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Experiences with incorporating power loss in shared tunnels into the hydro unit commitment

Hydro Power Scheduling Workshop, 12 September 2018

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SINTEF Energy Research

Outline

- Background of Short-term Hydro Optimization Program (SHOP)
- Determination of the unit PQ curve
- Methods for incorporating power loss in shared penstock
- Numerical results
- Conclusion

Short-term Hydro Optimization Program (SHOP)

Objectives

- maximize the profit by exploiting the options of buying and selling in the markets
- minimize cost for covering a load

Inputs

- **Deterministic** electricity price, inflow and/or load for each time period (hourly / minute)
- **Detailed** description of watercourses, plant and unit configurations
- Different alternatives for **coupling to mid-term planning** (independent water value, water-value functions…)

Main results

- Reservoir trajectories, **water flow** among hydraulic objects
- Traded volume against the market (for **bidding**)
- Plant and unit production/consumption schedules (for **energy delivery**)
- Optimal distribution of **ancillary services**

S
H
O
P

SHOP

Available extensions

- Head optimization on reservoir level
- Start reservoir in meter
- Residual reservoirs

- Creek intake
- Multiple creek intakes

- Physical overflow model
- Overflow cost for each reservoir
- Lose spill

- Reservoir constraints in meters
- Tactical reservoir limits

- Discharge and production
- One or more time steps
- Penalty variables

Multi-object constraints

- Junction gate in series
- Gate ramping
- Ramping over several time steps
- TTXY input format

- Plant constraints in MW and m3/s
- Block generation

- Time dependent start cost
- Flexible MIP
- Dynamic flexible MIP
- Generator priorities
- Time variant maximum production for generators
- Polynomial efficiency description
- Reserve constraints on area level
- Reserve schedule on generator level
- Soft min/max constraints
- Dynamic PQ segmentation

- Pelton turbines with needle combinations
- Modeling of forbidden zones

- Cut corrections
- Value of water in transit
- Feeding fee
- Contracts
- Multiple load and markets
- Marginal cost curves
- Shared ownership

- Common outlet
- Pumping in connection with a junction
- Tide dependent plant head
- Junction below plant

Authors

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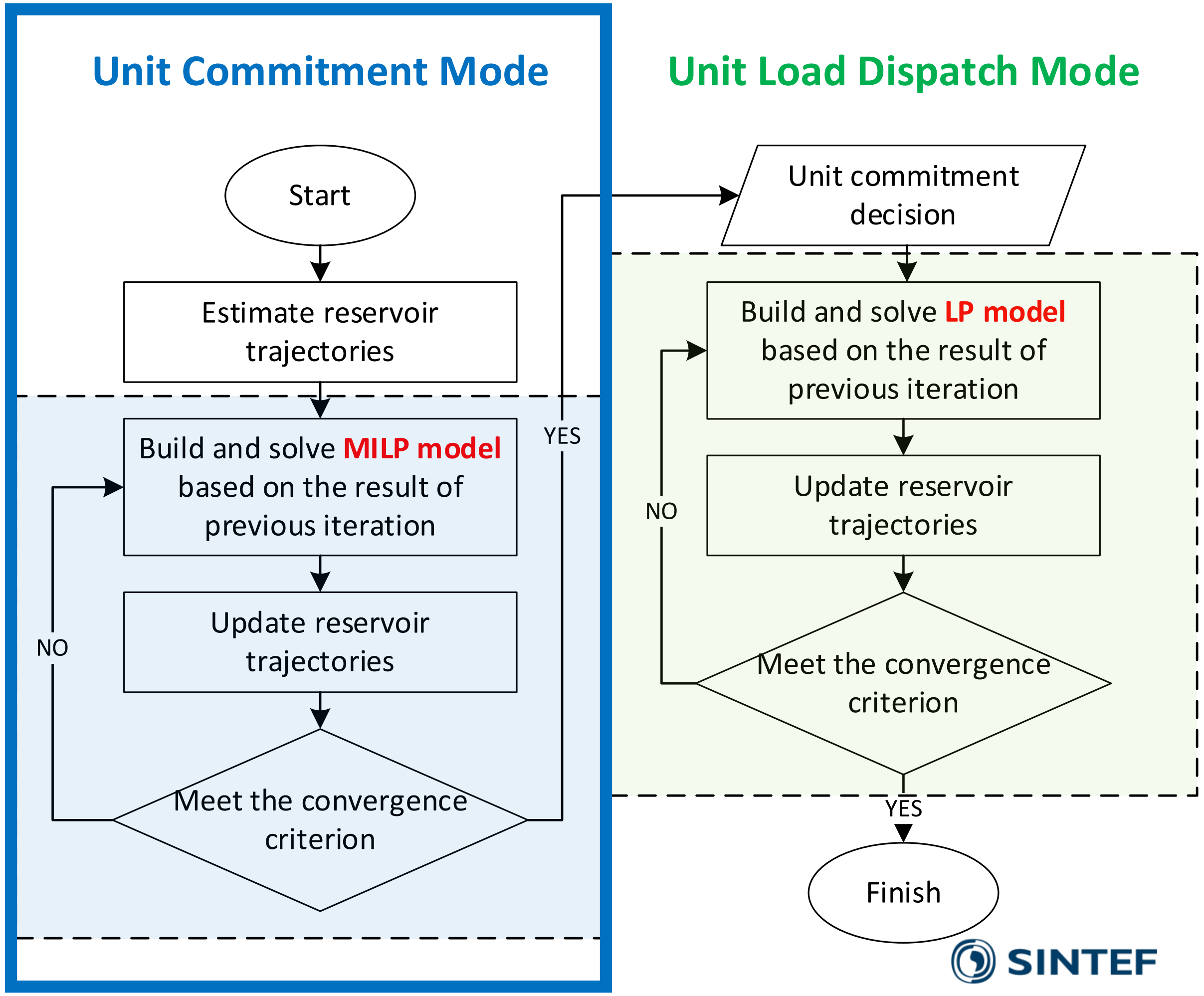
Jiehong Kong

- The solution strategy involves two modeling modes and employs **an iterative procedure** to refine the results
- Commercial solvers CPLEX & GUROBI
  Open Source solver CBC



Unit Commitment Mode

Start

Estimate reservoir trajectories

Build and solve **MILP model** based on the result of previous iteration

Update reservoir trajectories

Meet the convergence criterion

NO

YES

Unit Load Dispatch Mode

Unit commitment decision

Build and solve **LP model** based on the result of previous iteration

Update reservoir trajectories

Meet the convergence criterion

NO

YES

Finish

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Core equations in plant module in SHOP

Mathematical formulation

$$p_{i,t} = G \cdot \eta_i^{GEN}\left(p_{i,t}\right) \cdot \eta_i^{TURB}\left(h_{i,t}^{NET}, q_{i,t}\right) \cdot h_{i,t}^{NET} \cdot q_{i,t}$$

