 presents the fluctuation of electricity market price from January 1, 2017 to January 1, 2018. The figure 11 shows the condition of inflows to reservoirs. With these data, the SHOP can generate the one-year production plan by non-linear optimization.

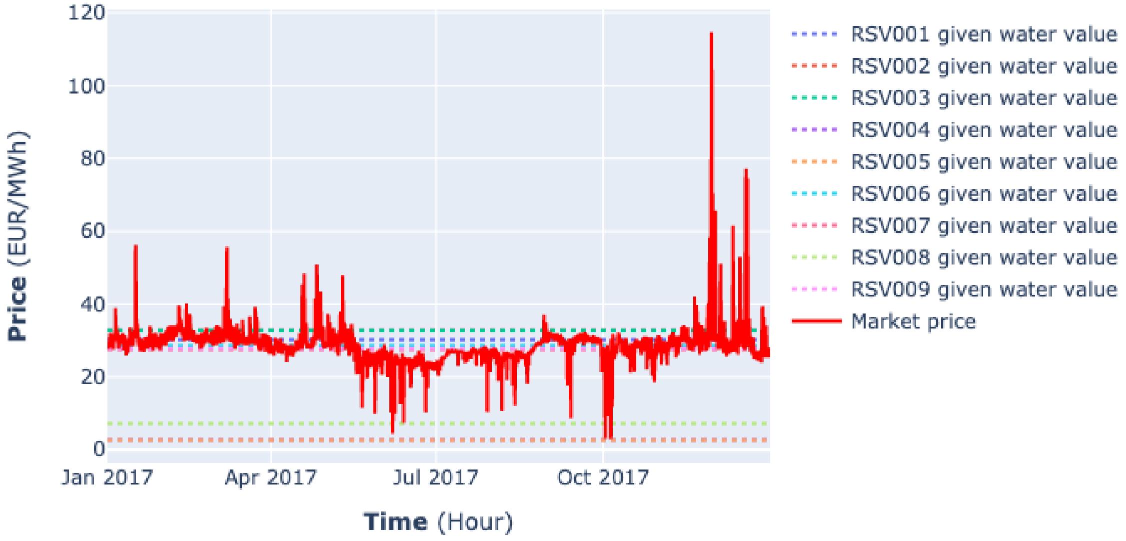

Figure 10: One-year market price and water price from SHOP

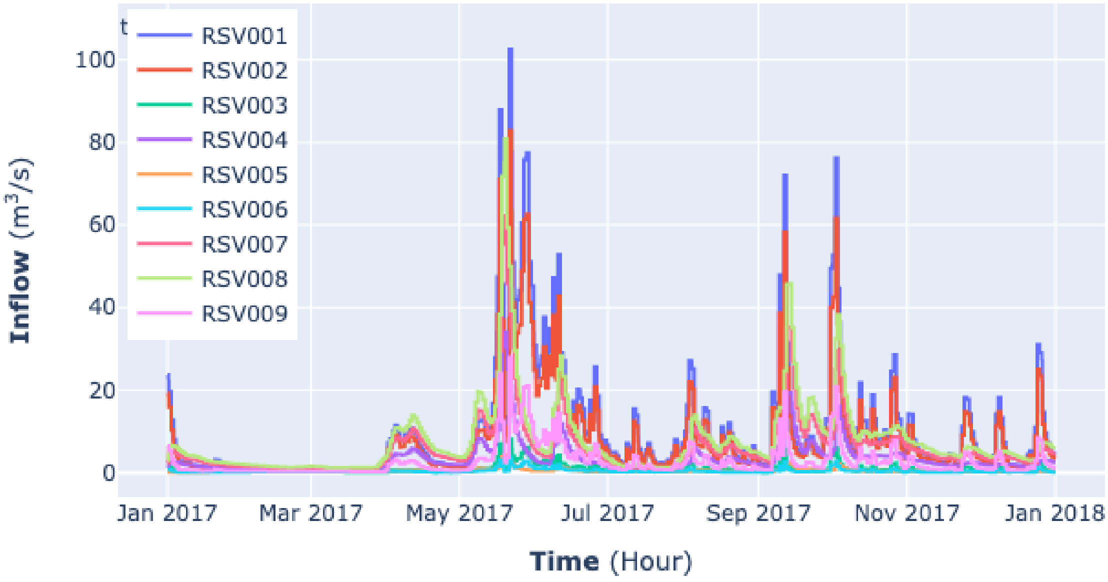

Figure 11: One-year inflow from SHOP

The example of production plan without considering the maintenance schedules is shown in the figure 12. It demonstrates that the variation of production generally follows the fluctuation of electricity prices. It fulfills the goal of obtaining the maximum selling profits when there is no influence from maintenance.

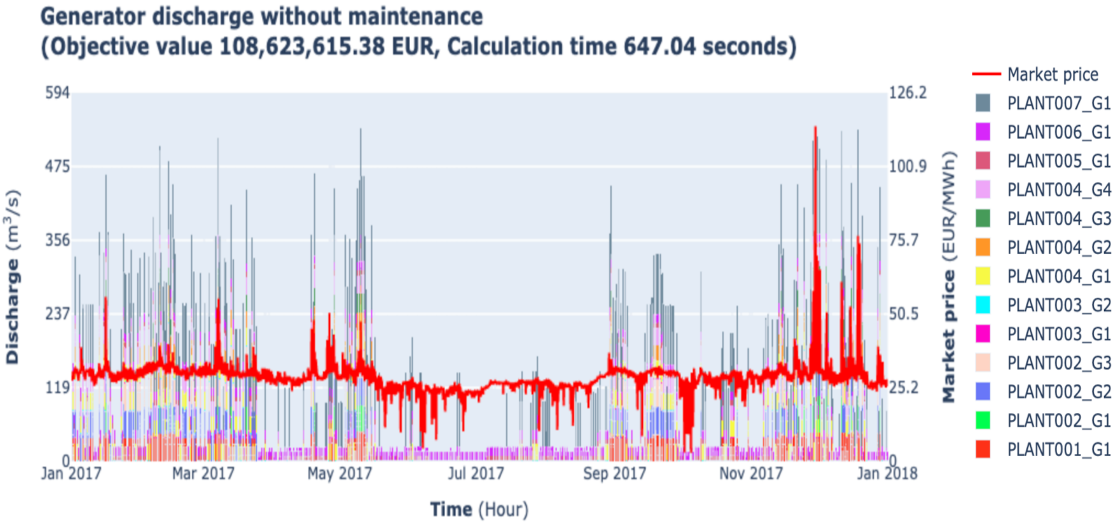

Figure 12: One-year generation from SHOP

4.2 Generator system description

The research object is assumed to be the vertical Francis generation unit in figure 13. The water first flows through the intake gate and wicket gate before it arrives at the turbine runner. The two gates are responsible for controlling the flow rate and water volume. When the water hits the turbine runner, the mechanical energy of water is transmitted to the turbine runner. The water that flows through the runner will finally go to the cooling water structure.

The shaft, which connects to the stuffing box (packing box) on the runner, rotates with the runner and transmits the mechanical energy of runner to the generator. The rotor around the shaft rotates and generates a spinning magnetic field. The stators further transform the moving magnetic field into the electrical current. The electricity flows out of the generator and into the circuit. The excitation transformer and main transformer would adjust the voltage level.

The modified electric current continues to flow to the switchboard and is put into use. To control the electricity generation, there is a speed regulator installed on the top of the generator. It can send signals to the brake governor and use the governor to control the opening and closing of the wicket gate.

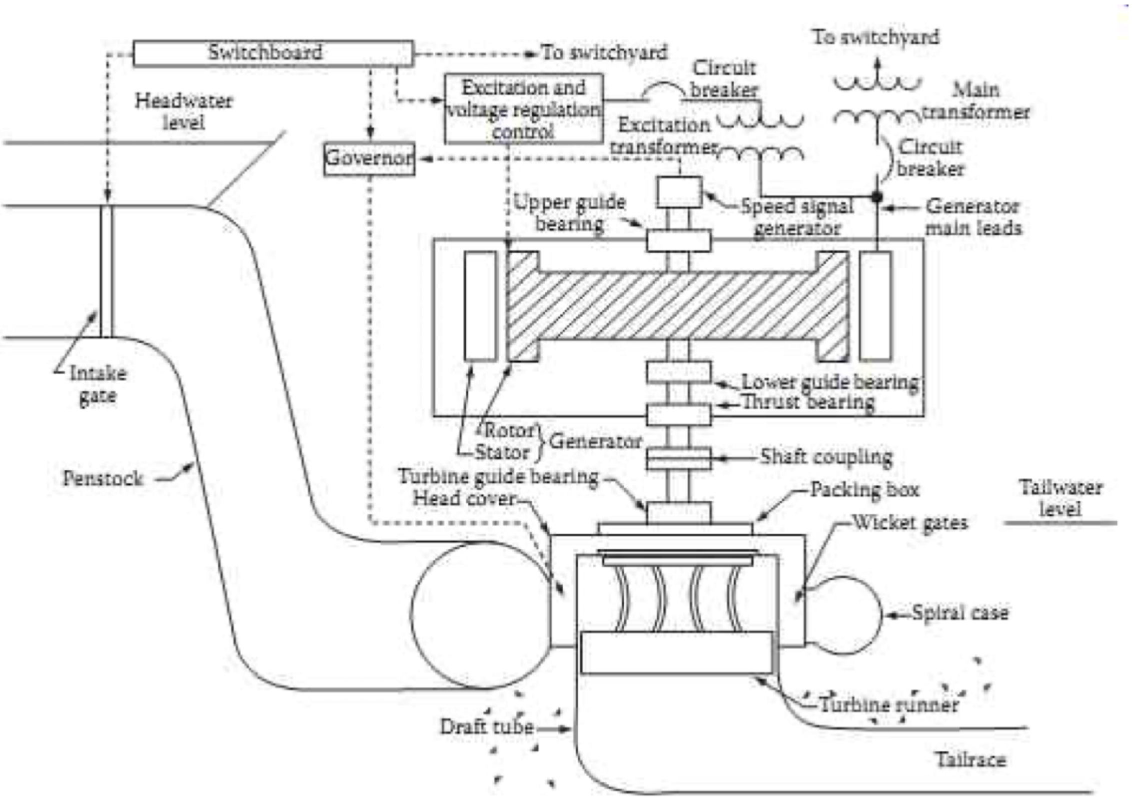

Figure 13: Vertical Francis unit arrangement (IEEE, 1988)

4.2.1 System analysis

To facilitate the research, the Francis generator is simplified as the figure 14. The Prussian blue line is the water flow. The red line represents the mechanical energy. The green line is the electric current. The three flows go through different components in the system, which suggests that components are playing different roles.

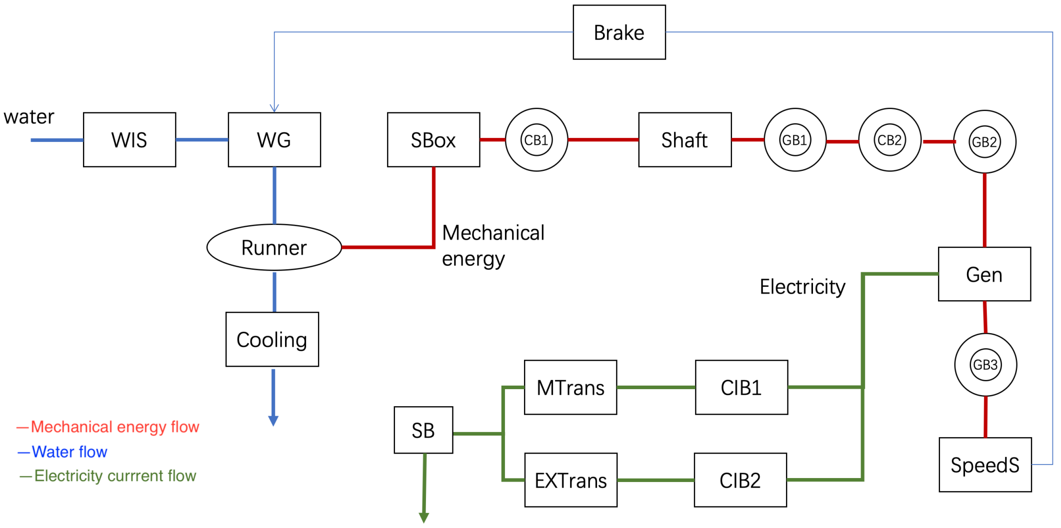

Figure 14: Francis unit arrangement

The table 4 describes the abbreviation and the function of components. Basically these components serve for three kind of flows, water, mechanical energy and electricity. Except components for flows, the remaining components, such as shaft and bearings are used to reduce the vibration of the turbine and generator. The stuffing box relies on its steel cover to slow down the wearing of other components. The speed regulator and brake are used to control the speed of water flow by detecting the voltage of generated electricity.

Table 4: Function of components

Function	**Components**
Intake water	Water intake structure (WIS)
Control water flow	Wicket gate (WG)
Cool water	Cooling Structure (Cooling)
Generate electricity	Generator (GEN)
Transmit mechanical energy	Runner, gear bearing (GB1, GB2, GB3)
Transmit electrical energy	Circuit breaker (CIB1,CIB2) Main transformer (MTrans) Excitation transformer (EXTrans) Switch board (SB)
Keeps the axle firmly	Carrier bearing (CB1, CB2)
Connect components	Shaft
Reduce wearing	Stuffing box (SBox)
Monitor speed	Speed regulator (SpeedS)
Send signals	Brake

The physical structure of the Francis unit is presented in the figure 15. The division and grouping of components are mainly based on the integrity of the sub-systems. Water flow system takes in the water and releases water. The turbine is responsible for converting the mechanical energy from water into mechanical energy of runner and shaft. The generator is to generate electricity by the swirling of rotors. Then the electricity flows through the electricity circuit. The brake system monitors and controls the electricity generation. The physical structure is the basis for failure simulation of the generator.

