Norwegian University of Science and Technology

Condition-based opportunistic maintenance of cascaded hydropower stations

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Research backgound

1.1 Hydropower in Norway

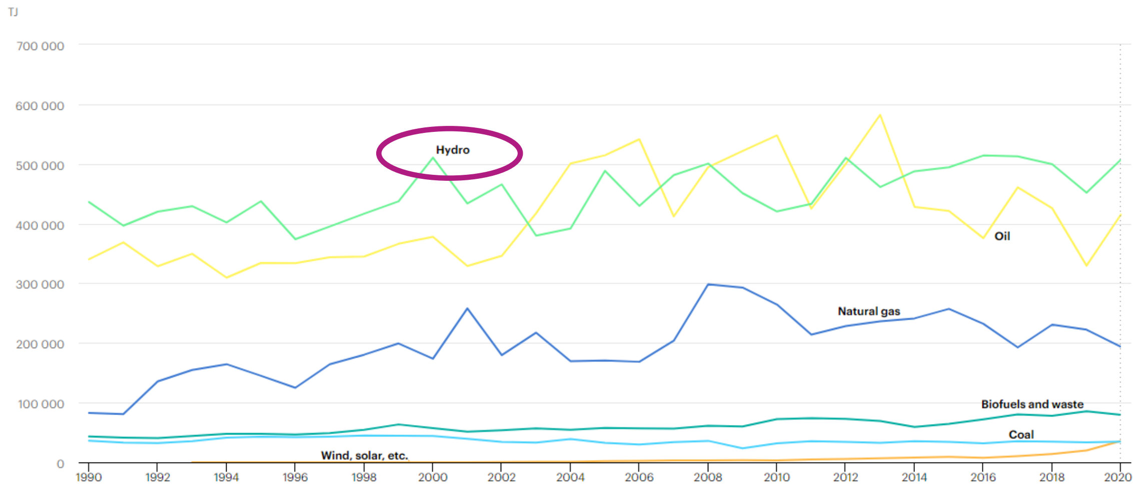


Figure 1-Total energy supply by source[1], Norway 1990-2020

Table 1- Developed hydropower system[2]

Category	Number	Average annual production [TWh]
Under 1 MW	579	0,8
1-10 MW	813	11,4
10-100 MW	264	43,4
Over 100 MW	83	82,5
Total	1 739	138,1

In February 2022, 87.1 % of total electricity generation in Norway comes from hydropower. Production from large power plants (LHPs) accounts for 59.8 % of overall hydropower generation.

1. https://www.iea.org/countries/norway
2. https://www.nve.no/energi/energisystem/vannkraft/

1.2 Cascaded power stations

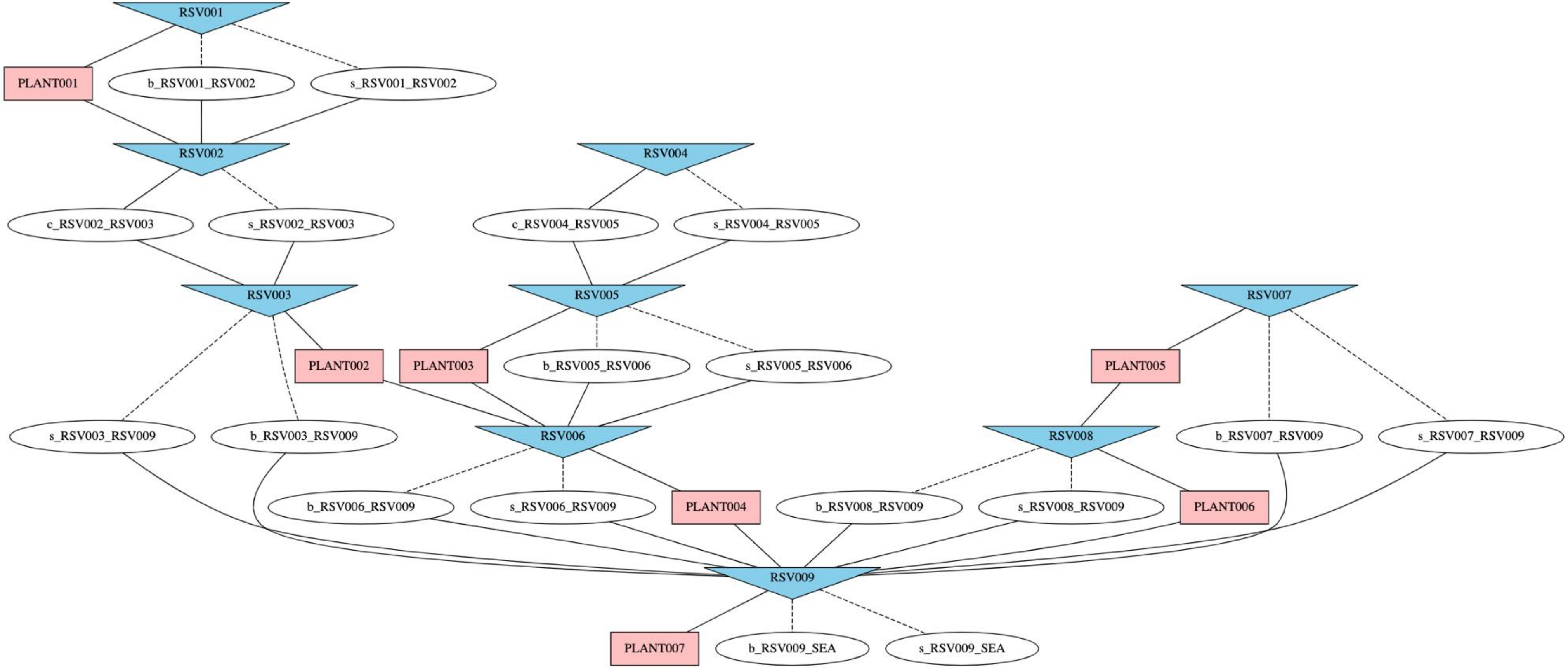


Figure 2- Topology of hydropower production in SHOP[3]