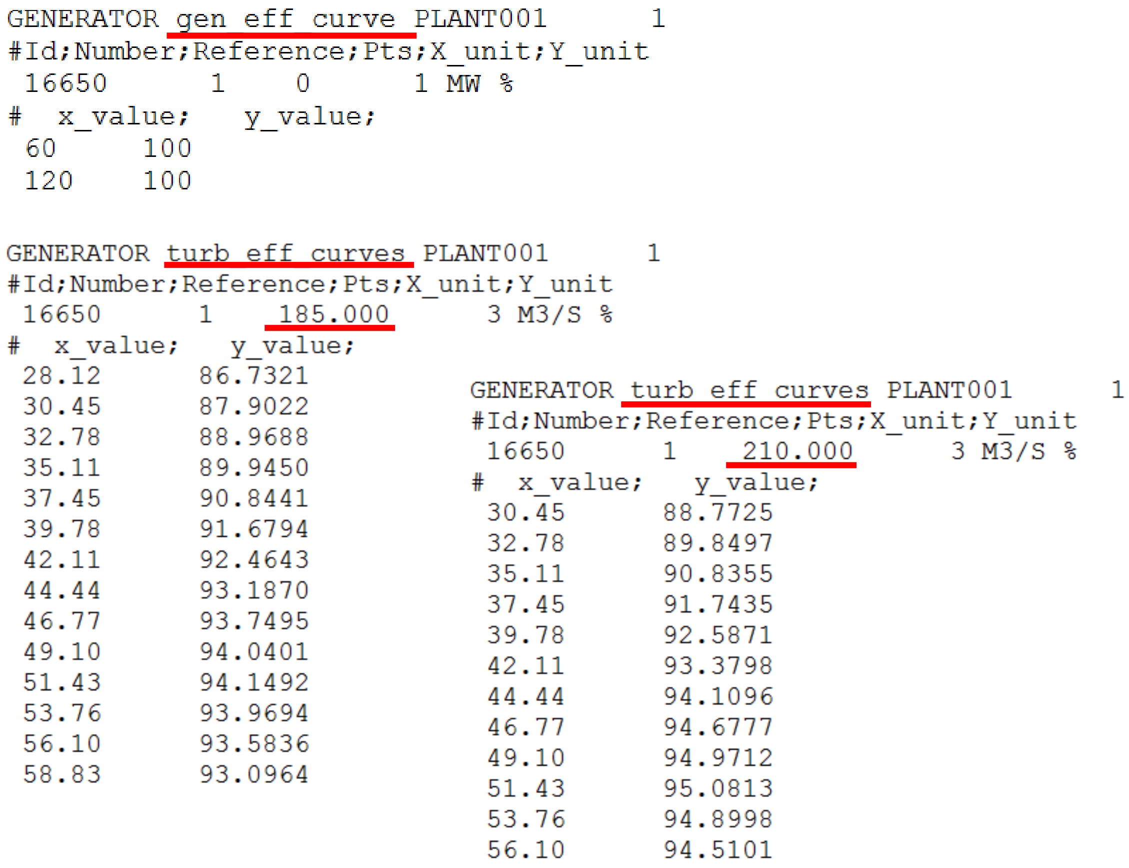
$$P_{i,t}^{MIN} \cdot \omega_{i,t} \leq p_{i,t} \leq P_{i,t}^{MAX} \cdot \omega_{i,t}$$

$$Q_{i,t}^{MIN}\left(h_{i,t}^{NET}\right) \cdot \omega_{i,t} \leq q_{i,t} \leq Q_{i,t}^{MAX}\left(h_{i,t}^{NET}\right) \cdot \omega_{i,t}$$

$$h_{i,t}^{NET} = H_t^{GROSS} - \alpha_n \cdot \left(q_{i,t} + \sum_{i' \in I_n \setminus \{i\}} q_{i',t}\right)^2$$

$$\sum_{i \in I} p_{i,t} = p_t^{SELL}$$

SHOP input



```
GENERATOR gen_eff_curve PLANT001       1
#Id;Number;Reference;Pts;X_unit;Y_unit
 16650       1     0        1 MW %
#  x_value;    y_value;
 60       100
 120      100
```

```
GENERATOR turb_eff_curves PLANT001       1
#Id;Number;Reference;Pts;X_unit;Y_unit
 16650       1     185.000       3 M3/S %
#  x_value;    y_value;
 28.12       86.7321
 30.45       87.9022
 32.78       88.9688
 35.11       89.9450
 37.45       90.8441
 39.78       91.6794
 42.11       92.4643
 44.44       93.1870
 46.77       93.7495
 49.10       94.0401
 51.43       94.1492
 53.76       93.9694
 56.10       93.5836
 58.83       93.0964
```

```
GENERATOR turb_eff_curves PLANT001       1
#Id;Number;Reference;Pts;X_unit;Y_unit
 16650       1     210.000       3 M3/S %
#  x_value;    y_value;
 30.45       88.7725
 32.78       89.8497
 35.11       90.8355
 37.45       91.7435
 39.78       92.5871
 42.11       93.3798
 44.44       94.1096
 46.77       94.6777
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$$h_{i,t}^{NET} = H_t^{GROSS} - \alpha_n \cdot \left(q_{i,t} + \sum_{i' \in I_n \setminus \{i\}} q_{i',t} \right)^2$$

$$\sum_{i \in I} p_{i,t} = p_t^{SELL}$$

SHOP input

```
GENERATOR attributes PLANT001      1
#Id Type Penstock Nom_prod Min_prod Max_prod Start_cost
 24839      0       1     120.000    60.000    120.000    0

GENERATOR  min_p_constr     PLANT001      1
#   Id   number   starttime         time_unit    period   data_type    y_unit   npts
    0     0    20161108060000000    HOUR         8760         -1       MW   1
#   time            y
20161108060000000   65

GENERATOR  max_p_constr     PLANT001      1
#   Id   number   starttime         time_unit    period   data_type    y_unit   npts
    0     0    20161108060000000    HOUR         8760         -1       MW   1
#   time            y
20161108060000000   95
```

Core equations in plant module in SHOP

Mathematical formulation

$$p_{i,t} = G \cdot \eta_i^{GEN}(p_{i,t}) \cdot \eta_i^{TURB}(h_{i,t}^{NET}, q_{i,t}) \cdot h_{i,t}^{NET} \cdot q_{i,t}$$

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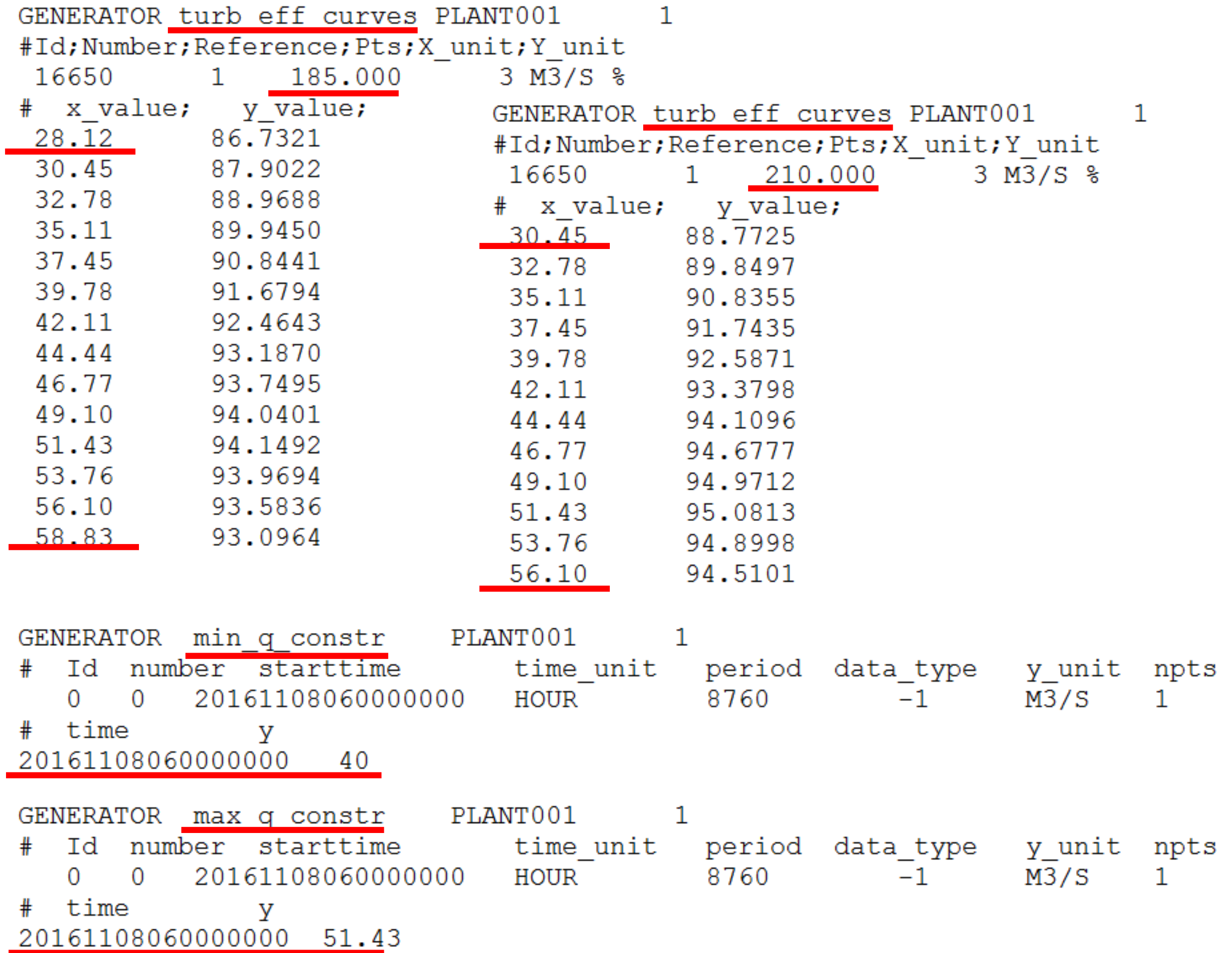
$$Q_{i,t}^{MIN}\left(h_{i,t}^{NET}\right) \cdot \omega_{i,t} \leq q_{i,t} \leq Q_{i,t}^{MAX}\left(h_{i,t}^{NET}\right) \cdot \omega_{i,t}$$

$$h_{i,t}^{NET} = H_t^{GROSS} - \alpha_n \cdot \left(q_{i,t} + \sum_{i' \in I_n \setminus \{i\}} q_{i',t}\right)^2$$

$$\sum_{i \in I} p_{i,t} = p_t^{SELL}$$

SHOP input