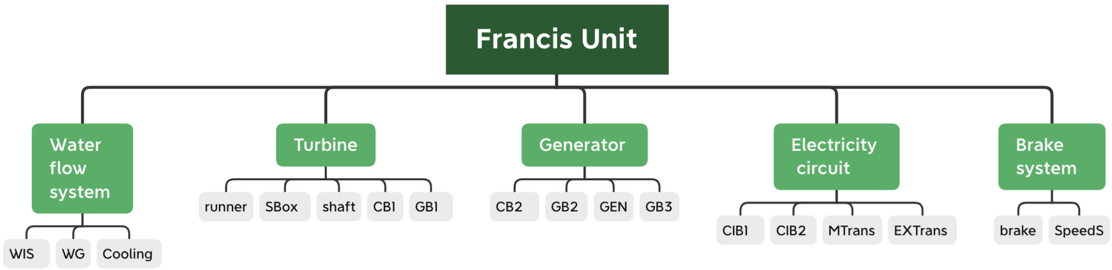

Figure 15: Physical structure of Francis unit

4.2.2 Component characteristics

The table 5 shows the failure parameters of components which are extracted from the literature BULUT and ÖZCAN (2021). BULUT and ÖZCAN give the fitted parameters of components by processing the data with MLE. To simplify the calculation in the thesis, it is assumed that the runner, speed regulator, shaft and switchboard have no failure in the one year. With the Weibull parameters and the physical structure, it is possible to build a failure simulation model for the Francis unit.

Table 5: Failure parameters (BULUT and ÖZCAN, 2021)

Components	Alpha	Beta
Main power transformer	7951.6180	0.60
Wicket gate	2347.4790	0.62
Circuit breaker	9432.2788	1.08
Brake system	8244.4591	0.35
Generator	7448.8073	0.59
Excitation transformer	7884.8522	0.65
Water intake structure	1293.1282	0.40
Gear bearing	12454.5339	1.39
Stuff box	4995.3470	1.15
Carrier bearing	9191.5872	1.98
Cooling water structure	4468.9582	0.62
Runner, Speed regulator, Shaft, Switchboard	-	-

The figure 16 presents all the the CDF curves of failures for the components in the system during one year (8760 hours). The curves of water intake structure and brake grow faster than those of other components, whereas carrier bearing and gear bearing fail much slower. In the reality, the reliability of the Francis unit will depend on all the components. Therefore, it is necessary to use a holistic perspective to observe the failure of the unit.

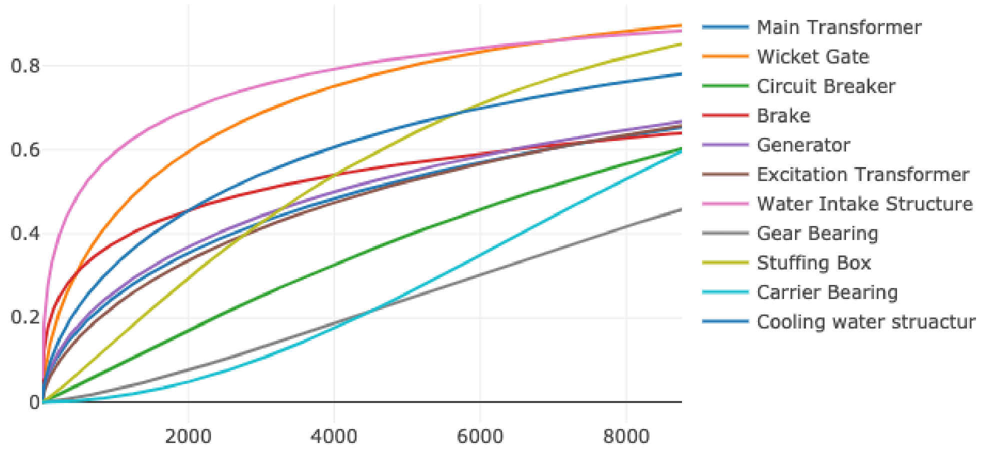

Figure 16: CDF of components in 8760 hours (BULUT and ÖZCAN, 2021)

4.3 Failure simulation

To simulate the Francis system, both the functional structure and physical configuration need to be considered. Because this system has a clear physical arrangement, the failure model for the Francis unit is built on its physical connection but some changes are made to fit for the functions.

The system contains five blocks, Water, Turbine, Generator, BrakeSys and Trans. The division of components is given in the table 6. The five blocks are connected by the flow variable in the codes. The failed variable of the system turns true when there is failure in any output from cooling water structure, switch board and brake.

Table 6: Block description

Blocks	Components
Water	Water intake structure, wicket gate, runner, cooling water structure
Turbine	Stuffing box, carrier bearing 1&2, shaft, gear bearing 1& 2
Generator	Gear bearing 3, generator
BrakeSys	Brake, speed regulator
Trans	Main transformer, excitation transformer, circuit breaker 1& 2, switchboard

The figure 17 is the reliability block diagram(RBD) for the Francis unit. If the water can not flow out from the cooling water structure, it suggests the water flow is clogged somewhere in the Block1 Water. The unit cannot generate electricity without fresh water. This is why cooling water structure is connected with stuffing box in the graph but not in the physical configuration. The runner is the only component that directly connects with stuffy box in the real structure.

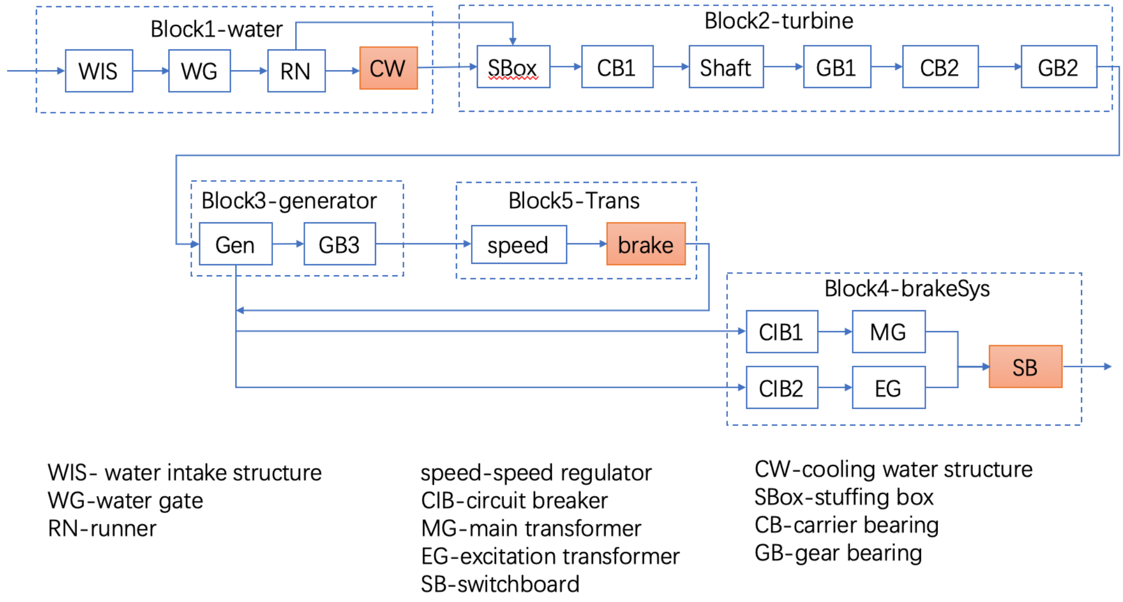

Figure 17: Reliability block diagram

The brake is used to regulate the water flow. If the water flow cannot be regulated, the operation is out of order. If switch board does not output the electricity, it indicates there is no electricity. Any of these three conditions will lead to the system failure. The three conditions are indicated by the outputs from cooling water structure, brake and switchboard. If any of the three outputs is None, the flow variable $failed$ will become true.

The failure could be calculated by many kinds of software as long as it can achieve the structure of RBD. The failure distribution of the Francis unit can also be derived in mathematics but the mathematical expression will be complicated. The better way is to simulate the RBD structure in fault tree software. Through modeling, the failure probability data of the Francis unit from 0 to 8760 hours can be calculated.

The figure 18 describes the distribution of failure data of the Francis unit. As it is mentioned before, the sum of reliability and failure probability is 1. The reliability reaches 0 at 7021 hour, which suggests that the hydroelectric unit fails after it is put into operation for around 9 months. It is worth noticing that the failure does not mean all the components fail and only represents the Francis unit can not perform its core functions.

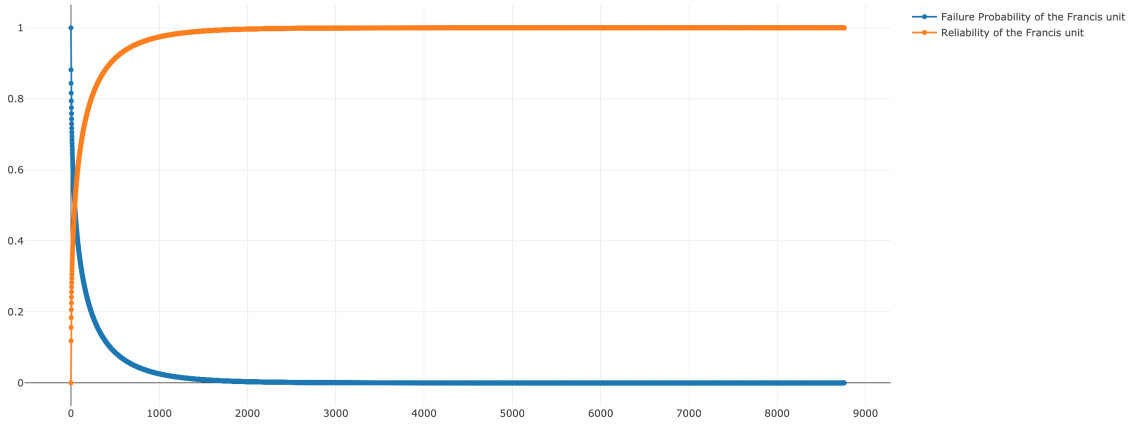

Figure 18: Simulated failure data

4.4 Dynamic maintenance scheduling

4.4.1 Assumptions and programming principle

It is assumed that the maintenance type is perfect maintenance. The maintenance team only spends one hour on repairing components. During the repair time, the Francis unit stops working and there is no electricity production in the maintenance hour. The cost of maintenance is defined as the money that the maintenance team spends on labor force. The cost is the real expenditure and does not contain the loss of electricity production and the cost of standby components. But the production loss will be calculated in another function, and the cost of standby components is paid by other stakeholders. After repairing, the reliability of system recovers to 1, which is the brand new state.

There are two thresholds, the CBM threshold and OM threshold. In the model, the CBM threshold is the alert level. The maintenance starts to be scheduled when the reliability of system reaches the alert level. The OM threshold is the upper limit of failure probability. Here the alert level is set to be 0.95 and the upper limit is 0.99. Based on the failure data of Francis unit, the failure probability reaches 0.95 at 710 hour and 0.99 at 1447 hour. The maintenance activities must be scheduled before 1447 hour. The setting of the alert level and upper limit is to present the results more concisely. It does not have any implication for practical use and only works for the academic research. Adjusting the parameters and obtaining practical results are discussed in the chapter 5.

To find the best maintenance time, the profit concept needs to be redefined. In this research, the accumulated profit is used to replace the traditional profit. The equation 11 gives the definition of traditional profit. It is the product of electricity production, market price and reliability. The traditional profit represents the virtual profit without maintenance.

$$\mathrm{TProfit(t)} = \mathrm{Electricity(t)} * \mathrm{Price(t)} * \mathrm{R(t)} \tag{11}$$

The accumulated profit is the accumulation of modified traditional profits. For instance, the accumulated profit at time t during the period $[p, p+710)$ refers to the profit that accumulates from p to $p+710$. When the maintenance is done from t to $t+1$, the hourly profit in this hour will be deducted from the whole accumulated profit. The best maintenance time is acquired by comparing the accumulated profits at each t. The highest profit during the period of $[p, p+710)$ will decide the maintenance time for this specific period.

The equation 12 and 13 show the two forms of accumulated profit. The first one is only used in the first time period to decide the first maintenance time point $PM1$. This equation is to use traditional profit to generate the accumulated profit. The second equation is used for finding maintenance time in later periods because the first maintenance at $PM1$ has already changed the reliability of the system.

$$\begin{aligned}\mathrm{AProfit1(PM1)} = \sum_{\mathrm{p}}^{\mathrm{PM1}} \mathrm{TProfit(t)} - \mathrm{penalty} * \mathrm{timelength} + \sum_{\mathrm{PM1+1}}^{\mathrm{p+709}} \mathrm{Electricity(t)} * \mathrm{Price(t)} * \mathrm{R(t}- \\ \mathrm{PM1} - \mathrm{timelength)}\end{aligned} \tag{12}$$

$$\begin{aligned}\mathrm{AProfit2(PM2)} = \sum_{\mathrm{p}}^{\mathrm{PM2}} \mathrm{Electricity(t)} * \mathrm{Price(t)} * \mathrm{R(t - PM1 - timelength)} - \mathrm{penalty} * \mathrm{timelength} \\ + \sum_{\mathrm{PM2+timelength}}^{\mathrm{p+709}} \mathrm{Electricity(t)} * \mathrm{Price(t)} * \mathrm{R(t - PM2 - timelength)}\end{aligned} \tag{13}$$

The strategies for selecting maintenance time in the period $[p, p+710)$ can be described as the simple three steps:

- **Step 1:** The beginning time p of one small period equals the last maintenance time plus maintenance duration (one hour).
- **Step 2:** If the highest profit equals penalty, the maintenance is done at $p+710$.
- **Step 3:** If the highest profit does not equal penalty, the maintenance is scheduled at the time of highest profit.

The selection strategy is represented by the accumulated profit function in the codes. To get all the maintenance dates, the table 7 presents all the relevant parameters for one year. The parameter $time$ and gap decides the alert level and upper limit. The $penalty$ is the maintenance cost. The $time\ length$ is the maintenance duration. The loop end is set to 8660 hour. This is to prevent the scheduling continues after 8760 hour. The loop end is not set to 8760 because the maintenance scheduling will continue for another loop after the $loopend$. The real end time is between $loopend$ and the value of $loopend$ plus $time$.