1.3 Single hydropower plant

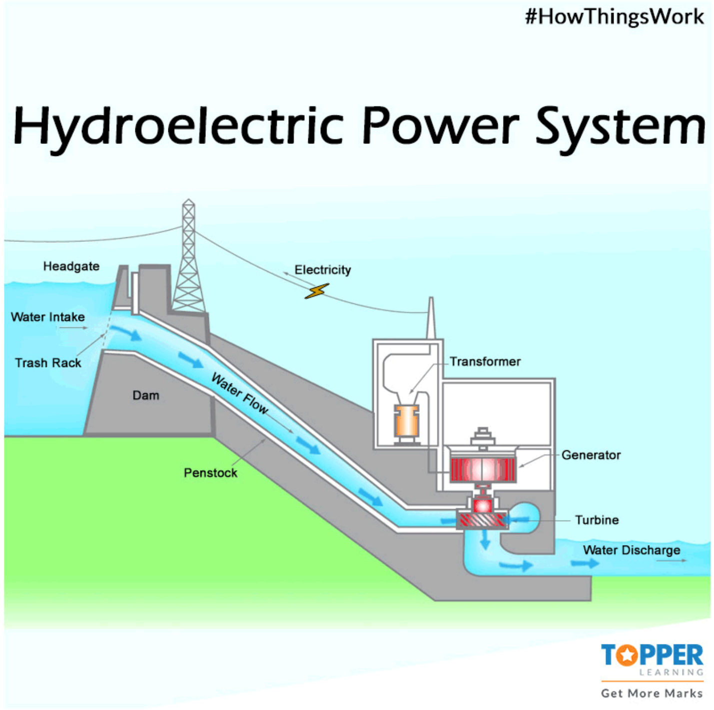


Figure 3- single plant[4]

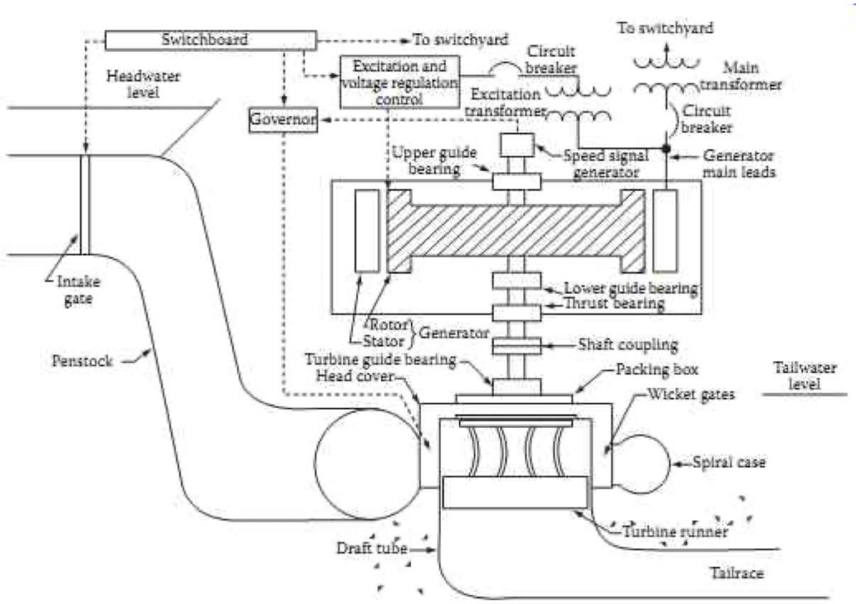


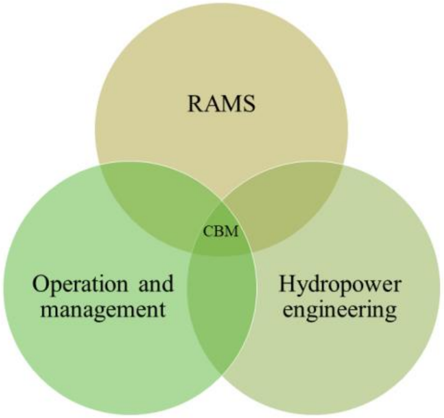
Figure 4- Vertical Francis turbine (IEEE, 1988)

Objectives and methods

2.1 Research problem

- How to consider the influence of electricity production in condition-based maintenance model?

- How to integrate the new CBM model with generator maintenance scheduling?



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2.1 Review of GMS

Table 2-Review of GMS study in hydropower

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

STHS: short-term hydro scheduling

GMS: generator maintenance scheduling

2.2 CBOM strategy

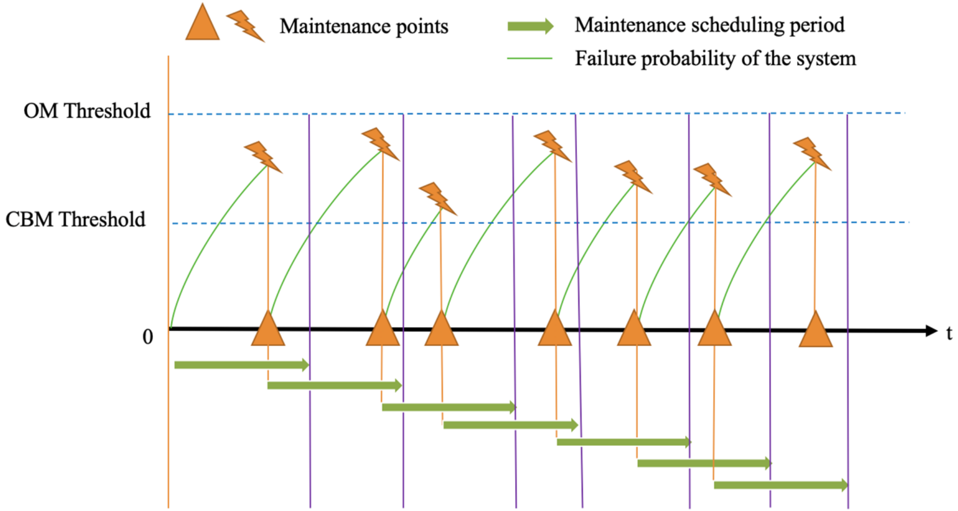

Figure 5- CBOM strategy

Opportunistic Maintenance (OM) is to schedule maintenance based on opportunities in operation considering dependence among components (AbSamat and Kamaruddin, 2014).