```
GENERATOR turb_eff_curves PLANT001       1
#Id;Number;Reference;Pts;X_unit;Y_unit
 16650       1     185.000       3 M3/S %
#  x_value;    y_value;
 28.12        86.7321
 30.45        87.9022
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 46.77        94.6777
 49.10        94.9712
 51.43        95.0813
 53.76        94.8998
 56.10        94.5101
```

```
GENERATOR  min_q_constr    PLANT001      1
#  Id   number  starttime         time_unit   period  data_type    y_unit   npts
   0    0    20161108060000000    HOUR        8760         -1      M3/S     1
#  time             y
20161108060000000   40
```

```
GENERATOR  max_q_constr    PLANT001      1
#  Id   number  starttime         time_unit   period  data_type    y_unit   npts
   0    0    20161108060000000    HOUR        8760         -1      M3/S     1
#  time             y
20161108060000000   51.43
```

Core equations in plant module in SHOP

Mathematical formulation

$$p_{i,t} = G \cdot \eta_i^{GEN}(p_{i,t}) \cdot \eta_i^{TURB}(h_{i,t}^{NET}, q_{i,t}) \cdot h_{i,t}^{NET} \cdot q_{i,t}$$

$$P_{i,t}^{MIN} \cdot \omega_{i,t} \leq p_{i,t} \leq P_{i,t}^{MAX} \cdot \omega_{i,t}$$

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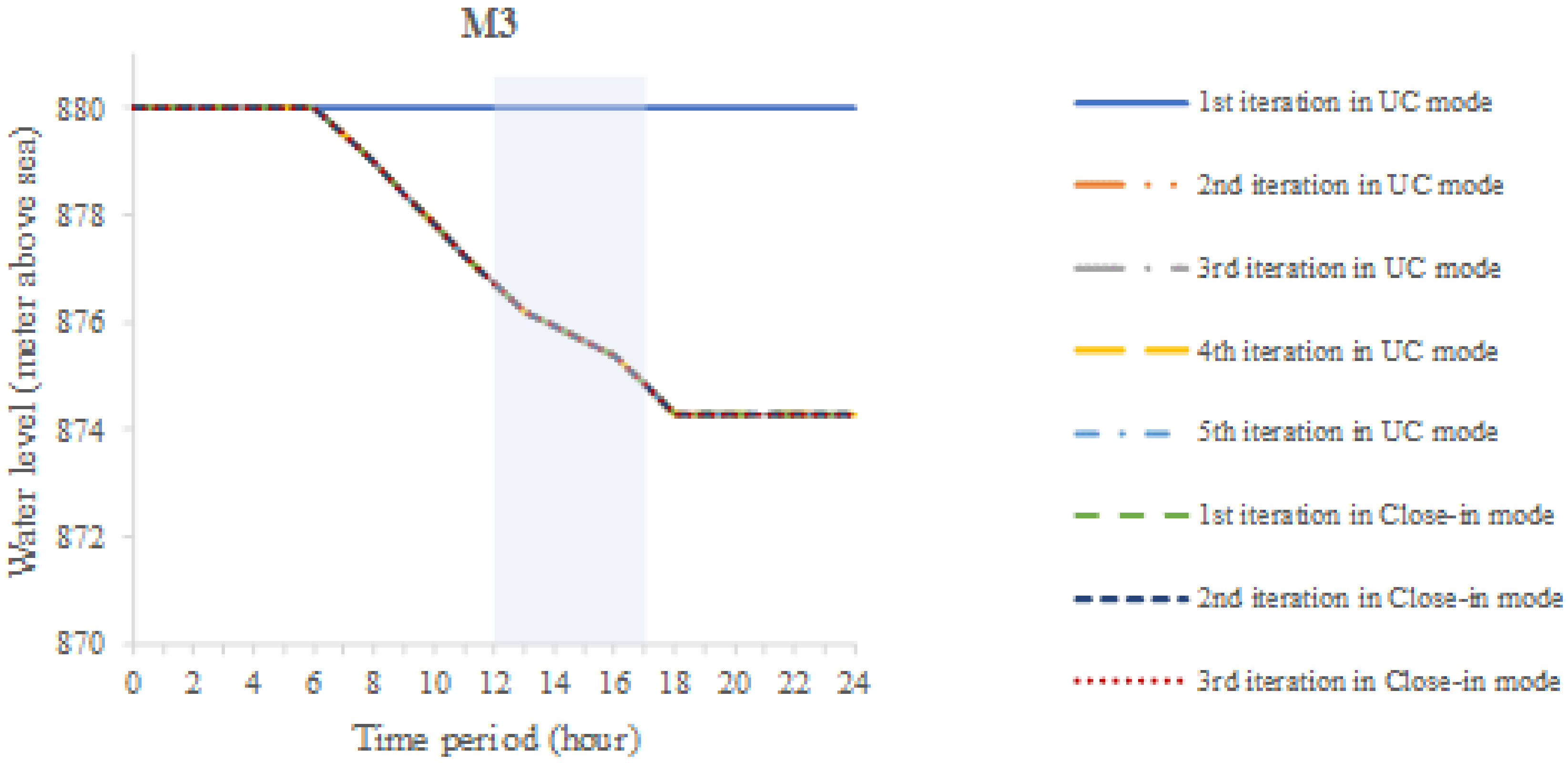
$$h_{i,t}^{NET} = H_t^{GROSS} - \alpha_n \cdot \left(q_{i,t} + \sum_{i' \in I_n \setminus \{i\}} q_{i',t} \right)^2$$

$$\sum_{i \in I} p_{i,t} = p_t^{SELL}$$

- SHOP is formulated as a **MILP** model
- How to convert the **nonlinear** & **nonconvex** hydropower production function into a **concave** piecewise **linear** unit PQ curve?
- How to take all the **limits** into account?

Determination of the unit PQ curve

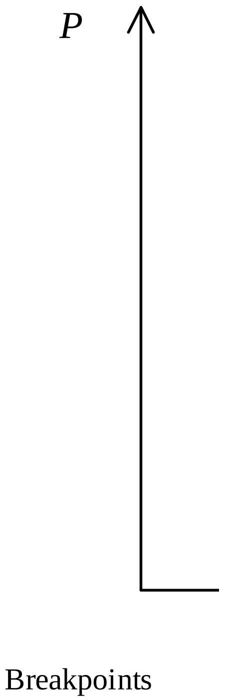