Table 7: Parameter setting

Parameter	Value	Explanation
t	0 h	Initial time point
time	1447 h	The length of one period
gap	710 h	The minimal gap between two maintenance actions
penalty	-1000 EUR	The cost of performing maintenance
loopend	8660 h	The end time of loop, smaller than 8760h
alert level	0.95	The minimum tolerable failure probability
upper limit	0.99	The maximum tolerable failure probability
the length of dataset	8760 h	The target period
time length	1 h	The duration of maintenance activities

4.4.2 Scheduling results

The one-year production data of PLANT004_G1 can be obtained by the SHOP model. The objective value is 108623615.38 EUR. The figure 19 is the histogram of electricity production in one year. Compared with the electricity price, the production is stopped during the summer when the market price is decreasing, but the production is almost consistent in the spring time. After 8595 hours, the production is halted until the end of this year, because the electricity price at the end of the year is relatively low. The production data is used as a basis for maintenance plan, in other words, the maintenance plan is for the generator 1 in the plant 004 during one year from 2017 January 1st to 2018 Januray 1st.

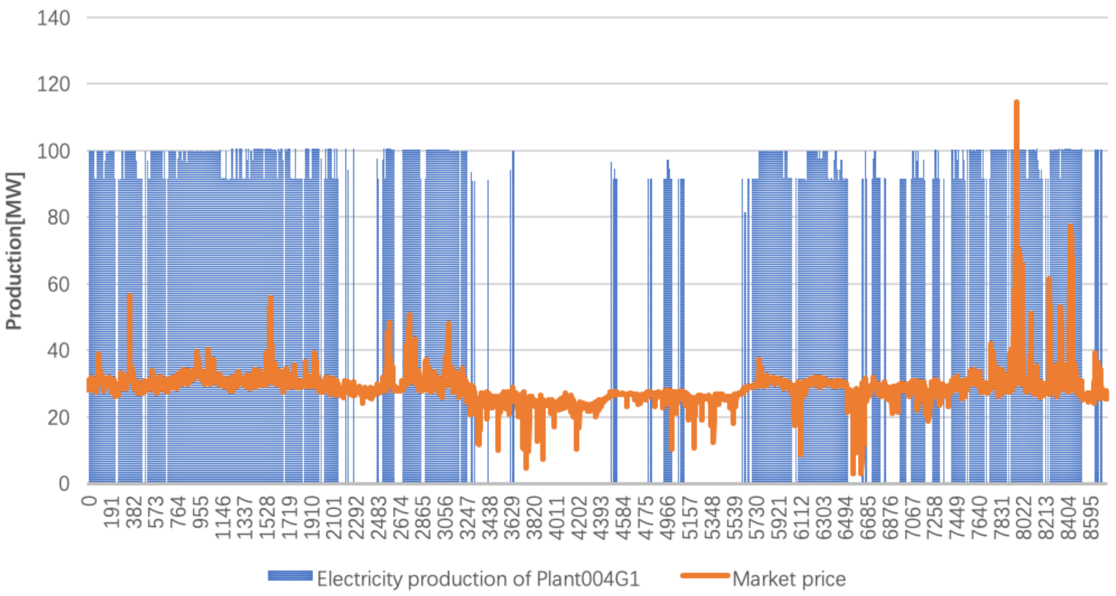

Figure 19: One-year electricity production in SHOP

The figure 20 shows the maintenance schedules in one year. The yellow dots denote the maintenance dates. There is a sharp decrease in accumulated profits at the maintenance dots. It is caused by the decrease of failure probability. Because the failure probability will be set back to 0 after the maintenance. Based on the parameter setting, the length of the objected period is 1447 hours and the gap between two yellow dots can not be smaller than 710 hours. Each selected yellow dot has the highest accumulated profit in the 1447 hours.

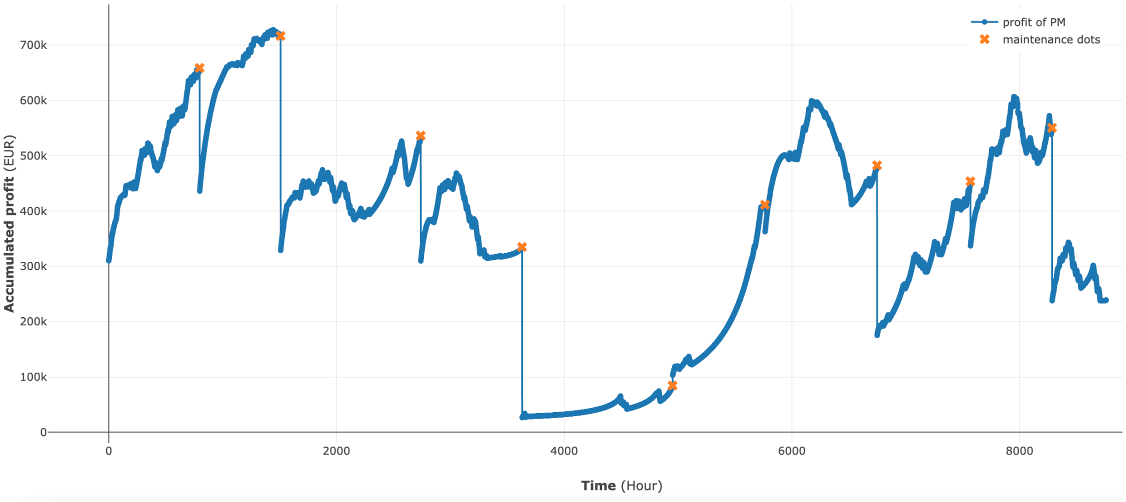

Figure 20: Maintenance schedule and profits

The maintenance time points and corresponding accumulated profit value are shown in the table 8. These profits cannot be compared with each other because they are obtained from different calculation periods. The value of accumulated profit is mainly influenced by the production condition. This satisfies the requirement that the production should be taken into consideration when the hydroelectric plant is planning its maintenance schedules. The results of maintenance dates are also a short-term plan due to the limit of time. It suggests that the PLANT004_G1 should be maintained for 1 hour on the nine dates, because maintenance activities on these date can assure the maximum accumulated profit value in the short term.

Table 8: Maintenance schedules

Labels	Time	Date	Profit value (EUR)
1	798	2017-02-03 06:00:00	658682.7659
2	1509	2017-03-04 21:00:00	716655.9512
3	2740	2017-04-25 04:00:00	536330.4262
4	3630	2017-06-01 06:00:00	334905.6495
5	4952	2017-07-26 08:00:00	84378.65846
6	5764	2017-08-29 04:00:00	411377.6384
7	6748	2017-10-09 04:00:00	482535.1022
8	7568	2017-11-12 08:00:00	453612.8654
9	8285	2017-12-12 05:00:00	550444.2719

However, the high alert level and upper limit setting are unacceptable in the practice though the maintenance schedules looks normal. The nine maintenance activities in one year can only make the highest reliability level fluctuate between 0.95 and 0.99. The abnormality exists because the failure data and operation data are all simulated and not the real time data. This is the inevitable limitation of the the results. For practice, it is recommended to use the real-time data as the input to the CBOM model. The sensitivity of the model and limitations will be described the next chapter.

Chapter 5

Discussion

This chapter discusses the sensitivity and limitations of the CBOM model. The parameters, $alert\ level$, $time$, $penalty$ and $time\ length$ are changed and the results under different conditions are compared. The CBOM model is also compared with age-based maintenance and corrective maintenance. Finally the limitations of CBOM model are summarized and presented.

5.1 Limits of the maintenance activities

The upper bound of the number of maintenance activities is dependent on the parameter gap. It is the lifetime when the failure probability reaches the alert level. For instance, the failure probability is 0.95 at 710 hour. If the alert level is set to be 0.95, the parameter gap will be 710 hour. The value of gap decides the minimum time interval between two maintenance activities. The calculation of accumulated profits is not started unless the failure probability arrives at the alert level and the minimal time interval is fulfilled. Under this condition, the maximum number of maintenance activities is the quotient of 8760 hours divided by 710 hours, which is 12.

Likewise, the lower limit of the maintenance times is decided by the maximum time interval. It corresponds to the parameter $time$. Contrary to gap, this parameter is the maximum gap between two maintenance activities. It represents the time when the failure probability increases to the OM threshold. The OM threshold is the upper limit of failure probability. For example, if the failure probability becomes 0.99 at 1447 hour and the OM threshold is also 0.99, the parameter $time$ will choose the value 1447 hour. With these parameters, the minimum number of maintenance activities is 6 which is the ratio of 8760 hours and 1447 hours. The equation 14 describes the upper and lower bounds for maintenance times.

$$\frac{8760}{\text{time}} \leq \text{The number of maintenance activities} \leq \frac{8760}{\text{gap}} \tag{14}$$

Similarly, the equation 15 shows the range of failure probability for this system. It can be concluded that the parameter gap decides the lower acceptance limit of failure probability and the parameter $time$ determines the upper acceptance limit of failure probability.

$$\text{F(gap)} \leq \text{Failure probability} \leq \text{F(time)} \tag{15}$$

5.2 Results at different alert levels

The alert level is the minimal acceptance limit of failure probability. As it is mentioned before, the alert level is decided by the parameter gap. The largest function of alert level is warning. If the failure probability of the system reaches the alert level at time T, the maintenance engineers will be reminded to begin to schedule maintenance plan from T. The maintenance activities are to be arranged after T. Before the time T, the failure condition is regarded as the acceptable condition. Maintenance activities are not scheduled before the failure probability exceeds the alert level.

The figure 21 shows three possible alert levels, which are 0.5, 0.75 and 0.95. Every alert level corresponds to one specific gap. For example, the system reaches the alert level 3 after 44 hours. The time 44 hour will become the value of the parameter gap. To control the variables, the another parameter $time$ is set to 1447 hour and keeps constant. It suggests that the upper limit of failure probability is always 0.99 according to the aforementioned equation 14. The alert level will be changed in this section and the range between the upper limit and the alert level will vary with the alert level change.

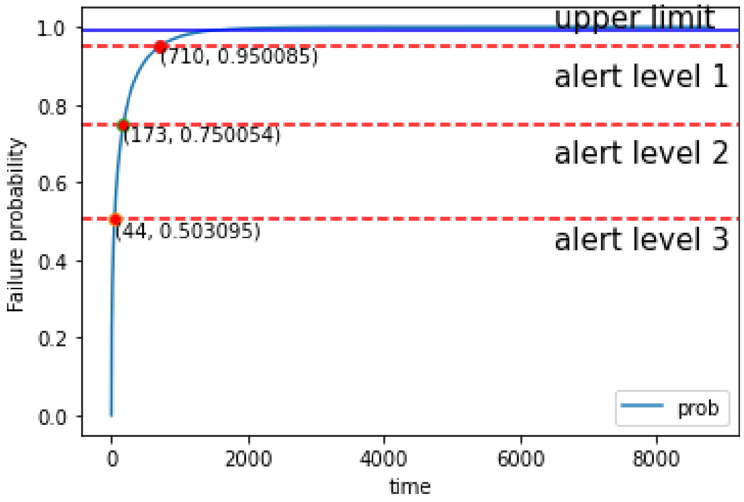

Figure 21: Alert levels

The picture 22, 23 and 24 show the accumulated profits and maintenance schedules for three alert levels. The three profit curves have the similar shape and only the regions around 3000 hours have some differences. The reason for the phenomena is that the profits are only accumulated in a specific period. This calculation period starts from the date when the failure probability is 0, and ends at $time$. What the CBOM model does is to select the highest accumulated profit. The selection period is the interval from gap to $time$ and is shorter than calculation period. The increase of alert levels does not change the value of the accumulated profit at every moment because the accumulated profits is more dependent on the production and calculation period. The alert level only affects the selection period.

Based on the equation 14, the alert level only influences the maximum number of maintenance activities. For alert level 3, the upper limit of maintenance number has been enhanced to 199. However, the number of real scheduled maintenance activities is still 15 and does not become extremely large though it could reach 199 in theory. This is related with the convergence feature which would be described later.