CBM is to repair components when deterioration exceeds a certain threshold. Condition-based opportunistic maintenance (CBOM) combines the advantages of both CBM and OM. It schedules maintenance considering both operation and real condition of components (Zhao et al., 2019; Zhang et al., 2021).

2.2 CBOM strategy

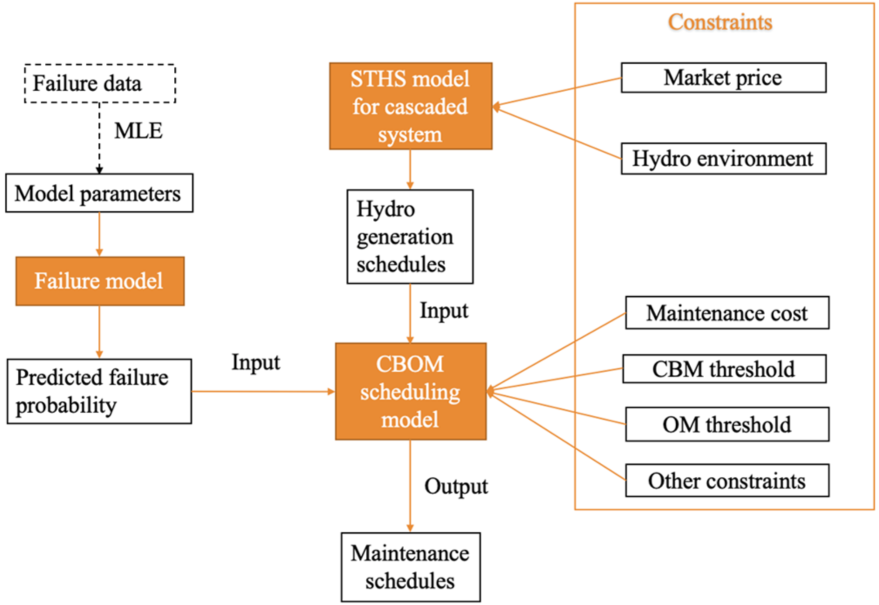

Figure 6- Framework

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Scheduling results

3.1 Inputs and outputs from SHOP

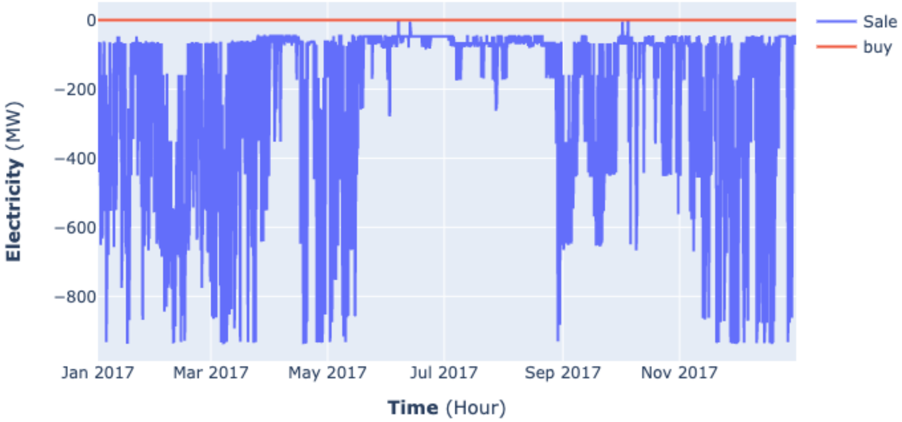

Figure 7- Market condition