Step 1: *Update the Trajectory of the Reservoir and Calculate the Gross Head of the Plant*

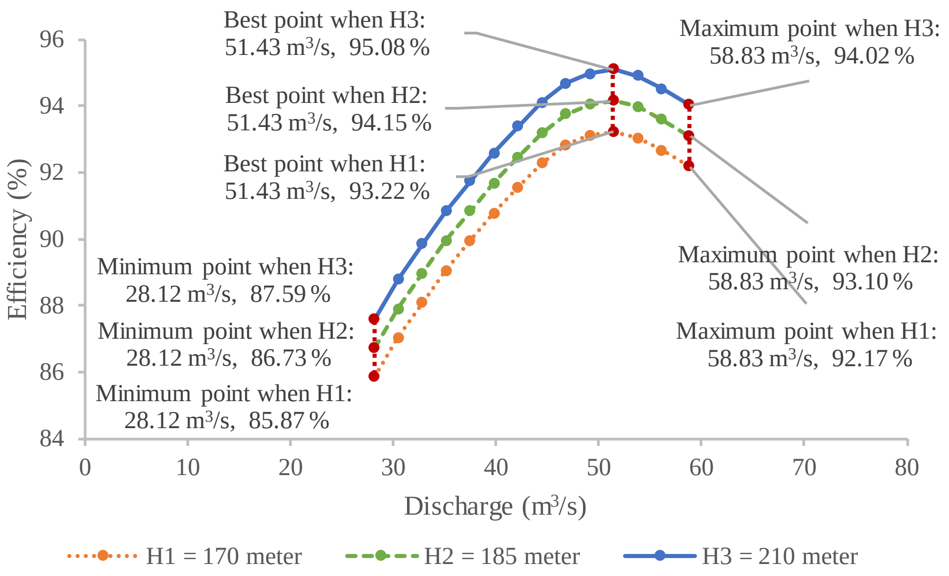


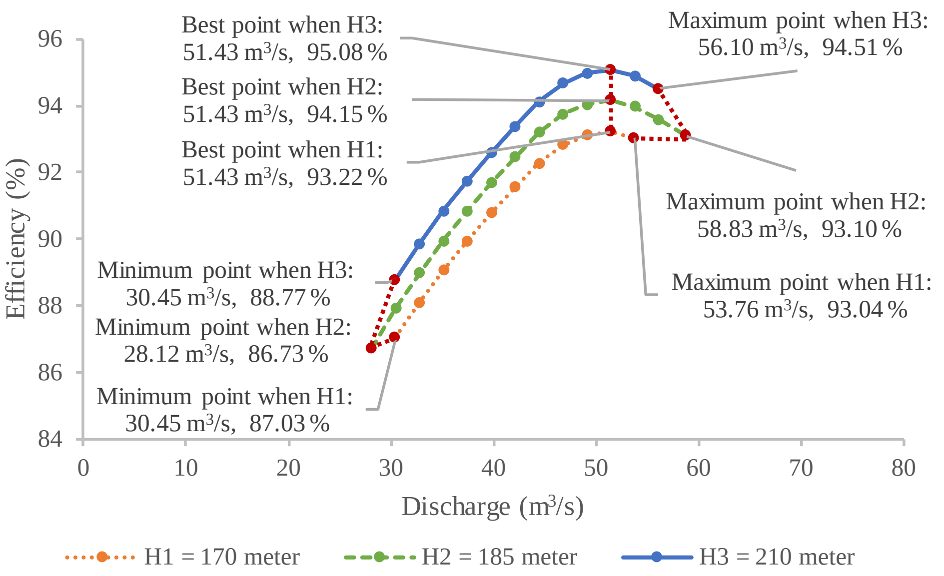
Determination of the unit PQ curve

__Step 1:__ Update the Trajectory of the Reservoir and Calculate the Gross Head of the Plant

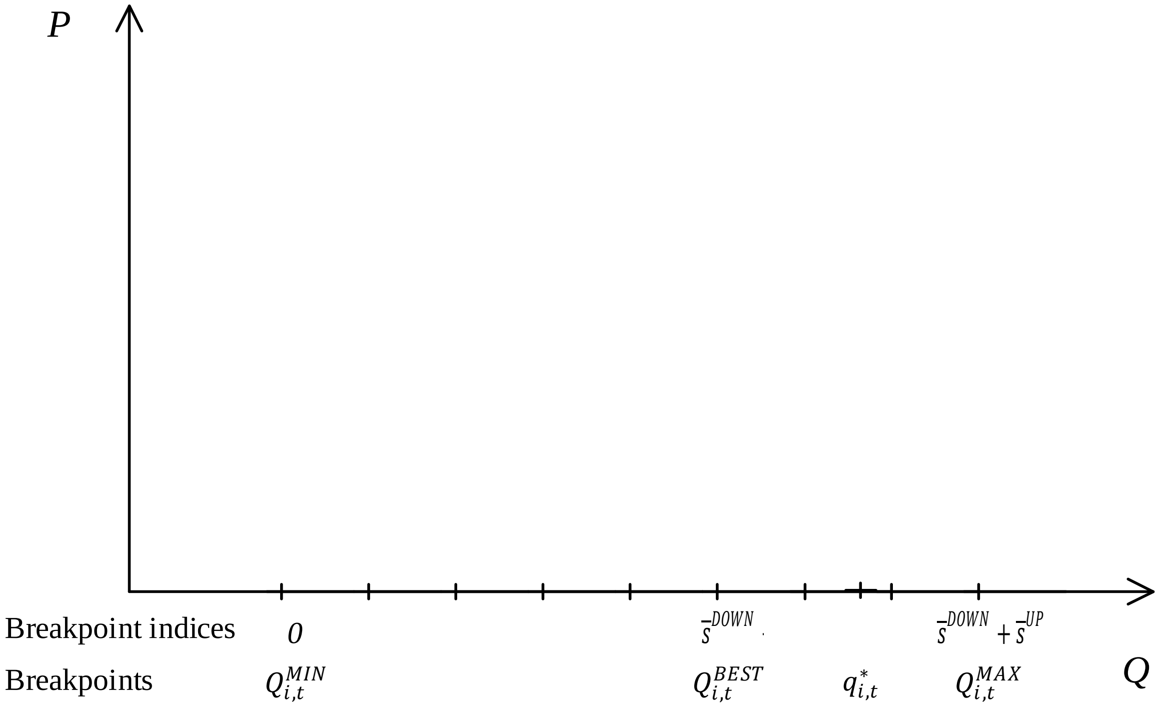
__Step 2__: Determinate the Head-dependent Minimum Water Discharge $Q_{i,t}^{MIN}$, Best Efficiency point $Q_{i,t}^{BEST}$ and Maximum Water Discharge $Q_{i,t}^{MAX}$ of the Unit




E1: Turbine efficiency curves with constant discharge limits


E2: Turbine efficiency curves with variable discharge limits

Determination of the unit PQ curve



***Step 1:** Update the Trajectory of the Reservoir and Calculate the Gross Head of the Plant*

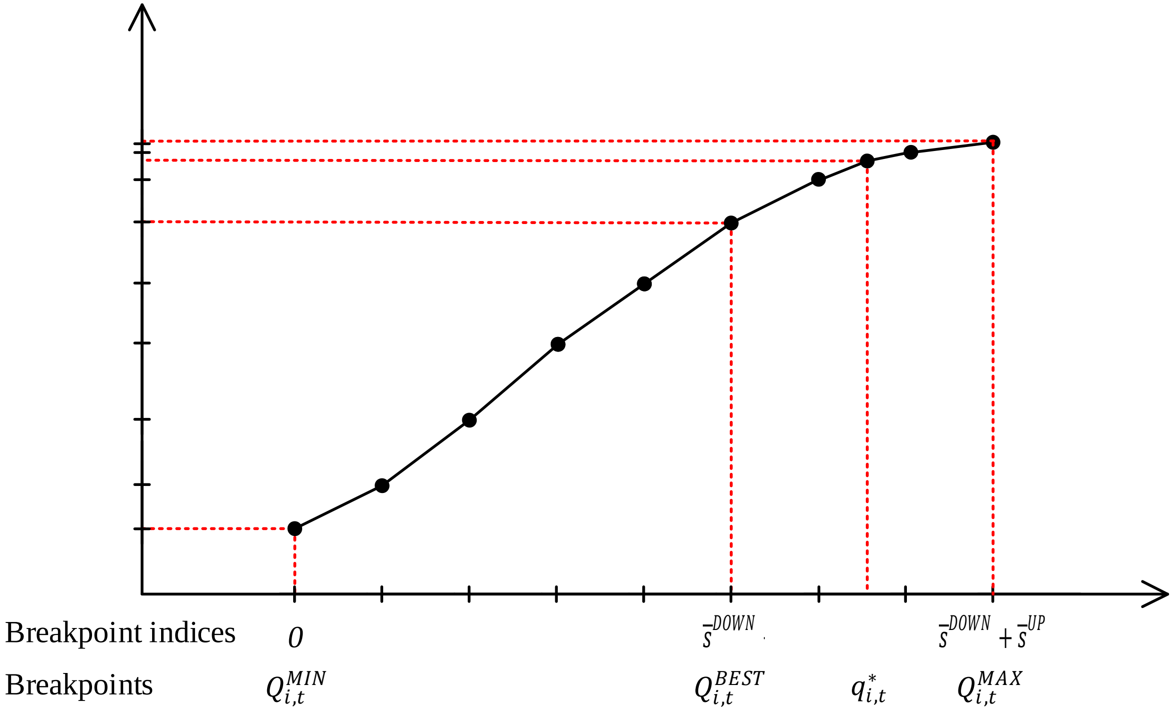
***Step 2**: Determinate the Head-dependent Minimum Water Discharge $Q_{i,t}^{MIN}$, Best Efficiency point $Q_{i,t}^{BEST}$ and Maximum Water Discharge $Q_{i,t}^{MAX}$ of the Unit*

***Step 3**: Equally Partition the Interval between the Minimum Water Discharge and the Best Efficiency Point into $\bar{s}^{DOWN}$ Segments.*

***Step 4**: Equally Partition the Interval between the Best Efficiency Point and the Maximum Water Discharge into $\bar{s}^{UP}$ Segments.*

***Step 5**: Add the Optimal Operating Point $q_{i,t}^{*}$ Resulting from the Previous Iteration as an extra breakpoint.*

Determination of the unit PQ curve



*Instead of predefined, **the breakpoints are computed in a dynamic sequence** with their corresponding net head*

Step 1: *Update the Trajectory of the Reservoir and Calculate the Gross Head of the Plant*