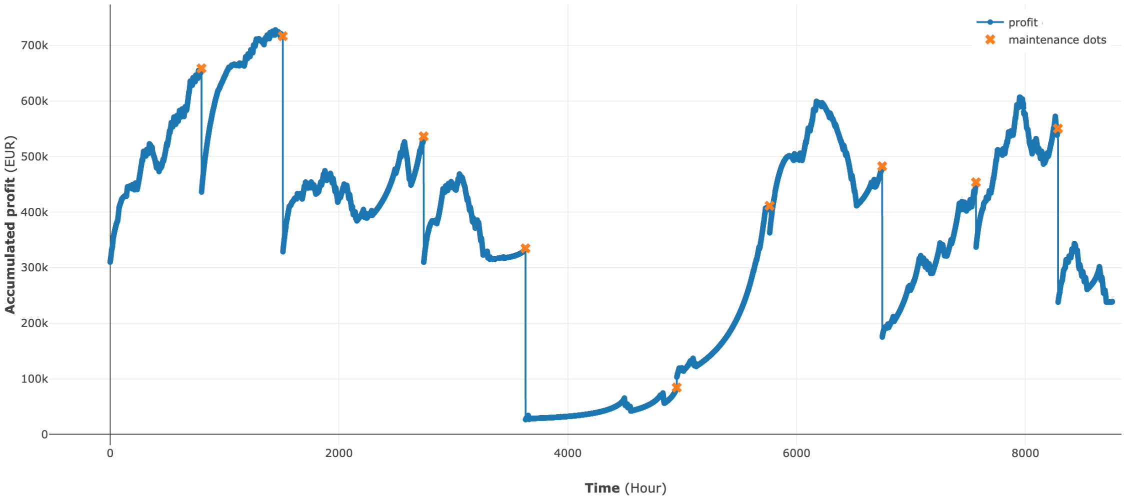

Figure 22: Alert level 1

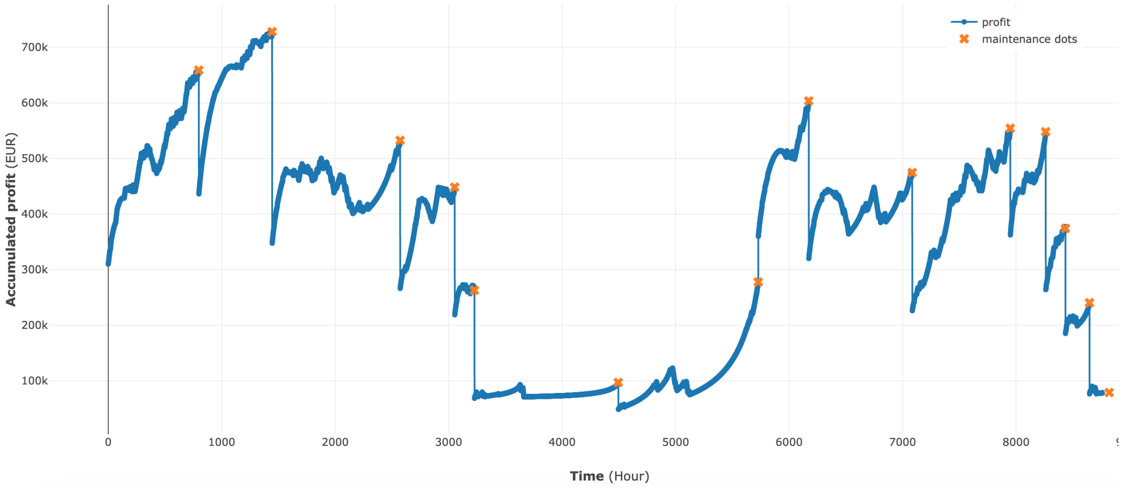

Figure 23: Alert level 2

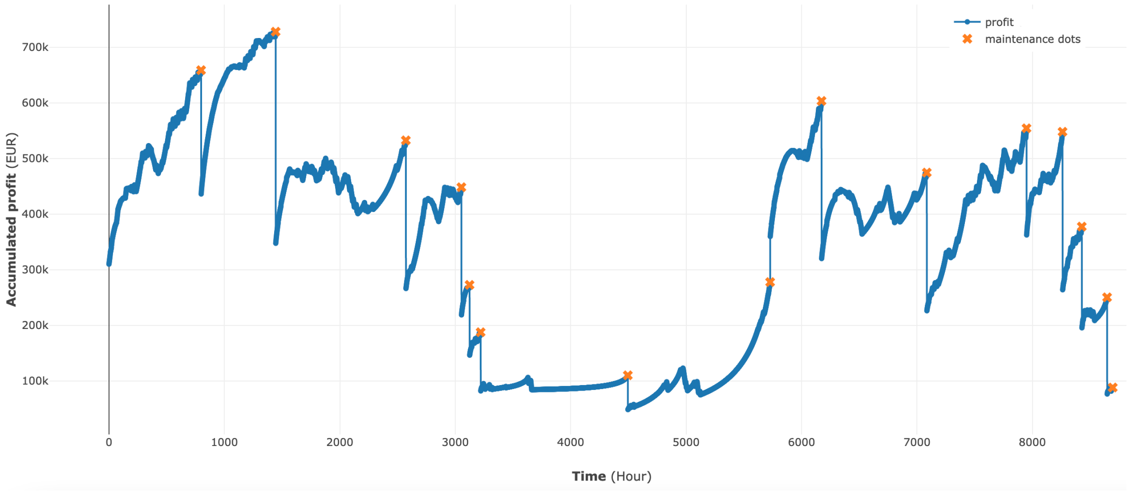

Figure 24: Alert level 3

Comparing the table 9, 10 and 11, most maintenance dates are same and the profit at the same date is also identical. It proves that the change of alert levels does not influence the calculation of accumulated profits. Because the length of the calculation period is not changed. The period in the experiment starts from the time when failure probability is 0 and ends at 1447 hours. What is changed by alert level is the time range where maintenance time could be scheduled. When the alert level increases to a higher failure probability, the number of maintenance activities decreases because the selection range is smaller. In other words, if the system accepts higher failure probability, less maintenance activities will be required for the system.

Table 9: Maintenance schedules on alert level 1

Number	Maintenance time	Date	Accumulated profit (EUR)
1	798	2017-02-03 06:00:00	658682.7659
2	1509	2017-03-04 21:00:00	716655.9512
3	2740	2017-04-25 04:00:00	536330.4262
4	3630	2017-06-01 06:00:00	334905.6495
5	4952	2017-07-26 08:00:00	84378.65846
6	5764	2017-08-29 04:00:00	411377.6384
7	6748	2017-10-09 04:00:00	482535.1022
8	7568	2017-11-12 08:00:00	453612.8654
9	8285	2017-12-12 05:00:00	550444.2719

Table 10: Maintenance schedules on alert level 2

Number	Time(hour)	Date	Accumulated profit (EUR)
1	798	2017-02-03 06:00:00	658682.7659
2	1444	2017-03-02 04:00:00	727884.1801
3	2572	2017-04-18 04:00:00	532520.5453
4	3053	2017-05-08 05:00:00	448233.4671
5	3227	2017-05-15 11:00:00	262881.9953
6	4495	2017-07-07 07:00:00	97033.98441
7	5728	2017-08-27 16:00:00	277679.2292
8	6173	2017-09-15 05:00:00	603410.5863
9	7085	2017-10-23 05:00:00	474569.0168
10	7949	2017-11-28 05:00:00	554232.878
11	8261	2017-12-11 05:00:00	547962.9869
12	8435	2017-12-18 11:00:00	374080.3387
13	8647	2017-12-27 07:00:00	240347.4855

Table 11: Maintenance schedules on alert level 3

Number	Time	Date	Accumulated profit (EUR)
1	798	2017-02-03 06:00:00	658682.7659
2	1444	2017-03-02 04:00:00	727884.1801
3	2572	2017-04-18 04:00:00	532520.5453
4	3053	2017-05-08 05:00:00	448233.4671
5	3124	2017-05-11 04:00:00	272676.408
6	3220	2017-05-15 04:00:00	187574.8277
7	4495	2017-07-07 07:00:00	110067.8279
8	5728	2017-08-27 16:00:00	277679.2292
9	6173	2017-09-15 05:00:00	603410.5863
10	7085	2017-10-23 05:00:00	474569.0168
11	7949	2017-11-28 05:00:00	554232.878
12	8261	2017-12-11 05:00:00	547962.9869
13	8428	2017-12-18 04:00:00	377464.8529
14	8647	2017-12-27 07:00:00	250284.9782
15	8696	2017-12-29 08:00:00	88130.71848

The figure 25 shows the influence of alert levels on the number of maintenance activities. When alert level is smaller than 0.6, the number of maintenance activities keeps unchanged. However, the number begins to decrease rapidly when the alert level exceeds 0.6. This trend indicates that the number of maintenance activities converges as the alert level decreases. The reason for convergence is that maintaining the Francis system in the early stage is not profitable. Under the existing parameter setting, the 15 profitable dates have been selected when the alert level is 0.6. There is no need to set the alert level lower than 0.6. This convergence feature can give maintenance teams a reference when they start to set the alert level.

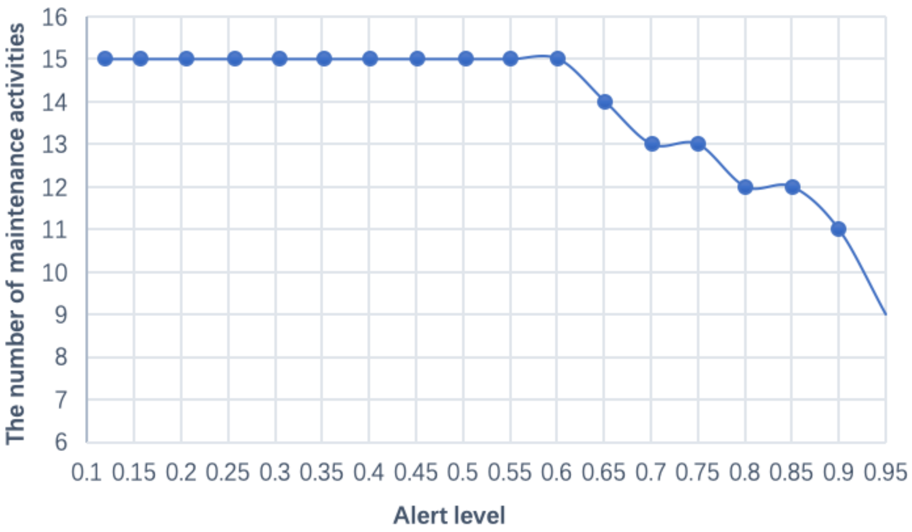

Figure 25: The influence of Alert levels

5.3 Results under different upper limits of failure probability

The upper limit of failure probability is the maximum acceptable failure probability which is determined by the parameter $time$. If the default setting of $time$ is 0.99 at 1447 hour, the system can not tolerate larger failure probability than 0.99. The change of $time$ could lead to some changes in the number of maintenance activities, because it influences the length of the calculation period for accumulated profits. Adjusting the $time$ is to change the minimum number of maintenance activities and the highest failure probability of the system. To control the variables, the another parameter gap is set to 710 hour, which corresponds to the alert level at 0.6. In the figure 26, three typical upper limits are selected.

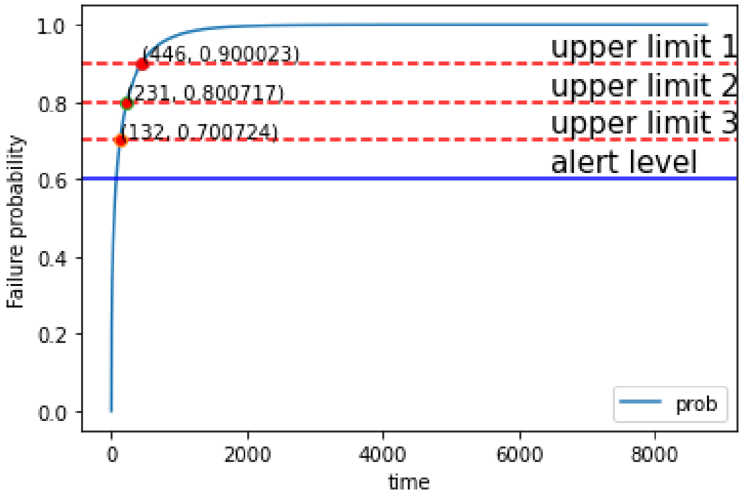

Figure 26: The upper limits

The figure 27, 28 and 29 show the results for upper limit 1, 2 and 3. The curves are different from previous figures. The accumulated profits are calculated in totally different periods. The number of maintenance is 37 for upper limit 1, is 65 for upper limit 2 and 93 for upper limit 3. The three tables in the appendix C give the specific dates of maintenance activities. It is clear that the dates become different when the upper limit changes. Compared with the result from the change of alert levels, the change of upper limits has more impact on the maintenance schedules.