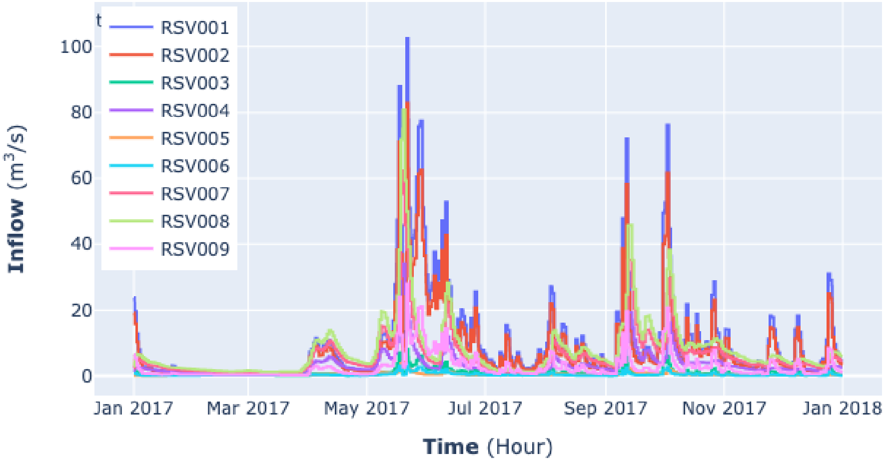

Figure 8- Inflow to different researvoirs

3.1 Inputs and outputs from SHOP

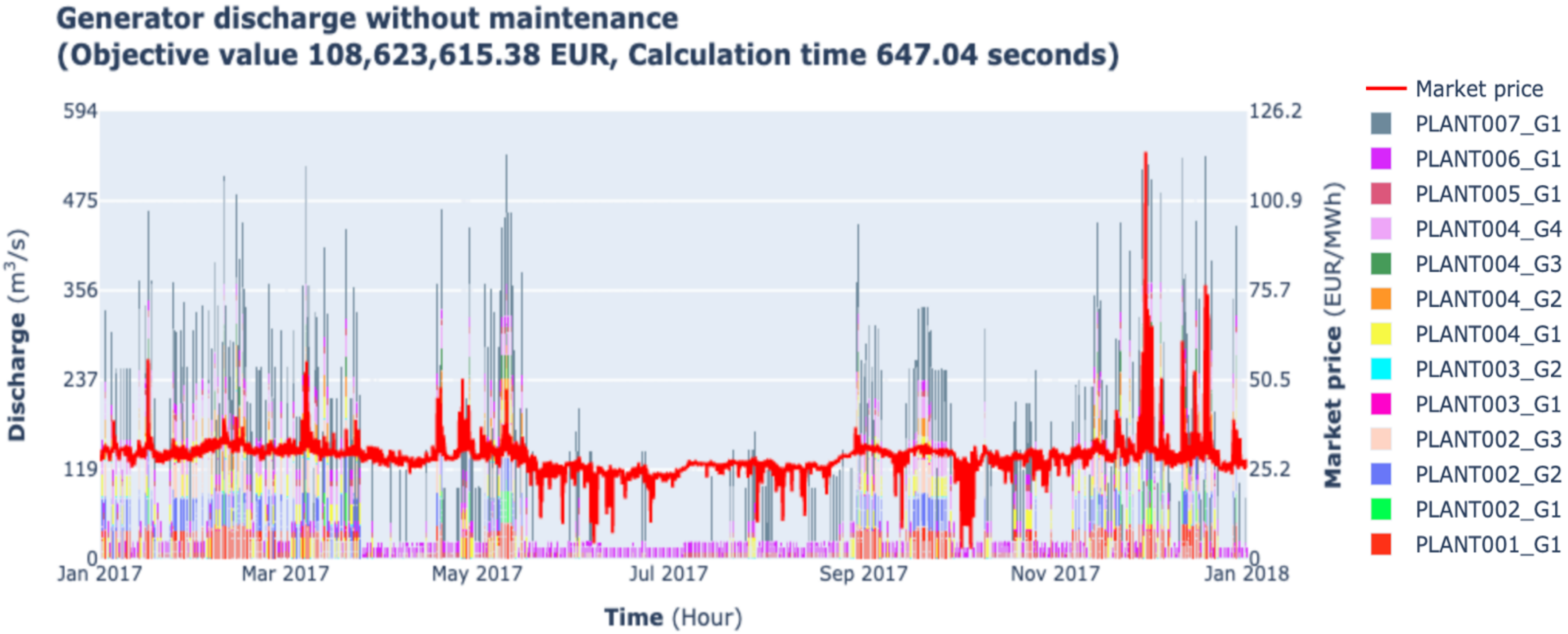

Figure 9- Outputs from SHOP

3.2 Structure of Francis unit

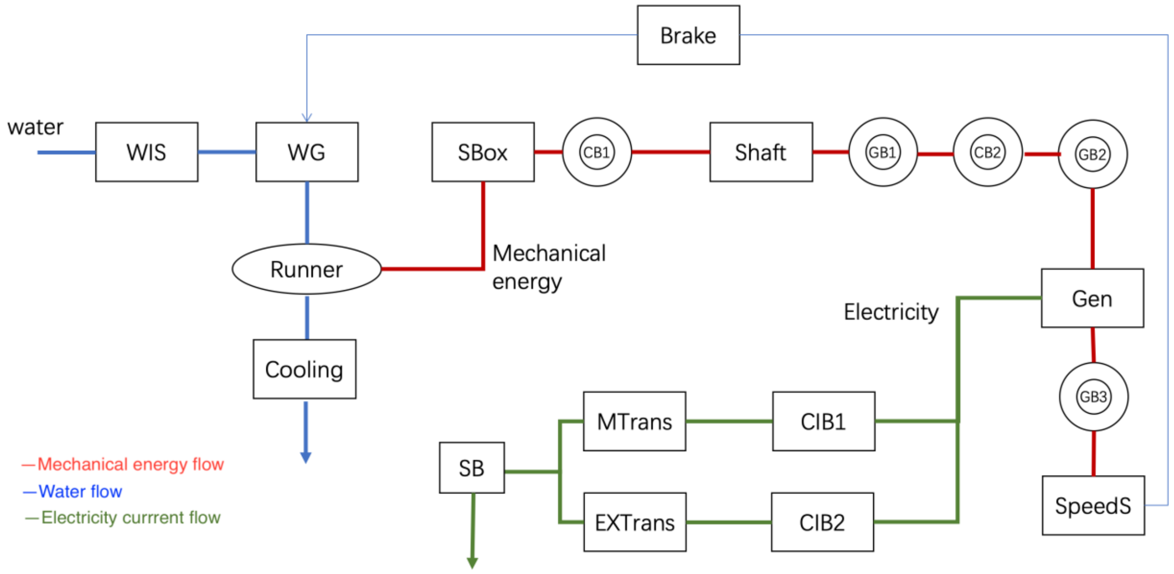

Figure 10-Structure of Francis turbine

Table 3-Function of Francis turbine

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

3.2 Failure simulation of Francis unit

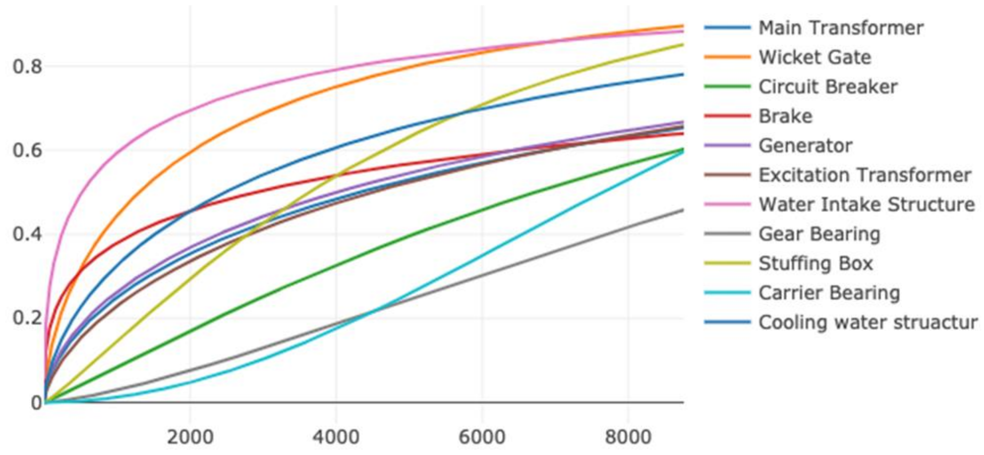

Figure 11-CDF of components in 8760h (BULUT and ÖZCAN, 2021)