Step 2*: Determinate the Head-dependent Minimum Water Discharge $Q_{i,t}^{MIN}$, Best Efficiency point $Q_{i,t}^{BEST}$ and Maximum Water Discharge $Q_{i,t}^{MAX}$ of the Unit*

Step 3*: Equally Partition the Interval between the Minimum Water Discharge and the Best Efficiency Point into $\bar{s}^{DOWN}$ Segments.*

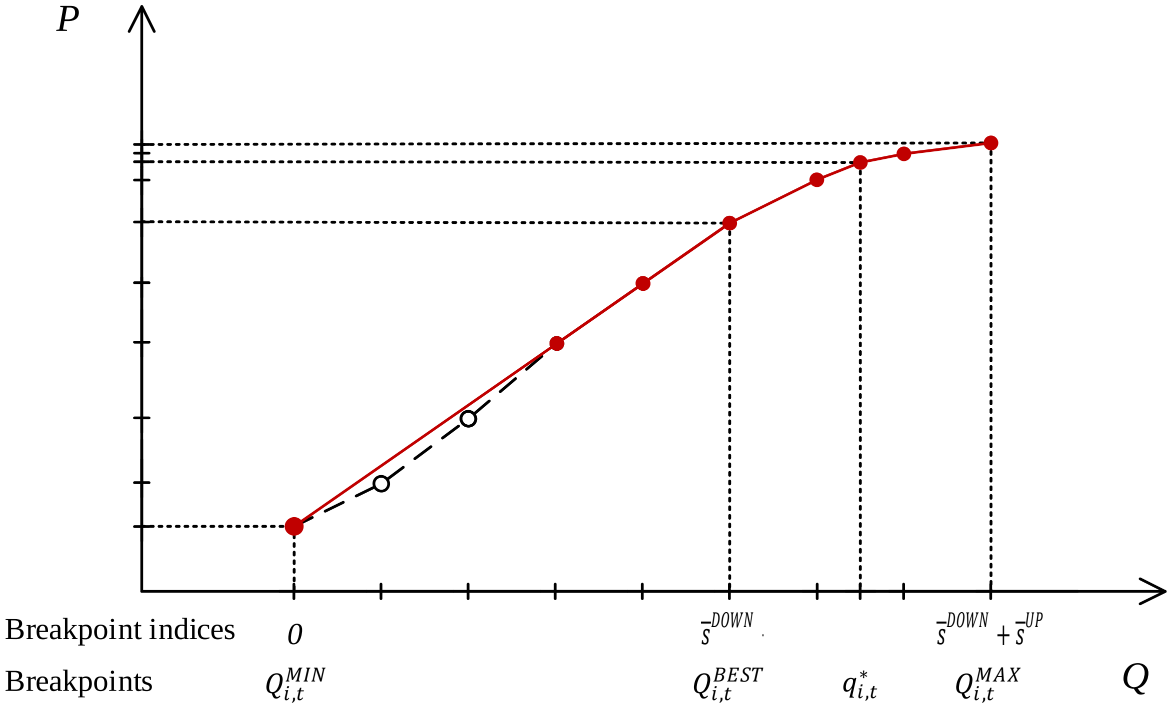
Step 4*: Equally Partition the Interval between the Best Efficiency Point and the Maximum Water Discharge into $\bar{s}^{UP}$ Segments.*

Step 5*: Add the Optimal Operating Point $q_{i,t}^{*}$ Resulting from the Previous Iteration as an extra breakpoint.*

Step 6*: Calculate the Corresponding Power Output of Each Breakpoint*

Determination of the unit PQ curve

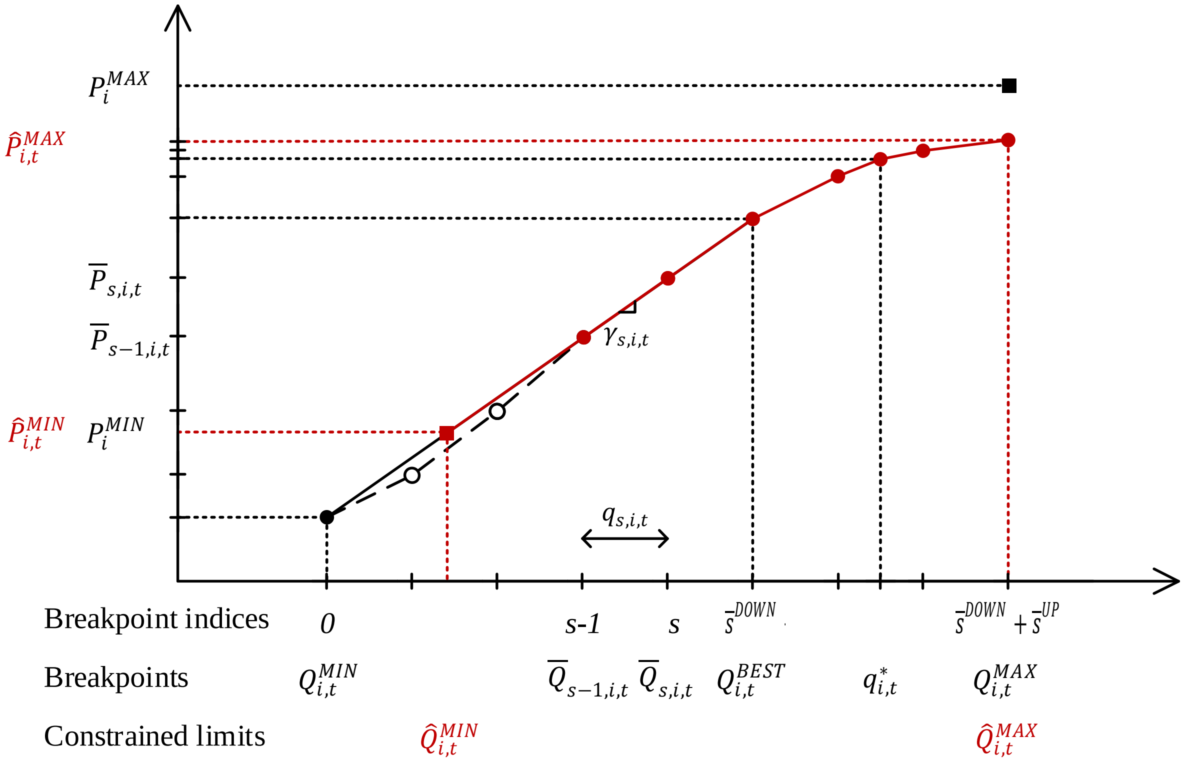
***Step 7**: Make Sure the Slope of Each Segment Non-increasing by Eliminating the Nonconcave Breakpoints*



Determination of the unit PQ curve

***Step 7**: Make Sure the Slope of Each Segment Non-increasing by Eliminating the Nonconcave Breakpoints*

***Step 8**: Define the Final Operating limits based on most restrictive rule*



$$p_{i,t} = \hat{P}_{i,t}^{MIN} \cdot \omega_{i,t} + \sum_{s=1,\dots,\bar{s}^{DOWN}+\bar{s}^{UP}} \gamma_{s,i,t} \cdot q_{s,i,t}$$

$$p_{i,t} \le \hat{P}_{i}^{MAX} \cdot \omega_{i,t}$$

$$q_{i,t} = \hat{Q}_{i,t}^{MIN} \cdot \omega_{i,t} + \sum_{s=1,\dots,\bar{s}^{DOWN}+\bar{s}^{UP}} q_{s,i,t}$$

$$0 \le q_{s,i,t} \le \bar{Q}_{s,i,t} - \bar{Q}_{s-1,i,t}$$

Core equations in plant module in SHOP

Mathematical formulation

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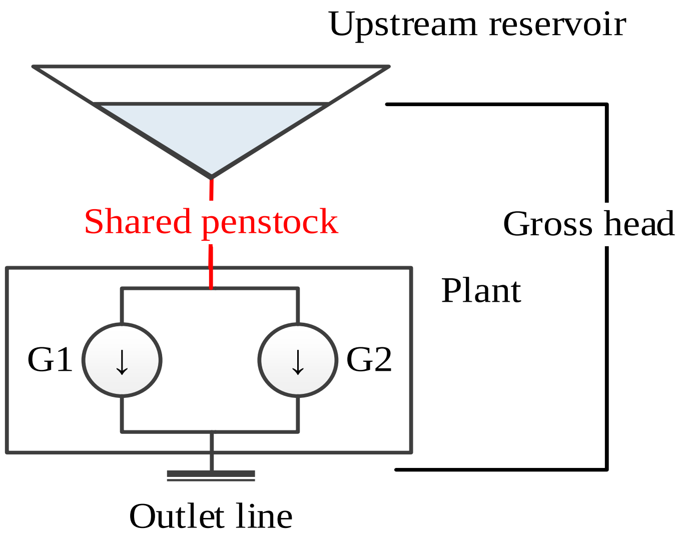
$$h_{i,t}^{NET} = H_t^{GROSS} - \alpha_n \cdot \left(q_{i,t} + \sum_{i' \in I_n \setminus \{i\}} q_{i',t} \right)^2$$

$$\sum_{i \in I} p_{i,t} = p_t^{SELL}$$

SHOP input