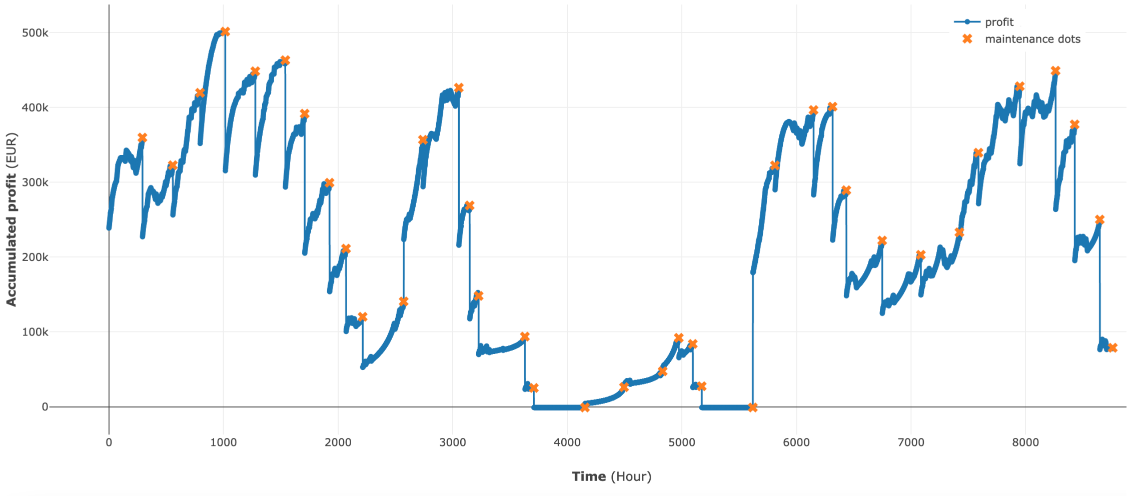

Figure 27: Upper limit 1

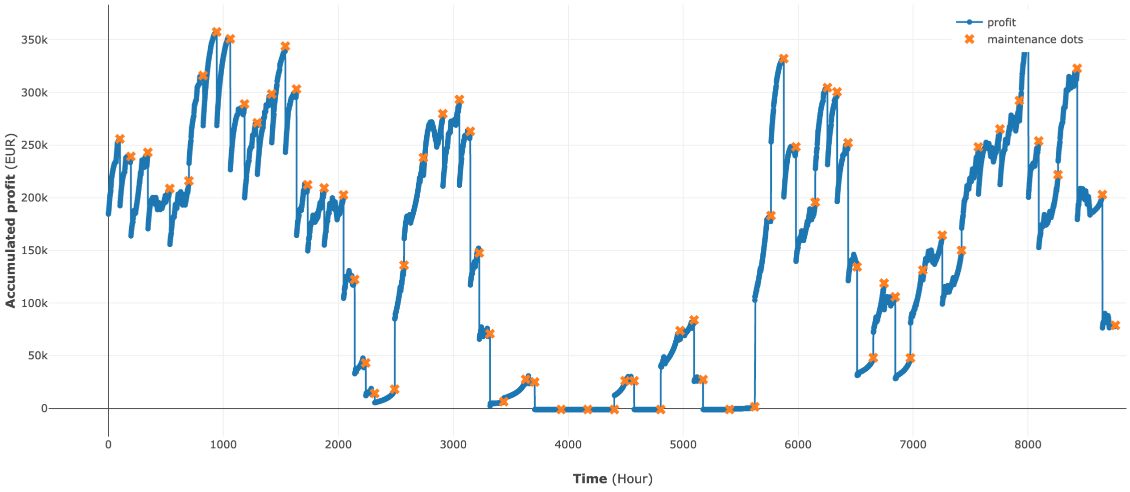

Figure 28: Upper limit 2

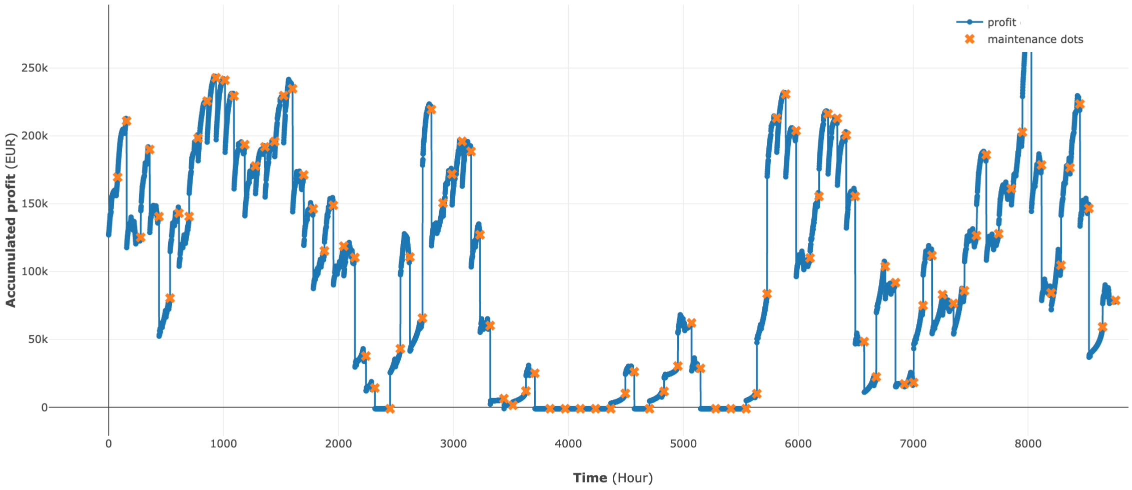

Figure 29: Upper limit 3

The figure 30 shows how the change of upper limits influences the number of maintenance activities. As the upper limits become larger, the number of maintenance activities decreases. This fits for the fact that the system does not require many maintenance activities if it can bear the high failure probability. The figure 31 is the area when the failure probability is approaching 1. The decreasing trend is still very apparent. The extreme condition is that the hydroelectric system allows the accident to happen. The coping strategy is to wait the machine run until the broken state. Under this extreme condition, maintenance is not scheduled before the accident happens, then CBOM strategy becomes corrective maintenance.

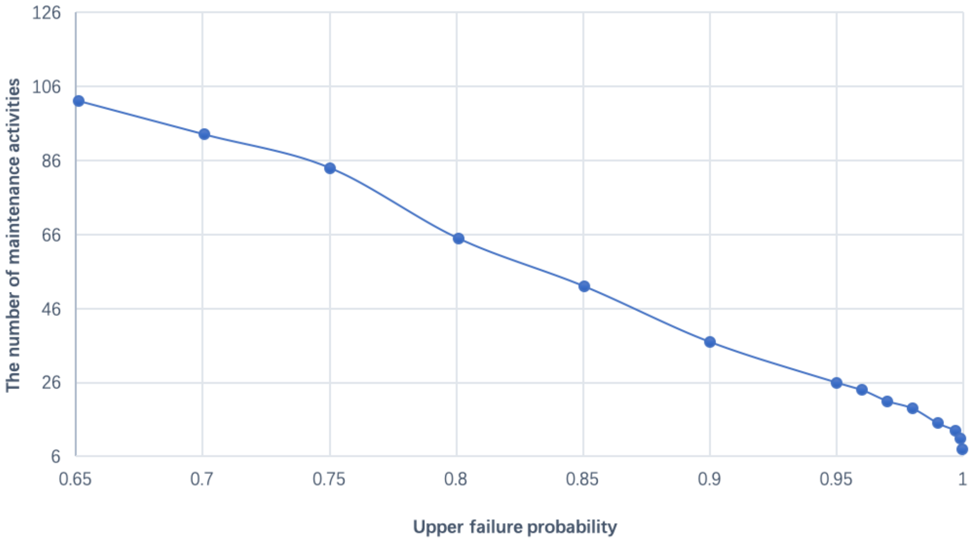

Figure 30: The upper limits

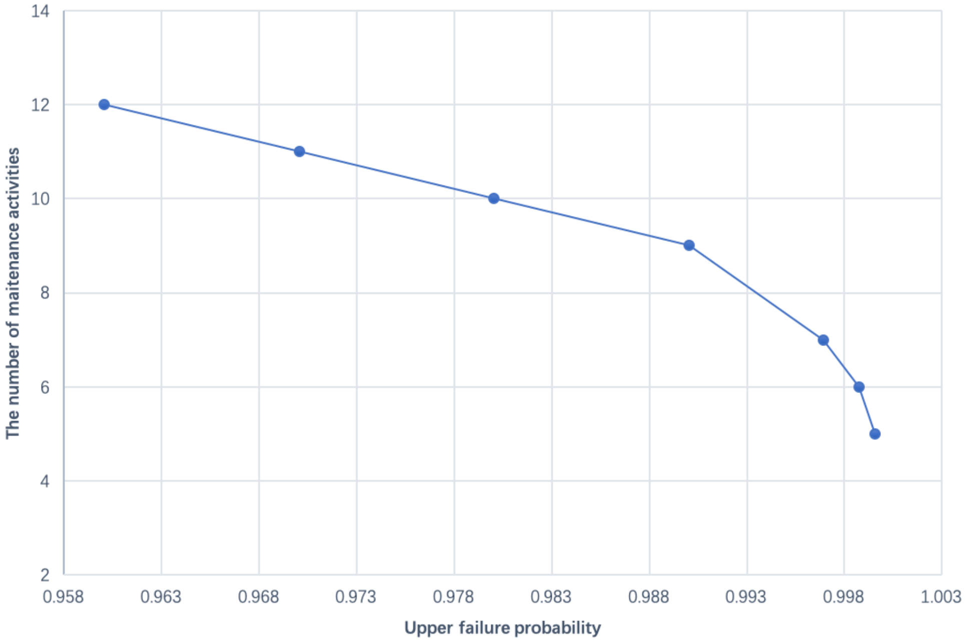

Figure 31: Details at the high failure probability area

Although the number of maintenance activities is huge, the workload of maintenance in the early stage is not so large in the reality. For example, it is easier to maintain a component with the mild degradation than to repair a severely broken component. In this thesis, the difference of maintenance tasks is not discussed and all the maintenance tasks are assumed to be homogeneous. But it is worth pointing out that the number of maintenance activities does not relate with the real workload of maintenance in the physical world.

5.4 The influence of penalty and maintenance duration

The parameter $penalty$ is the cost of maintenance in one hour. It is set to 1000EUR in the chapter 4. The maintenance is assumed to be the perfect maintenance which can recover the targeted component to the brand new state in the one hour. There exists a hidden assumption that the costs of standby components are burdened by other departments of the hydro company. The maintenance cost is only related with maintenance duration. For example, if the shaft of the generator is damaged, the cost will only include the wage for the maintenance team in the one hour. The team can choose either to repair it in one hour or replace it with a new shaft, but the new shaft is purchased by other departments and not counted in the maintenance cost.

In the experiment, $penalty$ is increasing from 0 EUR to -10000 EUR and other parameters keep same as the table 7 shows. The results show that he number of maintenance activities remains to be 9. It reflects that $penalty$ does not affect the number of maintenance activities. Because $penalty$ is the same for any selected time. In the calculation of accumulated profits, the same maintenance cost is deducted for every moment. It is still the vanished production at the moment that influences the value of accumulated profit. It suggests that CBOM model does not prioritize the maintenance cost but the profit of production.

Another parameter $time\ length$ is the maintenance duration. The default setting of maintenance duration is 1 hour because this is the minimal time resolution of the SHOP model. Setting the duration to 1 hour can minimize the influence of maintenance on production. It can be changed to a longer period when the CBOM model is applied in the industry. The figure 32 shows the results under the change of $time\ length$. The change of maintenance duration does not influence the maintenance dates and only slightly decreases the accumulated profit. This suggests that maintenance duration does not have a great effect on the maintenance schedules. The most influential factor is the original production plan.

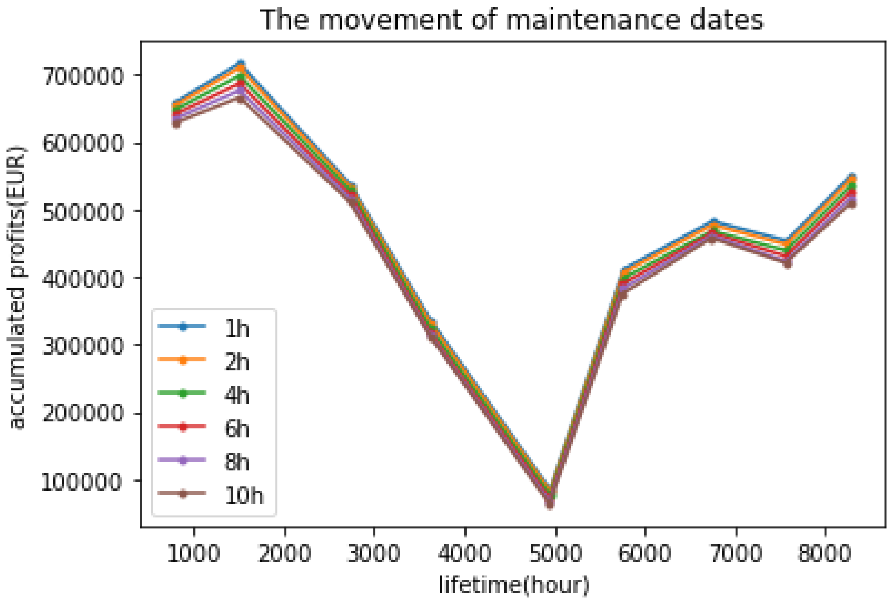

Figure 32: The influence of maintenance duration on profits

5.5 Comparison with other maintenance methods

The corrective maintenance is to conduct the maintenance when the generator is actually failed. For the Francis unit, the generator fails at 7021 hour. It indicates that the generator can be used until the winter. However, the failure probability has reached 0.99 at 1447 hour. With the assumption that the deterioration of generator can influence the profits, the plant obtains small profits from 1447 hour to 7021 hour. It does not meet the profitable requirement from the plant.

Generally, the plant adopts calendar-based maintenance or age-based maintenance (ABM). For the system with fixed failure property, the maintenance plan based on time or age will be identical. The time interval between two maintenance schedules is 710h if the failure probability needs to be lower than 0.95. The maintenance can be scheduled to 710h, 1420h, 2130h, 2840h, 3550h, 4260h, 4970h, 5680h, 6390h, 7100h, 7810h, 8520h. In the following description, this maintenance strategy is referred as ABM.

The figure 33 compares the difference of reliability between ABM and CBOM. The red line represents that the reliability of the generator is 0.01 and the blue line indicates that the reliability level is 0.05. It is noted that the reliability setting does not the meet the high reliability requirement in real industry. Setting the reliability to 0.05 or 0.01 is designed for simplifying the experiment.

Here it is assumed that ABM is traditional and conducts many maintenance activities to avoid accidents. The goal of ABM is to keep the reliability not lower than 0.05 not 0.01. CBOM is to keep the reliability not lower than 0.01, but the maintenance activities will be scheduled once the reliability is lower than 0.05. Compared with ABM, the CBOM method makes a trade-off between production and maintenance when the reliability shows that the maintenance needs to be planned. ABM ignores this kind of conflict between produciton and maintenance and only maintains the system on the predetermined dates.

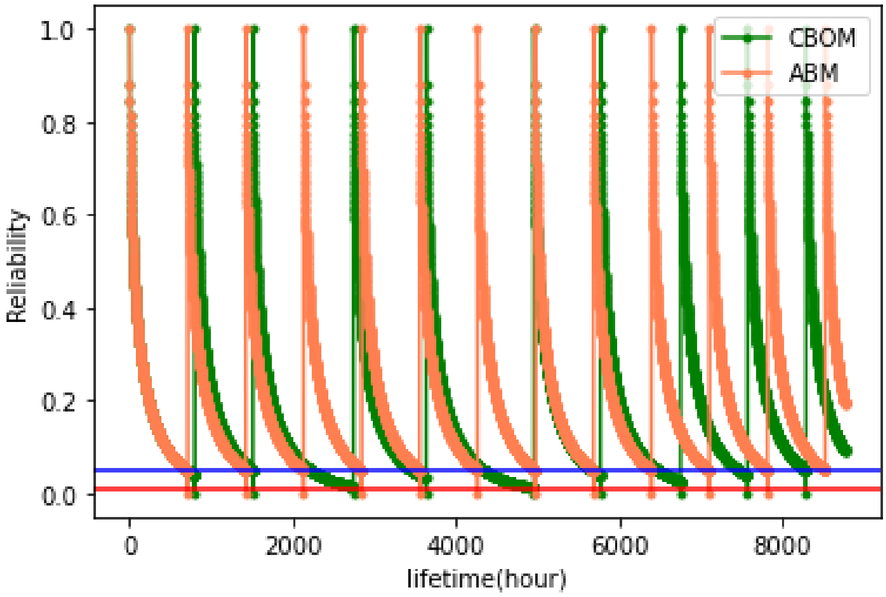

Figure 33: The comparison of CBOM and ABM

In the figure 34, it can be seen that the green line (CBOM) often bottoms out the blue horizontal line. It can be explained as the circumstance that postponing the maintenance activities is more profitable than conducting maintenance. Under this condition, the ABM strategy does not take the risk to generate electricity. But the CBOM method encourages the plant to produce under the recognised risk. This is the main difference between the two maintenance strategies. To some extent, CBOM is more profit-oriented and ABM is safety-oriented.