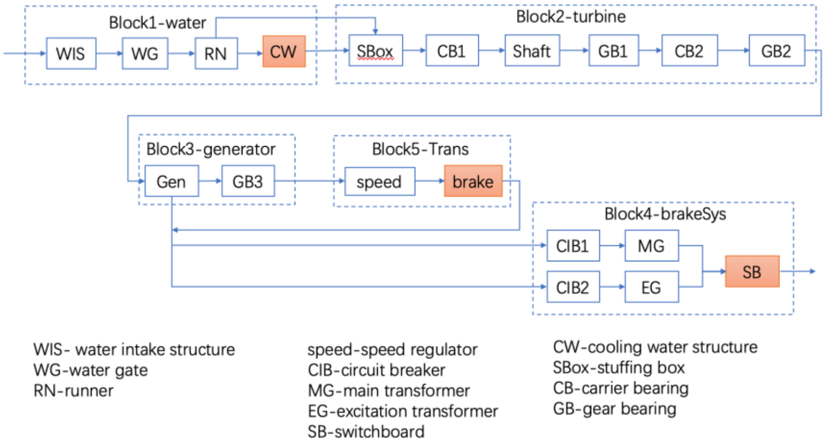

Figure 12- Reliability block diagram

3.2 Failure simulation of Francis unit

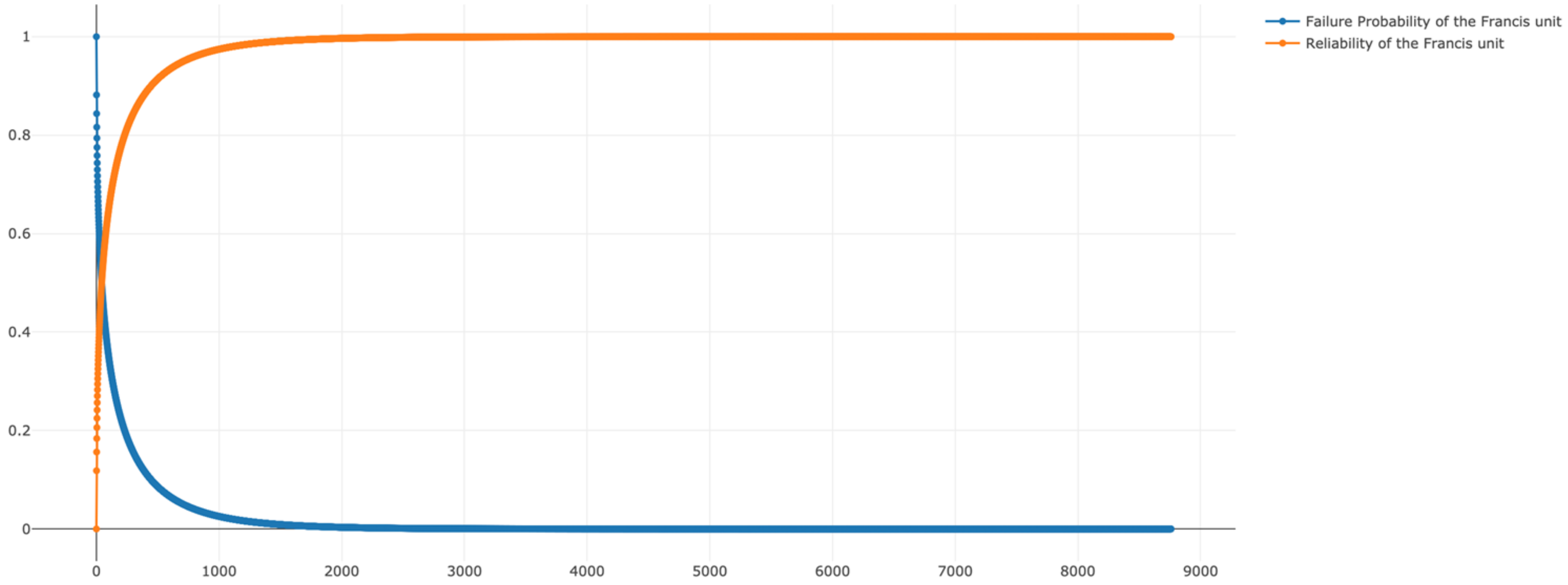

Figure 13- Failure simulation in 8760h

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3.2 Failure simulation of Francis unit

Initialization:

$$Aprofit(PM1) = \sum_{P}^{PM1} Tprofit(t) - penalty * timelength$$

$$+ \sum_{PM+1}^{p+gap-1} Electricity(t) * Price(t) * R(t - PM1 - timelength)$$

Accumulated profits:

$$Aprofit(PM2) = \sum_{p}^{PM2} Electricity(t) * Price(t) * R(t - PM1 - timelength)$$

$$-penalty * timelengt + \sum_{PM2+timelength}^{p+gap-1} Electricity(t) * Price(t) * R(t - PM2 - timelength)$$