```
## PLANT001
PLANT attributes PLANT001
#Id;Water_course;Type;Bid_area;Prod_area;Num_units;Num_pumps;
 24800       0       0       1       1       2       0
#Num_main_seg;Num_penstock;Time_delay;Prod_factor;Outlet_line;
     1       1       0     0.000      672
#Main tunnell loss
 0.000
#penstock loss
 0.001
```

Core equations in plant module in SHOP

Mathematical formulation

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$$h_{i,t}^{NET} = H_t^{GROSS} - \alpha_n \cdot \left(q_{i,t} + \sum_{i' \in I_n \setminus \{i\}} q_{i',t} \right)^2$$

$$\sum_{i \in I} p_{i,t} = p_t^{SELL}$$

- The determination of the unit PQ curve **precedes** the optimization. The operating status of **other** units remains **unresolved**.
- How to account for **loss in shared** penstocks, involving not only the flow through the unit but also the flow of all the other units that are connected to the same penstock?

Methods for incorporating loss in shared penstock

$$h_{i,t}^{NET} = H_t^{GROSS} - \alpha_n \cdot \left(q_{i,t} + \sum_{i' \in I_n \setminus \{i\}} q_{i',t} \right)^2$$

Method 1: Set power_loss /pq /previous

- **Directly includes** penstock loss in the PQ curve of the unit.
- Uses the **optimal results obtained in the previous iteration**.

$$\sum_{i \in I} p_{i,t} - \sum_{n \in N} \Delta p_{n,t} = p_t^{SELL}$$

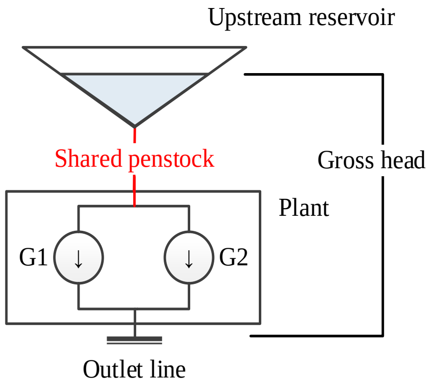
Method 2: Set power_loss /pq /proportional

- **Directly includes** penstock loss in the PQ curve of the unit.
- Assumes that all the units connected to the same penstock always operate **at the same fraction** of their allowable capacity range.