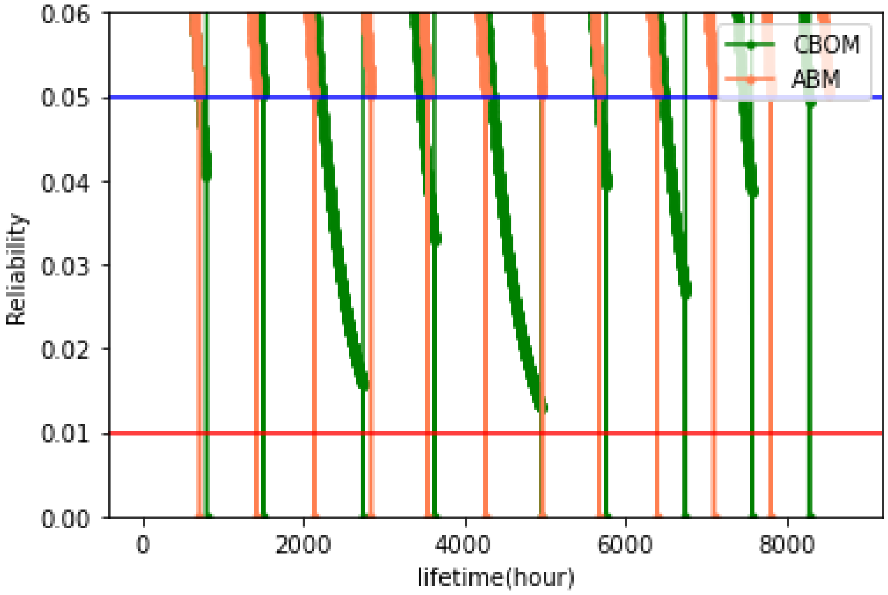

Figure 34: Details of CBOM and AGM

The figure 35 shows the hourly profits of ABM and CBOM. The hourly profit is the product of reliability, production from SHOP and market price. The sum of hourly profits for ABM is 2330355.941792865 EUR and for CBOM is 2458365.419632425 EUR. ABM conducts 12 maintenance activities and CBOM conducts 9 maintenance activities. With the same setting of maintenance cost, CBOM is more cost-efficient than ABM.

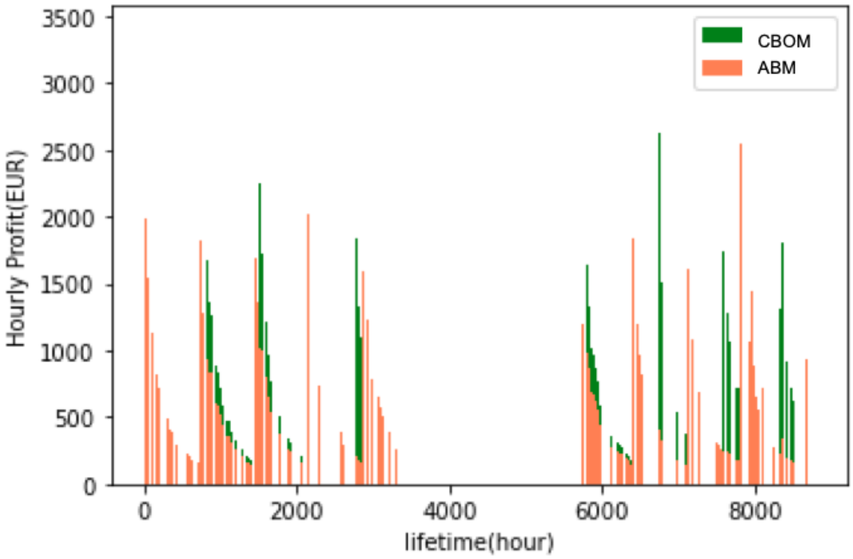

Figure 35: The hourly profit of CBOM and ABM

In reality, ABM can be changed and scheduled in various ways. The profitable effect may not appear under some special conditions, for example, the ABM allows the reliability of system to reach 0.99 or 1. It suggests that The comparison experiment of ABM and CBOM should always control the acceptable reliability level. For this research, this comparison is enough to prove that this CBOM method is able to be profitable when applied in the industry.

5.6 Limitations

5.6.1 Data collection

In this research, the failure data and operation data are generated by simulation. It depends on the failure distribution of components and the structure of the generator. However, this kind of data is not real and has the discrepancy with true failure data. Because it does not consider the influence of external environment and common caused failures among components.

To ensure the quality of failure data, a more accurate method is to collect the real data, analyze the failure history, predict the failure condition of the generator and validate the prediction. The prediction method could be black box model such as artificial neutral network, or use sufficient history data to estimate the parameters of failure distribution.

5.6.2 Profit calculation

There are two types of profit concept in this research. One is $hourlyprofit$ and the another is $accumulatedprofit$. The hourly profit is the product of hourly production, market price and reliability. The accumulated profit is the accumulation of hourly profits during one specific period. The two profits are not consistent with the concept of actual economic profit in the real life. The economic profit for the plant is the actual cash flow. The improvement on the actual monetary income may not appear when the model is applied in the industry unless the value of reliability can be quantified by money. In addition, it remains to be tested that the deterioration influences the production of generator.

5.6.3 Maintenance parameters

The maintenance related parameters include the maintenance cost, the maintenance duration, the alert level and the upper limit. All these parameters follow the assumption that any maintenance activity can be completed in one hour and the heterogeneous maintenance workload is ignored. The CBOM model assumes that each maintenance activity has the same property. In the reality, the cost, duration, workload for each maintenance activity can be different. This difference should be noted when the CBOM is applied in the industry.

Chapter 6

Conclusions and future work

6.1 Conclusions

This thesis presents the condition-based opportunistic maintenance framework for the maintenance of hydropower generator system. The deterioration of the Francis hydro unit is modeled and the condition-cased opportunistic maintenance model is designed to achieve maintenance schedules with the production data from SHOP. It succeeds to connect the short-term hydro scheduling research and the maintenance scheduling by inserting the condition-based opportunistic maintenance model. The trade-off between production and maintenance is made by optimizing the accumulated profits between two maintenance thresholds.

In the case study of PLANT004_G1, the CBOM model schedules 9 dates of maintenance activities in one year and calculates their corresponding accumulation profits. It proves that this framework can give concrete maintenance schedules for single Francis hydro unit. The parameter can also be flexibly adjusted to fit for the requirements from hydropower plants. The sensitivity analysis reflects that the accident penalty and maintenance duration do not influence the final results. The increasing upper OM thresholds or alert levels can decrease the number of maintenance activities.

Compared with age-based maintenance and corrective maintenance, the new CBOM model is more cost-efficient. It reduces or postpones unnecessary maintenance activities that bring the huge profit loss. When the CBOM model is used in the industry, it is recommended to adopt the real failure data and notice the assumption in the profit and maintenance.

6.2 Future work

This CBOM framework is a small progress made against the maintenance scheduling problem for cascaded hydropower system. Currently it can schedule for a single generator system but it does not give the holistic maintenance plan for cascaded plants. The maintenance for the cascaded system should achieve that both generators and plants have its own stoppage and maintenance periods. To realize this obejective, the following future work is proposed.

In most hydropower plants, one plant has multiple generators and these generators are connected. The next research direction is to develop multi-generator maintenance schedules for one specific plant. The production relationship and physical configuration of generators in the plant should be investigated.

After the multi-generator maintenance method is developed, the focus will be shifted to study the structure of the hydro cascaded system. It is worth researching how upstream plants influence the downstream plants. The sign of achieving the cascaded maintenance scheduling is that every generator and every plant in the cascaded system can be systematically maintained.

Appendix A

Constraints of STHS

Literature	Equality constraints	Inequality constraints
Pousinho et al. (2012)	water storage	water storage
	power generation	water discharge
	water head	water spillage
Bai et al. (2017)	power generation	operating zones constraints
	net head	water discharge
	average water storage	water spillage
	water balance	
Wang et al. (2017)	water balance	power generation
	water storage	water discharge
	net head	water spillage
		operating zones constraints
Wang et al. (2004)	water balance	water storage
	cycling condition	water discharge
	initial and end-of-study water storage	power generation limit
	delay release	generator output
		hydro systemwide power
		operating zones constraints
		power ramping
Marchand et al. (2019)	demand rate of automated generation control(AGC)	electricity load
	production rate of AGC	
	power generation	
	turbined flow	
Hermida and Castronuovo (2018)	water balance	Initial and final states of the reservoirs
	water head relationship	net efficiency
	Initial and final states of the reservoirs	minimum water discharge
		irrigation, industrial and urban (IIU) consumption
		water spillage
		water head
Guedes et al. (2017)	power generation	operating zones constraints
	mid-term planning demand	water discharge
	water balance	downstream flow limits
Shayesteh et al. (2016)	water balance	water discharge
	power generation	water spillage
Sharma and Abhyankar (2017)	water balance	water spillage
	initial and final reservoir volume	water storage
	forbidden zone constraints	turbine discharge rate limit
	power generation	power generation
		minimum up time and down time
		discharge ramping constraint
		forbidden zone constraints
Hidalgo et al. (2015)	demand load	power generation
		water resource

Literature	**Equality constraints**	**Inequality constraints**
		spinning reserve requirement
García-González et al. (2007)	power generation	minimum profit
	water balance	Conditional Value-at-Risk(CVaR)
	final reservoir level	reservoir storage volume constraint
	water from ecological flow	turbine efficiency limit
	power generation	turbine discharge rate limit
	logic constraints	
Mo et al. (2013)	water balance	minimum up time and down time
	power balance	turbine-generator capacity
	water head relationship	water storage
		water spillage
		water discharge
		water discharge ramping
Cristian Finardi and Reolon Scuzziato (2013)	plant load	water storage
	power generation	water discharge
	stream flow balance	
	penstock water balance	
	forbidden zone constraints	
	initial operation condition	
Ge et al. (2014)	water balance	water discharge
	initial and terminal reservoir storage limit	water outflow
	water time delay	water storage
	water-to-power generation	power generarion
		power output limit
Feng et al. (2017)	water balance	reservoir water level constraints
	inflow balance	discharge contraints
	water discharge balance	turbine discharge constraints
	initial and terminal water level	power output limit
Lu et al. (2015)	waterflow balance	spinning reserve constrain
	water balance	water storage
	power balance	water discharge
		turbine-generator output
		generator unit ramp rate limits
		forbidden zone constraints
		minimum up time and down time
Naresh and Sharma (2002)	system load balance	water storage
	reservoir flow balance	turbine discharge rate limit
	spillage model	net reservior release
	intial and terminal reservoir volume	
	power generation	
Mahor and Rangnekar (2012)	water balance	water storage
	release of reservoir	water discharge
	initial and terminal reservoir storage limit	power generation limit
		water spillage
Skjelbred et al. (2020)	water balance	water storage
	power generation	turbine discharge rate limit
	inflow balance	generator production limit
	net head	
	start-up decision of unit	
	energy balance	
Pérez-Díaz et al. (2010a)	terminal reservoir volume	water storage
	system boundary condition	
	inflow balance	
Ma et al. (2013)	water balance	water discharge
	tail water level	unit commitment rule
	final reservoir level	water level and volume of reservoirs
		mean diurnal water discharge
Catalão et al. (2010a)	water conservation	water storage
	power generation	water discharge
	head equation	water spillage

Literature	**Equality constraints**	**Inequality constraints**
Catalão et al. (2010b)	water balance	water storage
	power generation	water discharge
	head equation	discharge ramping constraint
	logic constraints	water spillage
Catalão et al. (2012)	water balance	water storage
	power generation	water discharge
	head equation	discharge ramping constraint
	logic constraints	water spillage
Catalao et al. (2009)	water balance	water storage
	head equation	water discharge
	power generation	water spillage
Ge et al. (2018)	water balance	reservoir level limits
	water release limits	water flow limits
	power production function	power output limit
Fu et al. (2011)	reservoir flow balance	power production limits
	intial and terminal reservoir water level	water level
		outflow limit
Li et al. (2015)	water balance	water level limits
	water level-storage curve	water discharge limits
	tailwater elevation curves	
	water comsumption constraints	
Mariano et al. (2007)	water balance	water storage
	power generation	water discharge
	water head	water spillage
Bensalem et al. (2007)	water balance	water storage
	load constraints	water discharge
Cong et al. (2002)	power balance	generator power output
		minimum up time and down time
Pérez-Díaz et al. (2010b)	water balance	flow limits
	initial and final reservoir volume	water spillage
	power generation	
Jia (2013)	water balance	reservior level limit
	intial and terminal reservior level	power production limits
	initial state of units	water discharge
		operating zones constraints
		minimum up time and down time
Kladnik et al. (2011)	water storage	water level limit
	power generation	water storage limit
	water discharge balance	water ramping limit
	head-generation efficiency	water spillage
	initial water level	water dischage limit
		water head limit
		generation efficiency limit
Villavicencio et al. (2015)	water balance	water ramping limit
	water discharge balance	water spillage
	power generation	water flow limits
	adjacency of blocks	irrigation limit
	initial state of units	power limit
		operating zones constraints
Borghetti et al. (2008)	terminal reservoir volume	water flow limits
	switch-on/switch-off rules	flow variation
	water balance	water spillage
		water consumption
Zhong et al. (2020)	initial and terminal forebay levels	power ramping
	continuity equation	reservoir up and down limit
	water discharge balance	water discharge
	net head	forebay level
	power generation	turbine flow
	expected electricity output	production limits
Jiekang et al. (2008)	water balance	power output limit