3.2 Failure simulation of Francis unit

Table 4-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

3.3 Plant004G1 scheduling results

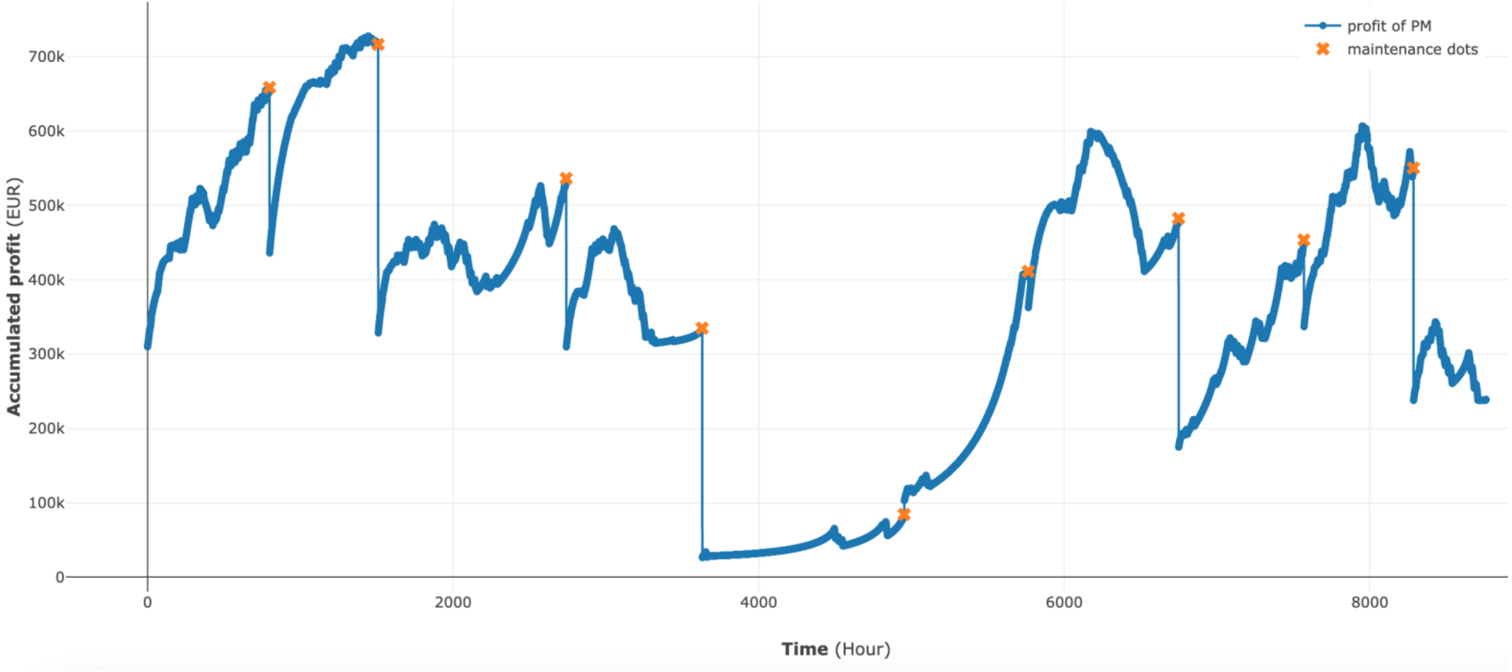


Figure 14- Maintenance scheduling for Plant004 G1

Sensitivity analysis

4.1 Important parameters

Parameters: *alert level* , *upper limit*, *penalty* and *time length*

- **alert level**: minimal acceptance limit of failure probability, decided by *gap*
- **upper limit**: maximum acceptable limit of failure probability, decided by *time*