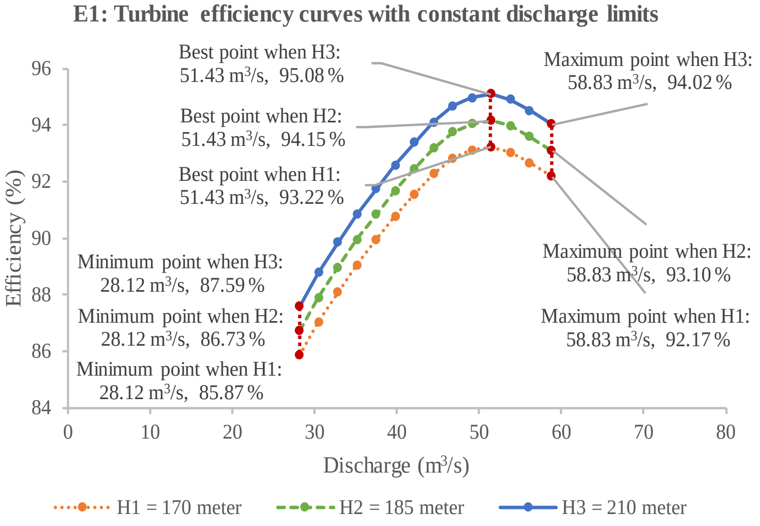
Method 3: Set power_loss /busbar

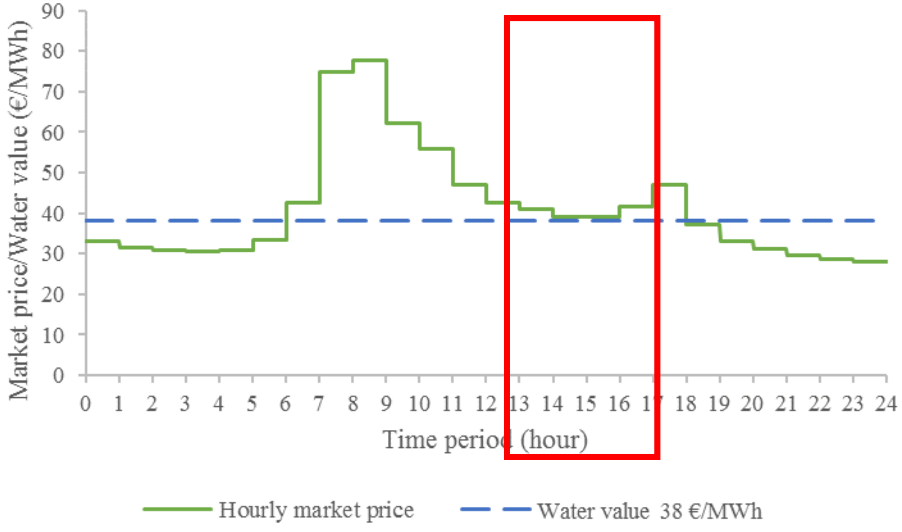
- First **excludes** the penstock loss in the PQ curve, causing over-estimated power generation for the given discharge.
- Then **subtracts** the sum of power loss for each unit, which is equal to the sum of power loss in each penstock, from the plant energy balance constraint, i.e. busbar.
- The sum of power loss in a shared penstock is a **cubic** function of the total flow through the penstock, which is approximated by **a convex piecewise linear function**.

Numerical results – Datasets



General Configurations	
Outlet line (Meter above sea)	672
Maximum unit production (MW)	60
Minimum unit production (MW)	120
Unit start-up cost (€)	0


E1: Turbine efficiency curves with constant discharge limits

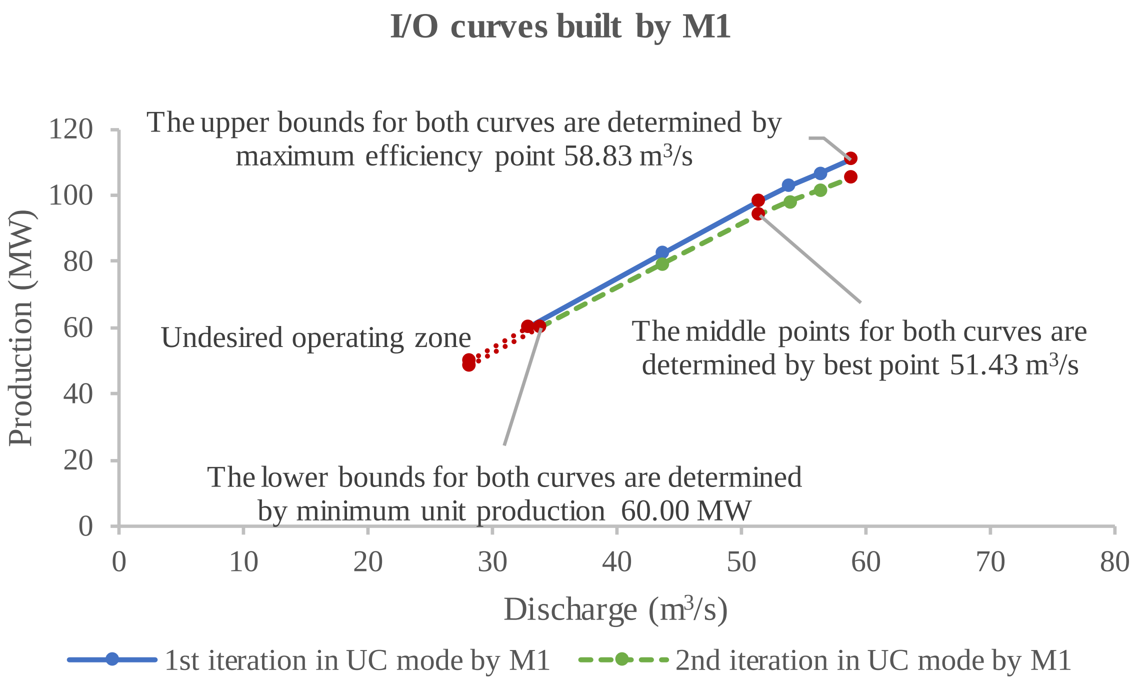


Numerical results – Comparison of Methods

Method 1: Set power_loss /pq /previous

Method 2: Set power_loss /pq /proportional

Method 3 (Default): Set power_loss /busbar



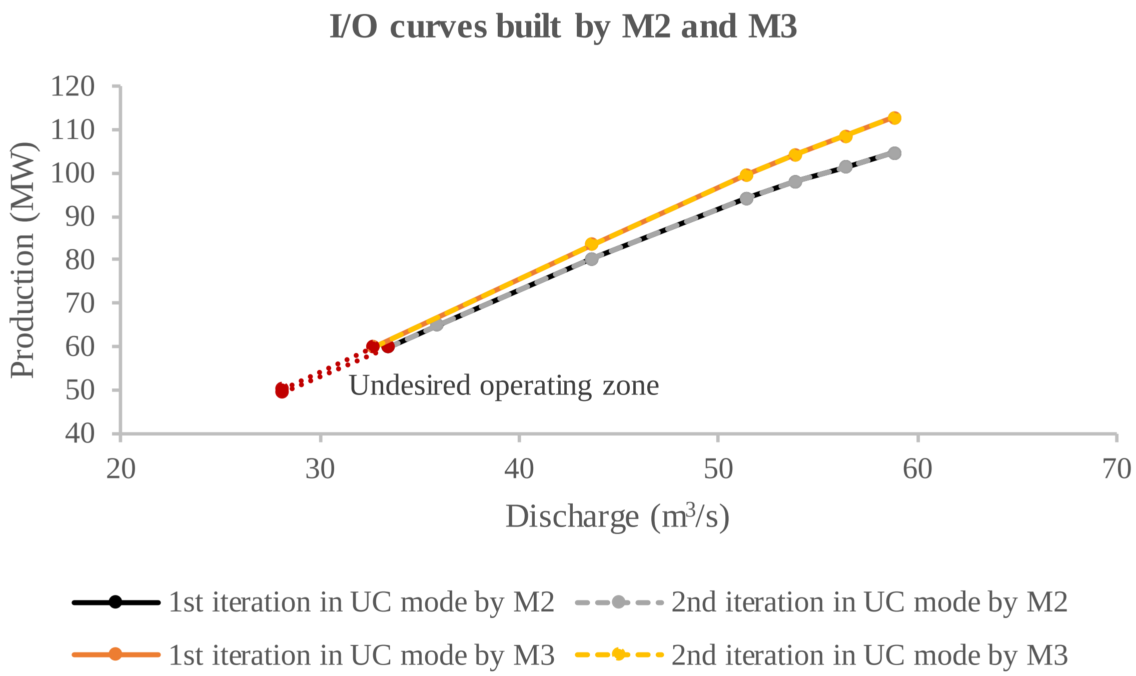
I/O curves built by M1

The upper bounds for both curves are determined by maximum efficiency point 58.83 m^3/s

Undesired operating zone

The middle points for both curves are determined by best point 51.43 m^3/s

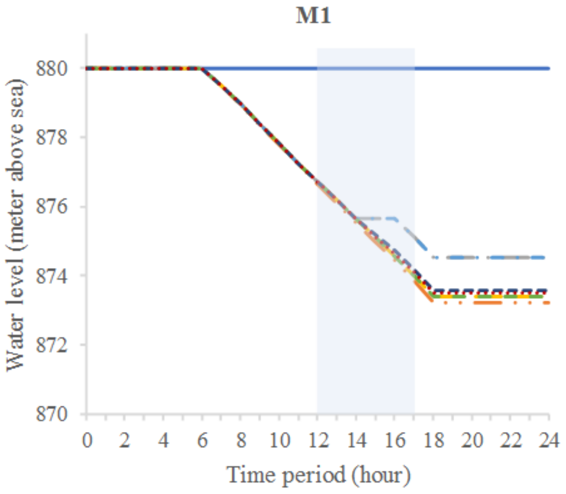
The lower bounds for both curves are determined by minimum unit production 60.00 MW

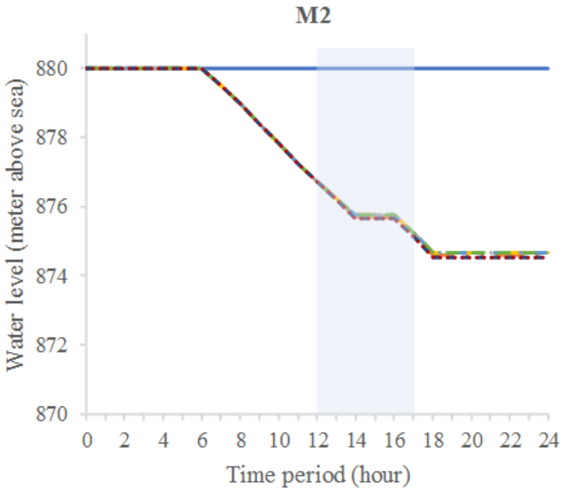


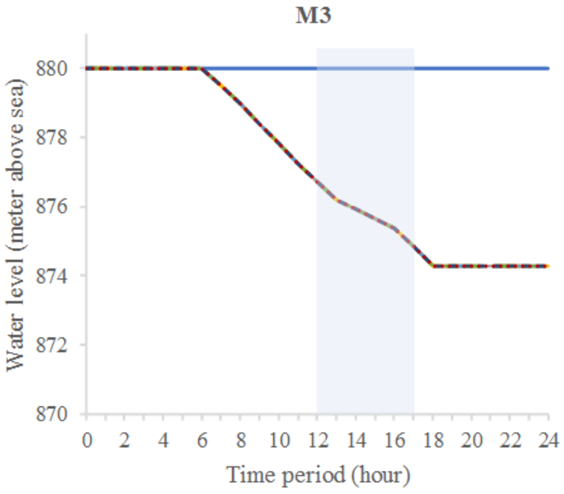
I/O curves built by M2 and M3