Literature	**Equality constraints**	**Inequality constraints**
	power genration	chance constraints
		water discharge limit
		reservoir volume limit
Silva E Castro and Saraiva (2017)	water balance	water flow limits
	final reservoir level	power generation limit
		water dischage limit
		pumping volume
		launch volume limit
Tong et al. (2013)	water balance	water storage
	water discharge balance	water discharge
	water flow	shut-down/start-up costs
	water head	minimum up/down time constraints
	water storage	operating zones constraints
	water discharge balance	
	hydropower production	
Wang (2009)	water balance	reservoir maximum and minimum volume
	water head	outflow limit
	intial boundary	water ramping limit
	power generation	operating zones constraints
	water storage	water dischage limit
	water dischagre	

Appendix B

Cascaded hydro system characteristics

B.1 Turbine efficiency of 13 generators

B.1.1 PLANT001, PLANT005, PLANT006, PLANT007

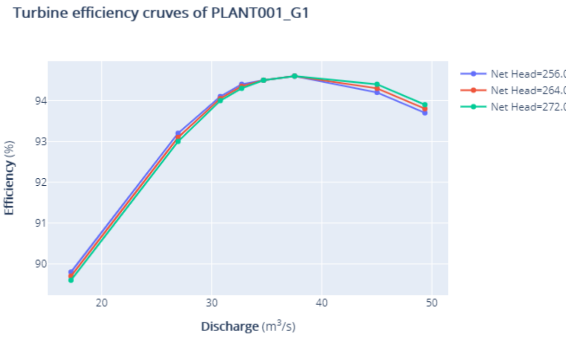

Figure 36: PLANT001 turbine efficiency

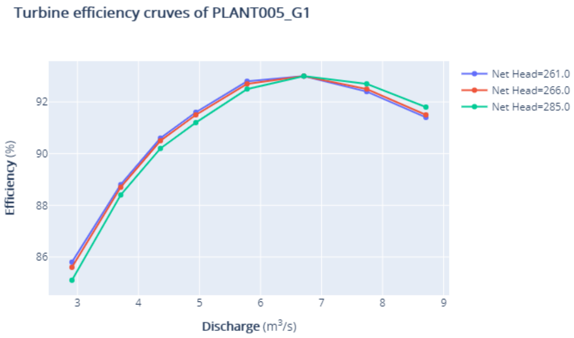

Figure 37: PLANT005 turbine efficiency

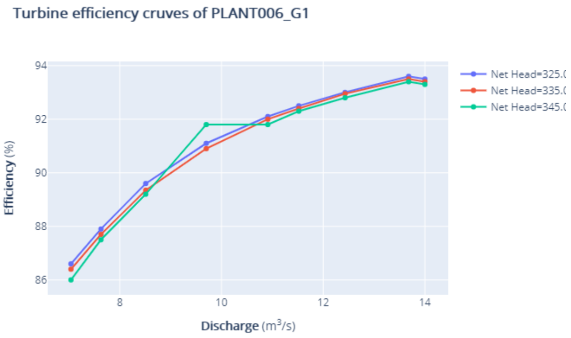

Figure 38: PLANT006 turbine efficiency

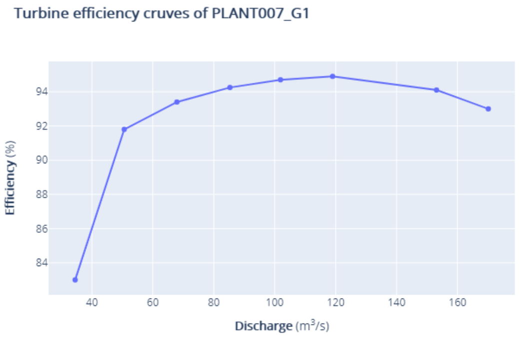

Figure 39: PLANT007 turbine efficiency

B.1.2 PLANT002

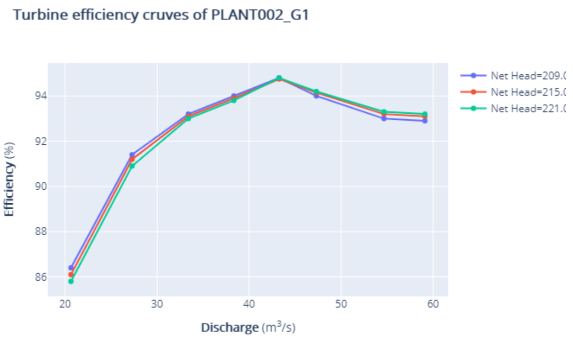

Figure 40: PLANT002 G1 turbine efficiency

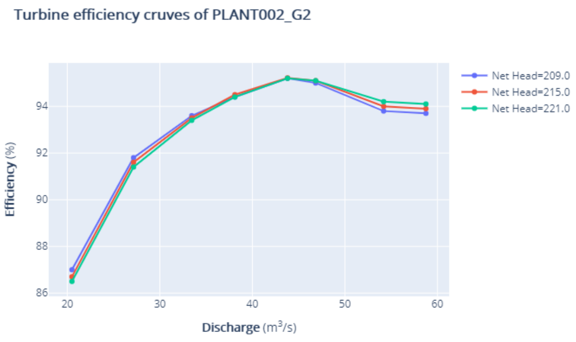

Figure 41: PLANT002 G2 turbine efficiency

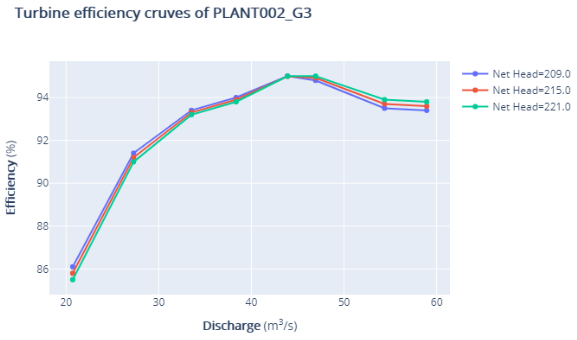

Figure 42: PLANT002 G3 turbine efficiency

B.1.3 PLANT003

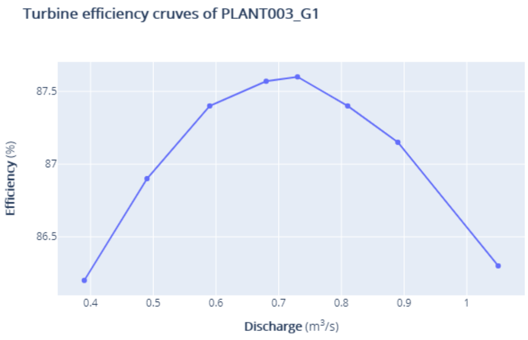

Figure 43: PLANT003 G1 turbine efficiency

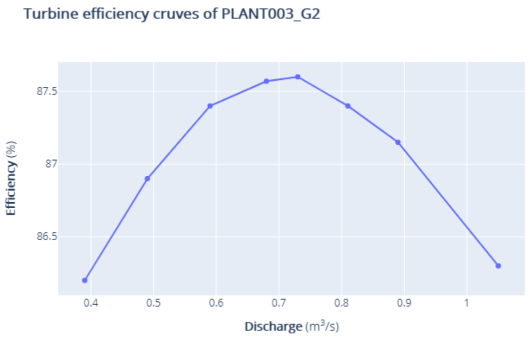

Figure 44: PLANT003 G2 turbine efficiency

B.1.4 PLANT004

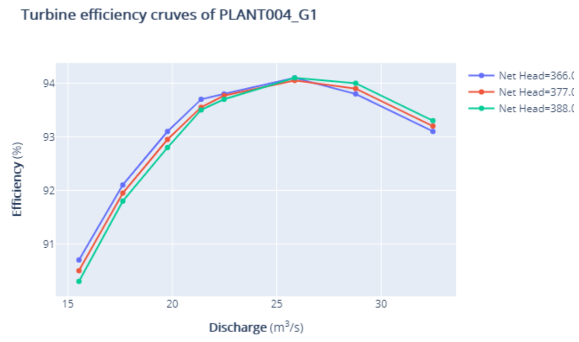

Figure 45: PLANT004 G1 turbine efficiency

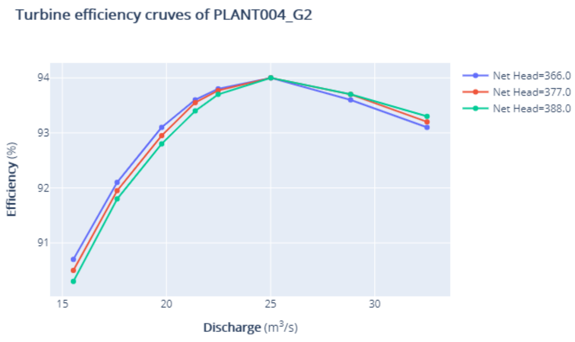

Figure 46: PLANT004 G2 turbine efficiency

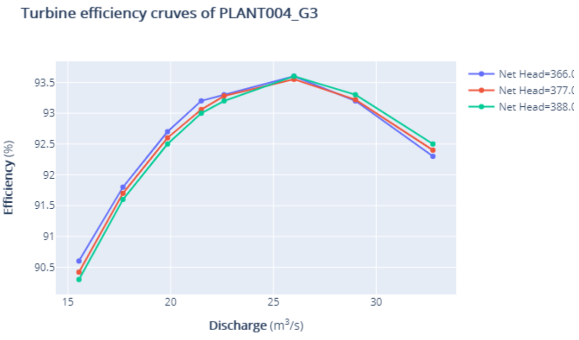

Figure 47: PLANT004 G3 turbine efficiency

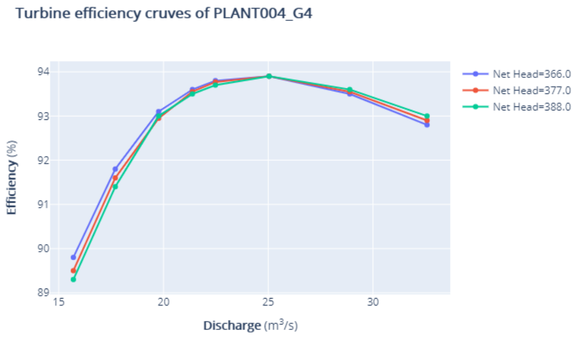

Figure 48: PLANT004 G4 turbine efficiency

B.2 The reservoir volume and height relationship

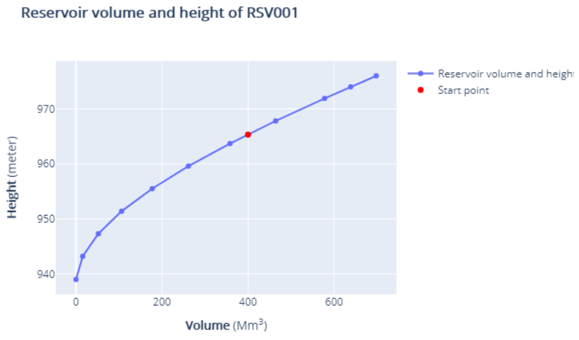

Figure 49: RSV001

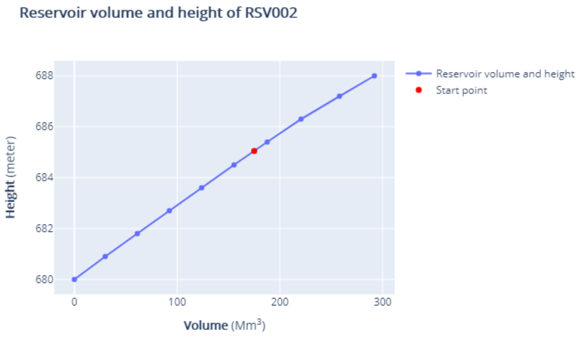

Figure 50: RSV002

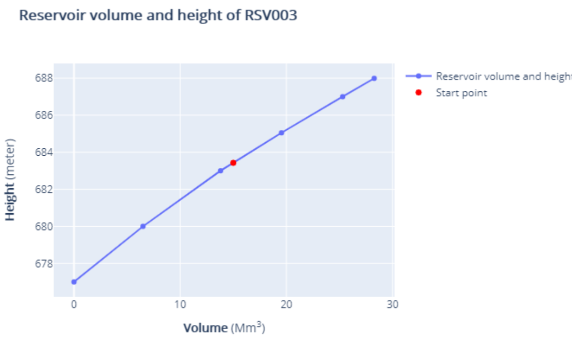

Figure 51: RSV003

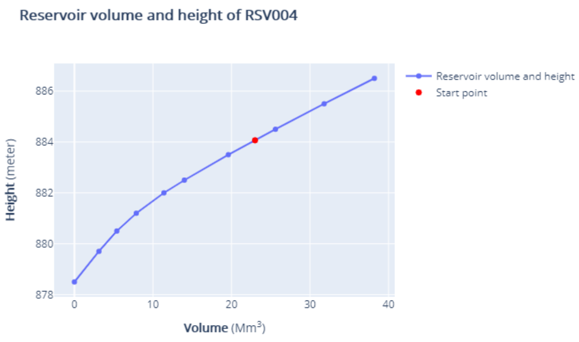

Figure 52: RSV004

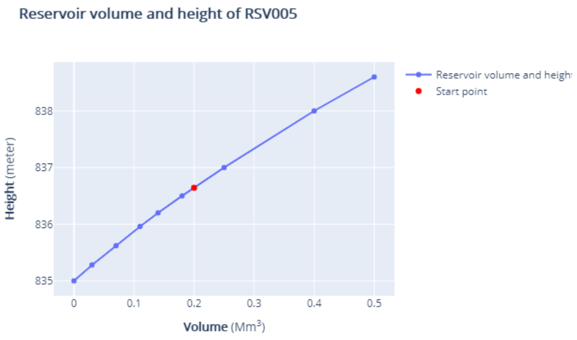

Figure 53: RSV005

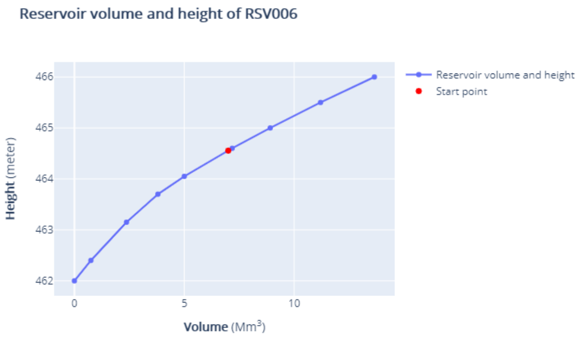

Figure 54: RSV006

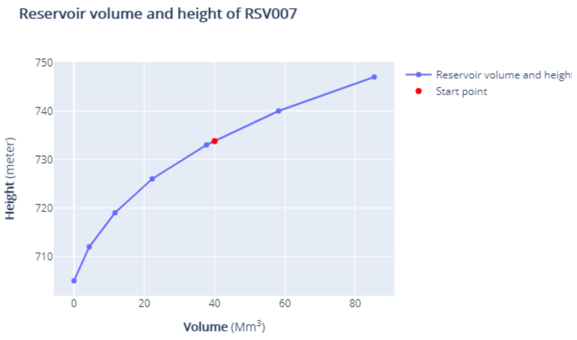

Figure 55: RSV007

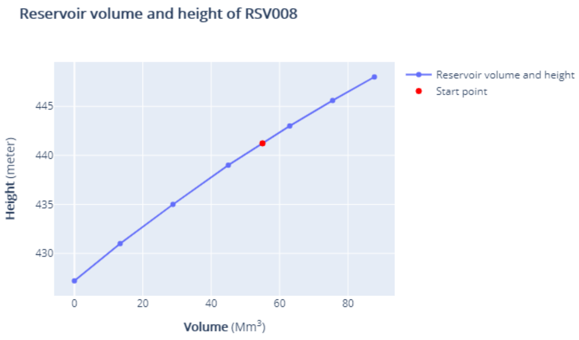

Figure 56: RSV008

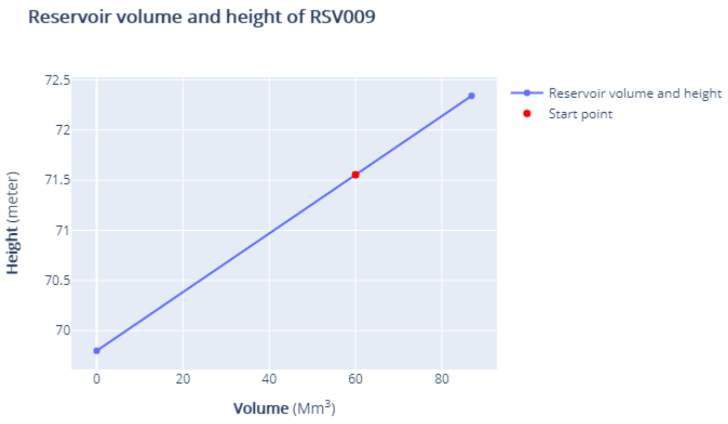

Figure 57: RSV009

Appendix C

Maintenance conditions of upper limits

C.1 Maintenance schedules of upper limit 1

Number	Maintenance time	Date	Accumulated profit (EUR)
1	292	2017-01-13 04:00:00	359867.9606
2	557	2017-01-24 05:00:00	322926.287
3	795	2017-02-03 03:00:00	419758.0348
4	1015	2017-02-12 07:00:00	501576.7861
5	1277	2017-02-23 05:00:00	448568.0396
6	1539	2017-03-06 03:00:00	463355.2872
7	1708	2017-03-13 04:00:00	391838.0424
8	1925	2017-03-22 05:00:00	299521.3889
9	2069	2017-03-28 05:00:00	211436.7303
10	2214	2017-04-03 06:00:0	120288.217
11	2572	2017-04-18 04:00:00	140799.441
12	2740	2017-04-25 04:00:00	356946.4628
13	3053	2017-05-08 05:00:00	426550.7027
14	3148	2017-05-12 04:00:00	269127.1885
15	3226	2017-05-15 10:00:00	148204.6491
16	3630	2017-06-01 06:00:00	93805.67426
17	3708	2017-06-04 12:00:00	25130.8265
18	4154	2017-06-23 02:00:00	-1000
19	4495	2017-07-07 07:00:00	26201.64479
20	4832	2017-07-21 08:00:00	47365.38584
21	4973	2017-07-27 05:00:00	92137.84357
22	5095	2017-08-01 07:00:00	83966.82955
23	5173	2017-08-04 13:00:00	27409.15788
24	5619	2017-08-23 03:00:00	-1000

25	5812	2017-08-31 04:00:00	322667.6536
26	6149	2017-09-14 05:00:00	396714.923
27	6315	2017-09-21 03:00:00	401232.7078
28	6435	2017-09-26 03:00:00	289477.062
29	6748	2017-10-09 04:00:00	222245.5471
30	7085	2017-10-23 05:00:00	203142.8321
31	7422	2017-11-06 06:00:00	233198.2408
32	7588	2017-11-13 04:00:00	339669.8378
33	7949	2017-11-28 05:00:00	428460.7315
34	8261	2017-12-11 05:00:00	449242.99
35	8428	2017-12-18 04:00:00	377464.8529
36	8647	2017-12-27 07:00:00	250284.9782
37	8760	2018-01-01 00:00:00	78860.61933

C.2 Maintenance schedules of upper limit 2

Number	Maintenance time	Date	Accumulated profit (EUR)
1	100	2017/01/05 4:00	255862.5331
2	195	2017/01/09 3:00	239222.5041
3	343	2017/01/15 7:00	243098.0516
4	534	2017/01/23 6:00	208783.4747
5	700	2017/01/30 4:00	216019.9652
6	823	2017/02/04 7:00	316024.3586
7	942	2017/02/09 6:00	357438.2408
8	1060	2017/02/14 4:00	350850.8234
9	1184	2017/02/19 8:00	288996.3687
10	1295	2017/02/23 23:00	271190.7834
11	1420	2017/03/01 4:00	298489.0028
12	1539	2017/03/06 3:00	343923.9248
13	1636	2017/03/10 4:00	303168.0754
14	1733	2017/03/14 5:00	212350.6485
15	1877	2017/03/20 5:00	209272.6342
16	2045	2017/03/27 5:00	202684.6946
17	2142	2017/03/31 6:00	122425.5028
18	2238	2017/04/04 6:00	43266.37659
19	2316	2017/04/07 12:00	14304.15908