$$\frac{8760}{time} \leq \#of\ maintenance\ activities \leq \frac{8760}{gap}$$

$$F(gap) \leq Failure\ probability \leq F(time)$$

Alert level

Upper limit

4.2 Alert level

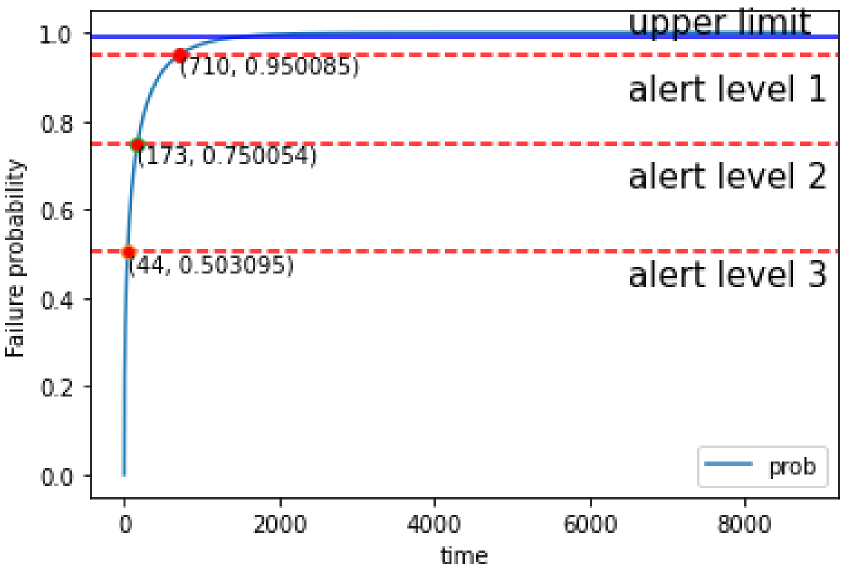


Figure 15- different alert levels

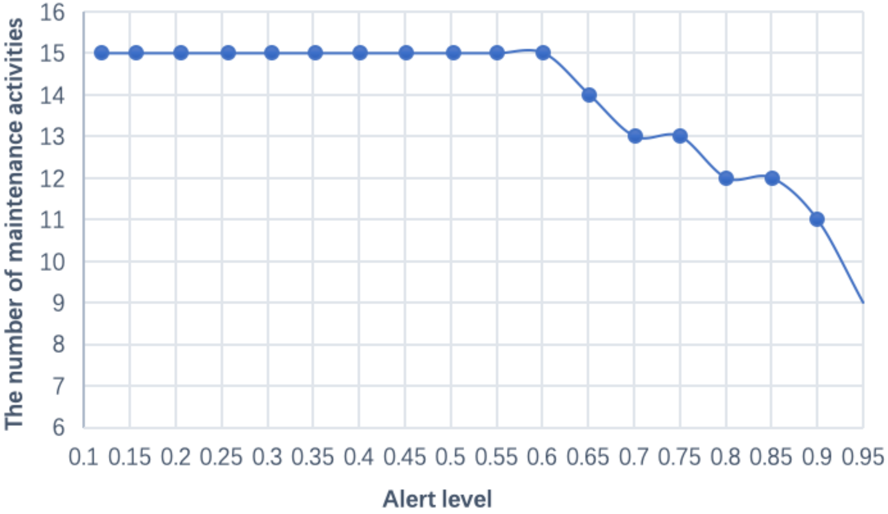


Figure 16- influence of alert levels

4.3 Upper limits

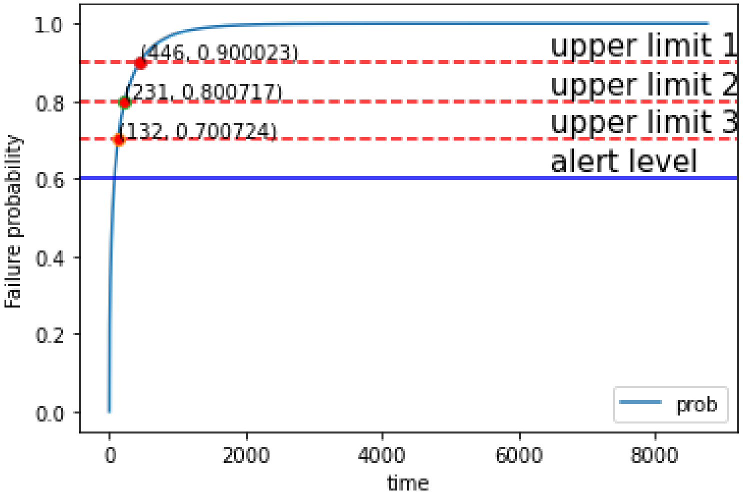


Figure 17- different upper limits

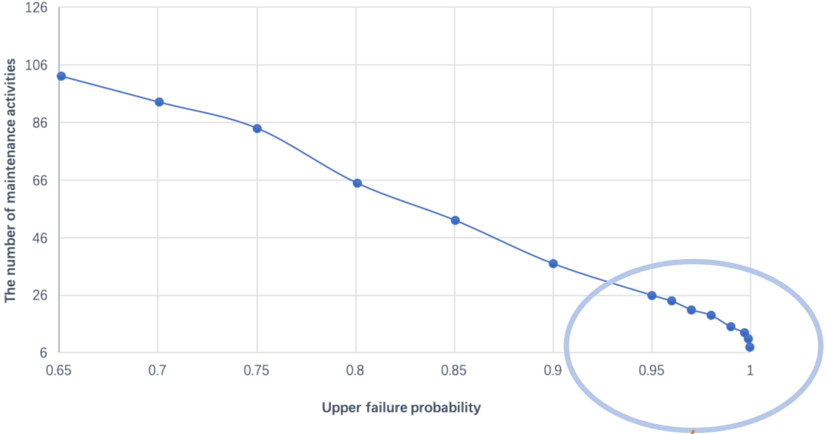
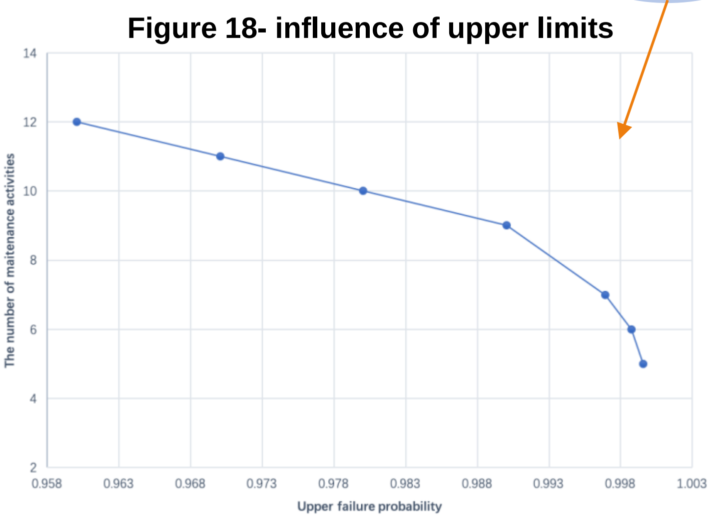