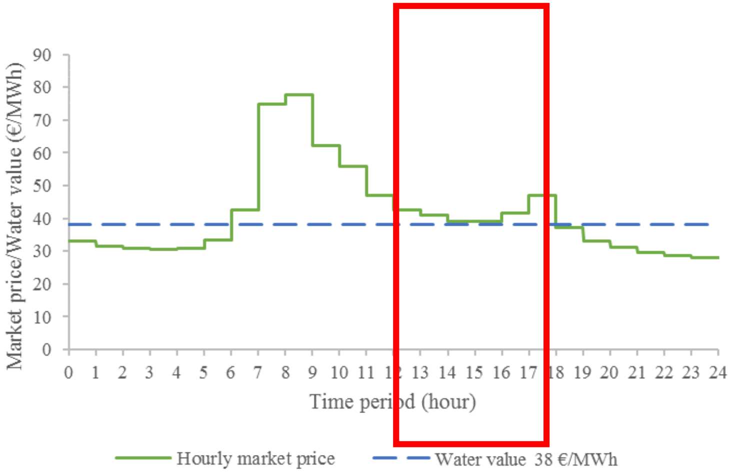
Undesired operating zone

Numerical results – Comparison of Methods









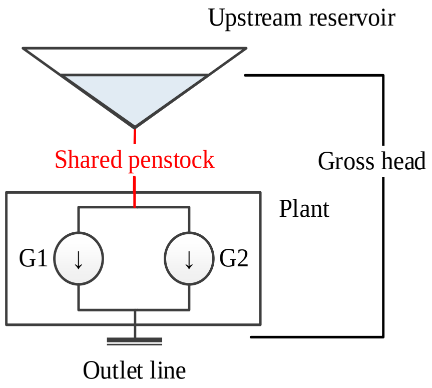
	M1			**M2**			**M3**		
Instance	Production Revenue	Reservoir Value	**Total Profit**	Production Revenue	Reservoir Value	**Total Profit**	Production Revenue	Reservoir Value	**Total Profit**
S1	117,588.81	147,118.76	**264,707.57**	105,467.63	159,807.10	**265,274.73**	109,365.24	156,070.49	**265,435.73**

M1 is flip-flop

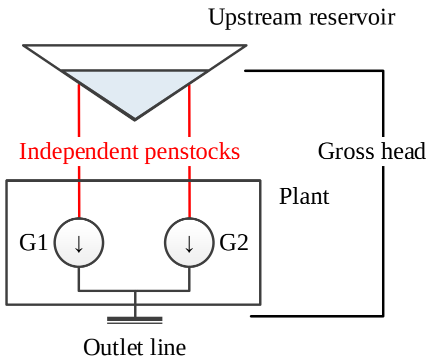
M3 is the best

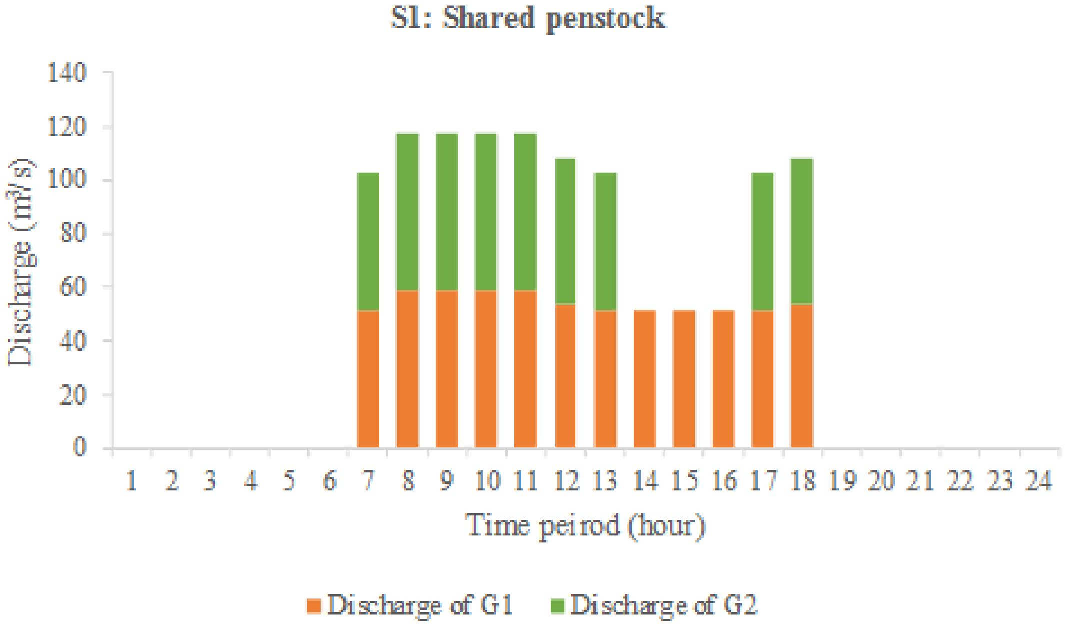
Numerical results – Comparison of Modeling Penstock

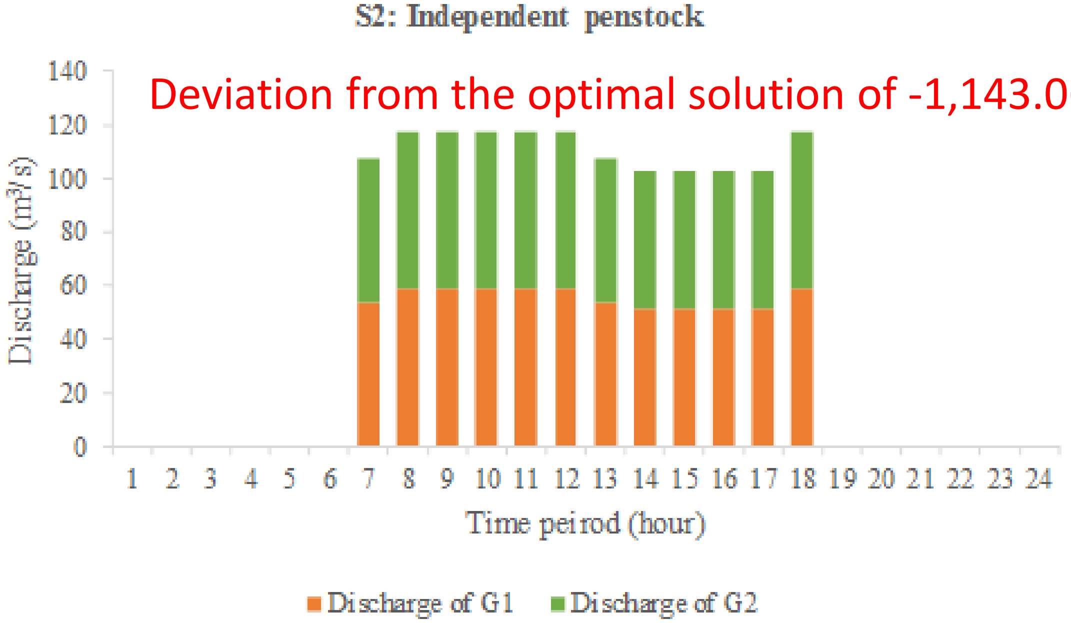
$$\Delta h = \alpha \cdot (q_1 + q_2)^2$$



$$\Delta h = \alpha \cdot ({q_1}^2 + {q_2}^2)$$




S1: Shared penstock


S2: Independent penstock

Deviation from the optimal solution of -1,143.06 €

Conclusion

Method 1: Set power_loss /pq /previous

- When the predicted market price for electricity is **close** to the water value at the end of the scheduling horizon, the power production is likely to **oscillate** between iterations

Method 2: Set power_loss /pq /proportional

- Can avoid the flip-flop problem but suggests the units to **operate in the same pattern**

Method 3: Set power_loss /busbar

- Gives **better** optimization result but potentially might **increase computational time**, since the unit penstock loss should be introduced to unit energy balance constraints to improve accuracy, especially when delivering reserves.

SINTEF

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