20	2490	2017/04/14 18:00	18247.8329
21	2572	2017/04/18 4:00	135952.3644

22	2740	2017/04/25 4:00	238078.5201
23	2909	2017/05/02 5:00	279738.2212
24	3053	2017/05/08 5:00	293244.3766
25	3148	2017/05/12 4:00	263037.4414
26	3226	2017/05/15 10:00	147666.9321
27	3319	2017/05/19 7:00	70954.64031
28	3439	2017/05/24 7:00	6435.669806
29	3630	2017/06/01 6:00	27652.97524
30	3708	2017/06/04 12:00	25130.8265
31	3939	2017/06/14 3:00	-1000
32	4170	2017/06/23 18:00	-1000
33	4401	2017/07/03 9:00	-1000
34	4495	2017/07/07 7:00	26201.64479
35	4573	2017/07/10 13:00	26201.64479
36	4804	2017/07/20 4:00	-1000
37	4973	2017/07/27 5:00	73849.06365
38	5095	2017/08/01 7:00	83966.82955
39	5173	2017/08/04 13:00	27409.15788
40	5404	2017/08/14 4:00	-1000
41	5623	2017/08/23 7:00	1551.631664
42	5764	2017/08/29 4:00	183065.6151
43	5875	2017/09/02 19:00	332135.2779
44	5981	2017/09/07 5:00	248331.0153
45	6149	2017/09/14 5:00	195706.145
46	6255	2017/09/18 15:00	304550.6231
47	6339	2017/09/22 3:00	300532.8436
48	6435	2017/09/26 3:00	252163.5969
49	6513	2017/09/29 9:00	134419.4453
50	6654	2017/10/05 6:00	48149.94247
51	6748	2017/10/09 4:00	118900.4953
52	6845	2017/10/13 5:00	105927.3347
53	6977	2017/10/18 17:00	47916.02063
54	7085	2017/10/23 5:00	131314.5475
55	7254	2017/10/30 6:00	164428.4348
56	7422	2017/11/06 6:00	150041.002
57	7568	2017/11/12 8:00	248245.9394
58	7756	2017/11/20 4:00	265249.3096
59	7925	2017/11/27 5:00	292244.3858

60	8003	2017/11/30 11:00	347880.5978
61	8093	2017/12/04 5:00	253940.2759
62	8261	2017/12/11 5:00	221865.3392
63	8428	2017/12/18 4:00	322828.7907
64	8647	2017/12/27 7:00	203036.504
65	8760	2018/1/1 0:00	78860.61933

C.3 Maintenance schedules of upper limit 3

Number	Maintenance time	Date	Accumulated profit (EUR)
1	78	2017/01/04 6:00	169549.6298
2	156	2017/01/07 12:00	211002.8701
3	279	2017/01/12 15:00	125249.1678
4	357	2017/01/15 21:00	189947.1299
5	438	2017/01/19 6:00	140543.2019
6	534	2017/01/23 6:00	80477.99264
7	612	2017/01/26 12:00	143030.2939
8	700	2017/01/30 4:00	140575.6591
9	778	2017/02/02 10:00	198378.1264
10	856	2017/02/05 16:00	225573.4284
11	934	2017/02/08 22:00	242806.6376
12	1012	2017/02/12 4:00	241030.177
13	1090	2017/02/15 10:00	229369.4105
14	1184	2017/02/19 8:00	193547.1496
15	1277	2017/02/23 5:00	177814.1804
16	1360	2017/02/26 16:00	191917.1055
17	1444	2017/03/02 4:00	195843.4263
18	1522	2017/03/05 10:00	229675.2821
19	1600	2017/03/08 16:00	234745.1081
20	1697	2017/03/12 17:00	171248.9396
21	1780	2017/03/16 4:00	146277.6683
22	1877	2017/03/20 5:00	115215.1543
23	1955	2017/03/23 11:00	148861.6508
24	2045	2017/03/27 5:00	118774.0052
25	2142	2017/03/31 6:00	110384.7898
26	2238	2017/04/04 6:00	37809.64111
27	2316	2017/04/07 12:00	14304.15908
28	2448	2017/04/13 0:00	-1000

29	2538	2017/04/16 18:00	43174.76208
30	2621	2017/04/20 5:00	110706.4488
31	2730	2017/04/24 18:00	65796.10599
32	2808	2017/04/28 0:00	219421.1959
33	2909	2017/05/02 5:00	150583.6558
34	2987	2017/05/05 11:00	171843.8035
35	3075	2017/05/09 3:00	195967.8491
36	3153	2017/05/12 9:00	188540.7704
37	3231	2017/05/15 15:00	127125.9356
38	3319	2017/05/19 7:00	60256.82939
39	3439	2017/05/24 7:00	6435.669806
40	3517	2017/05/27 13:00	1522.148744
41	3630	2017/06/01 6:00	12049.17337
42	3708	2017/06/04 12:00	25130.8265
43	3840	2017/06/10 0:00	-1000
44	3972	2017/06/15 12:00	-1000
45	4104	2017/06/21 0:00	-1000
46	4236	2017/06/26 12:00	-1000
47	4368	2017/07/02 0:00	-1000
48	4495	2017/07/07 7:00	10259.95136
49	4573	2017/07/10 13:00	26201.64479
50	4705	2017/07/16 1:00	-1000
51	4832	2017/07/21 8:00	11730.0192
52	4952	2017/07/26 8:00	30426.98569
53	5071	2017/07/31 7:00	62188.33327
54	5149	2017/08/03 13:00	28728.24904
55	5281	2017/08/09 1:00	-1000
56	5413	2017/08/14 13:00	-1000
57	5545	2017/08/20 1:00	-1000
58	5639	2017/08/23 23:00	10051.00244
59	5728	2017/08/27 16:00	83666.83474
60	5812	2017/08/31 4:00	213078.7242
61	5890	2017/09/03 10:00	230750.276
62	5981	2017/09/07 5:00	203798.6372
63	6102	2017/09/12 6:00	110049.8942
64	6180	2017/09/15 12:00	155459.9445
65	6258	2017/09/18 18:00	216204.3778
66	6339	2017/09/22 3:00	212920.8901

67	6417	2017/09/25 9:00	200573.6004
68	6495	2017/09/28 15:00	155512.1117
69	6573	2017/10/01 21:00	48431.99052
70	6678	2017/10/06 6:00	22412.7236
71	6756	2017/10/09 12:00	103839.7488
72	6845	2017/10/13 5:00	91871.25162
73	6923	2017/10/16 11:00	17239.20467
74	7003	2017/10/19 19:00	18298.04939
75	7085	2017/10/23 5:00	75037.0685
76	7163	2017/10/26 11:00	111866.6692
77	7254	2017/10/30 6:00	83062.72137
78	7350	2017/11/03 6:00	76572.77258
79	7445	2017/11/07 5:00	85922.22079
80	7550	2017/11/11 14:00	126522.9178
81	7635	2017/11/15 3:00	186025.401
82	7743	2017/11/19 15:00	127870.7978
83	7853	2017/11/24 5:00	161170.4722
84	7949	2017/11/28 5:00	202765.248
85	8027	2017/12/01 11:00	265591.1474
86	8116	2017/12/05 4:00	178526.1948
87	8199	2017/12/08 15:00	84303.32034
88	8285	2017/12/12 5:00	104697.6302
89	8363	2017/12/15 11:00	176560.6403
90	8450	2017/12/19 2:00	223451.5069
91	8528	2017/12/22 8:00	146536.2361
92	8647	2017/12/27 7:00	59283.17604
93	8760	2018/1/1 0:00	78860.61933

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