Figure 18- influence of upper limits



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4.4 Penalty, time length

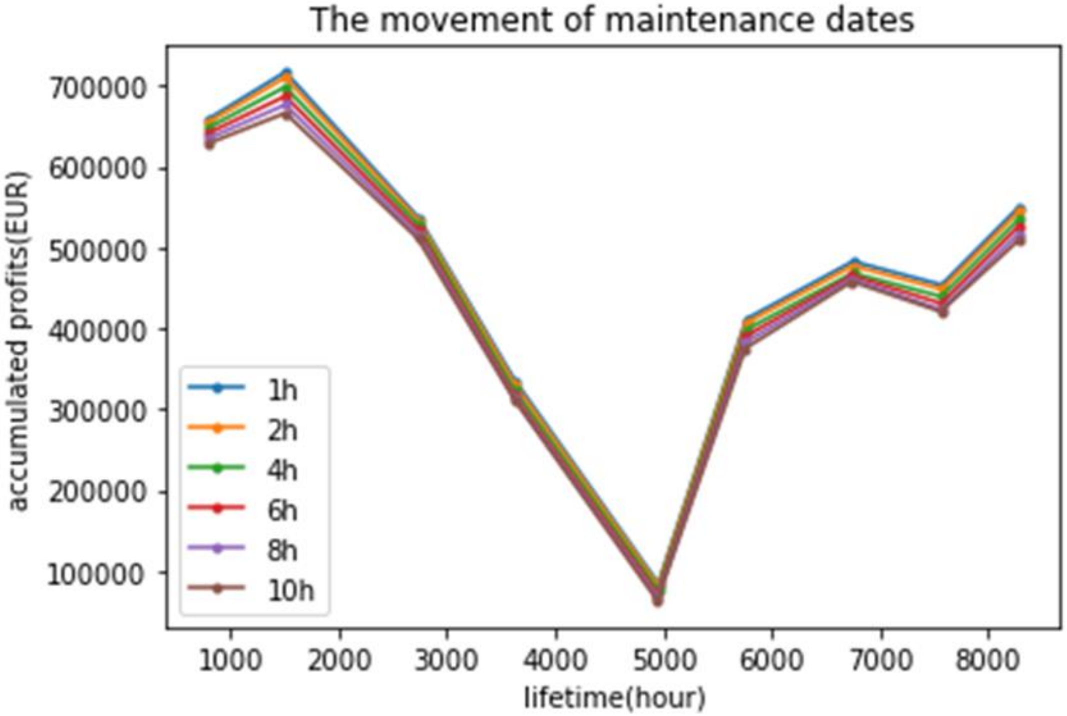


Figure 19- influence of maintenance duration

time length: maintenance duration
penalty: the cost of maintenance

penalty does not affect the number of maintenance activities. Because *penalty* is the same for any selected time.

4.5 CBOM and ABM

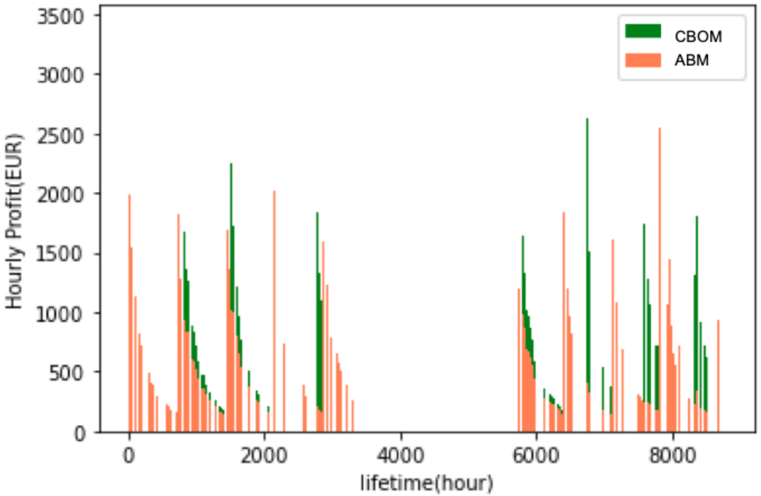


Figure 19- hourly profit of CBOM and ABM

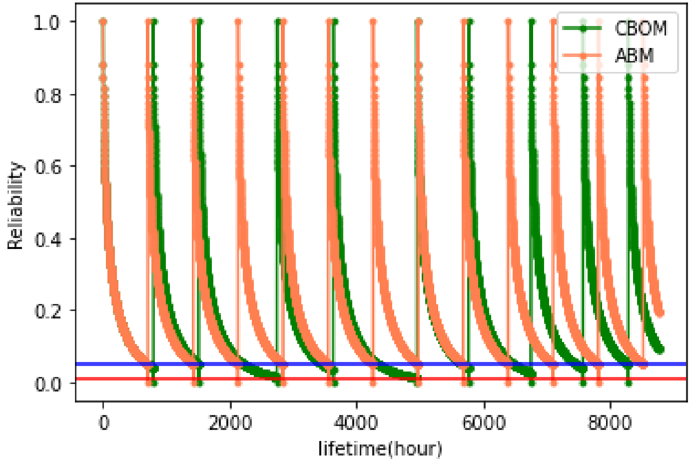
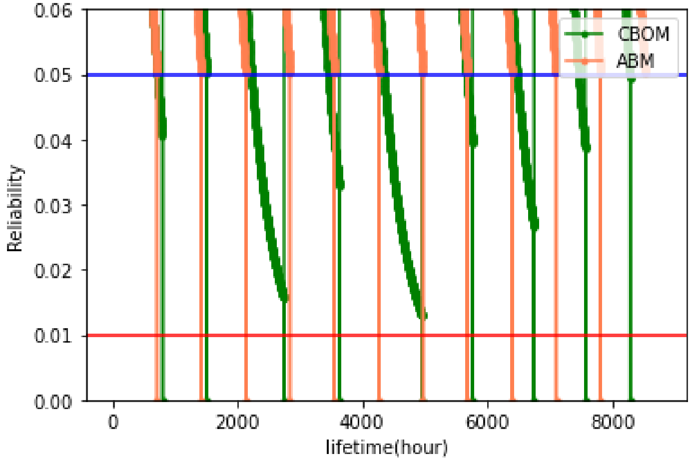


Figure 20- Comparison of CBOM and ABM



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.

Limitations and conclusions

5.1 Limitations

- **Data collection**
  In this research, 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.

- **Profit calculation**
  There are two types of profit concept in this research. Hourly profit is the product of hourly production, market price and reliability. accumulated profit is the accumulation of hourly profits during one specific period. The improvement on the actual monetary income may not appear unless the value of reliability can be quantified by money.

- **Maintenance parameters**
  Parameters include maintenance cost, maintenance duration, alert level and 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. 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.

5.2 Conclusions

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

This paper presents CBOM model for a cascaded hydro system. It succeeds to fit into STHS model. Case study of PLANT004 G1 shows that trade-off between production and maintenance is made by optimizing the accumulated profits between two maintenance thresholds. Sensitivity analysis reflects that accident penalty cost and maintenance duration do not influence the final results, but increasing thresholds can decrease the number of maintenance activities. Compared with ABM and corrective maintenance, CBOM model reduces and postpones unnecessary maintenance activities that will bring the huge profit loss.

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Thanks for listening!