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DOCTORAL THESIS

-Summary-

Decision support system for dispatching one set of power generation units

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CONTENT OF THESIS

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1 INTRODUCTION

1.1 Structure of the doctoral thesis

The present work is structured in 7 chapters, a brief presentation of the content of the thesis being highlighted in **Figure 1.1**.

Figure 1.1. Structure of the doctoral thesis.

1.2 General considerations and the current state of research

The increase in installed capacity in wind power plants contributes to an increased uncertainty of the required balancing energy in the scheduling stage of the Transmission System Operator, in particular due to the intermittent character of the primary agent.

Most of the times it is necessary to supplement the ancillary services in periods when the share of wind energy production in the hourly production of the power system control area is high. Taking these aspects into account, it is very important to analyze the factors that influence the variable hourly production costs for power generation units in hydroelectric power plants. The operating mode of each hydropower unit affects the final energy production cost.

Optimization of the generation schedules of power generation units in power systems has been a topic of interest for several decades. There are many scientific works that propose optimization models, most of them using linear or mixed-integer programming [1, 2, 3, 4, 5]. During the research, relevant papers were analyzed and the aspects that can be applied in practice were identified.

Optimization of the generation schedules of power generation units can have various objectives. In this work, the objective is to reduce (minimize) the generation cost influenced by the operating mode of hydropower units.

The simulation of short-term generation scheduling of power generation units in hydropower plants is not a very researched topic in the literature, the practical details for implementing the application being very few. Articles dealing with the simulation methodology, without precise details are [6, 7, 8], the main purpose of these articles being the optimization models. More detailed models and closer to real production processes can be found in the researches [9, 10, 11, 12]. The paper [13] presents the simplified simulation methodology compared to the real process to achieve very low simulation times.

Failure modes and assessment of pronounced wear and tear associated with flexible operation of generation units in hydropower plants are presented in papers [14] and [15]. Knowing the costs of replacing or repairing the equipment, the costs associated with flexible operation can be calculated.

1.3 Research objectives

Using a bottom-up strategy, this paper analyzes the possibilities of developing an IT application that optimizes generation schedules, under the conditions of simplifying the mathematical model, so that the latter lead to minimal impact on the quality of the obtained solution.

The research carried out during the doctoral stage was focused on the following objectives:

- Identification, evaluation and analysis of production costs influenced by the operating decisions of the hydropower units;
- Proposing an algorithm for simulating generation schedules at the power generation unit level that corresponds to the real production process and captures its particularities;
- Proposing an algorithm to optimize generation schedules in the unit commitment stage, prior to the delivery day;
- Validation of the proposed module for simulation, by modeling the generation units and simulating the real generation schedules of a section of hydropower plants;
- Validation of the optimization-simulation application, called OptSimHydro, by comparing the real generation schedules with the optimized ones.

2 DESCRIPTION OF ANCILLARY SERVICES AND BALANCING MARKET. HISTORY AND TRENDS

2.1 General aspects regarding the energy market

The wholesale electricity market was introduced in Romania in 2005 and consists of several specific markets [16, 17, 18].

Among the specific markets that make up the wholesale energy market, the centralized market for ancillaey services trades power reserves, necessary for the safe operation of the national power system (NPS).

2.2 Ancillary services market and balancing market

In Romania, the ancillary services market is managed by Transelectrica. The reserved capacities on this market are:

- Secondary reserve/automatic frequency restoration reserve (aFRR);
- Fast tertiary reserve/ manual frequency restoration reserve (mFRR);
- Slow tertiary reserve /replacement reserve (RR);
- Voltage regulation.

From July 1, 2024, the new types of balancing capacity reserves are: aRRF, mRRF, RR. **Figure 2.1** shows the types of reserves and their validity.

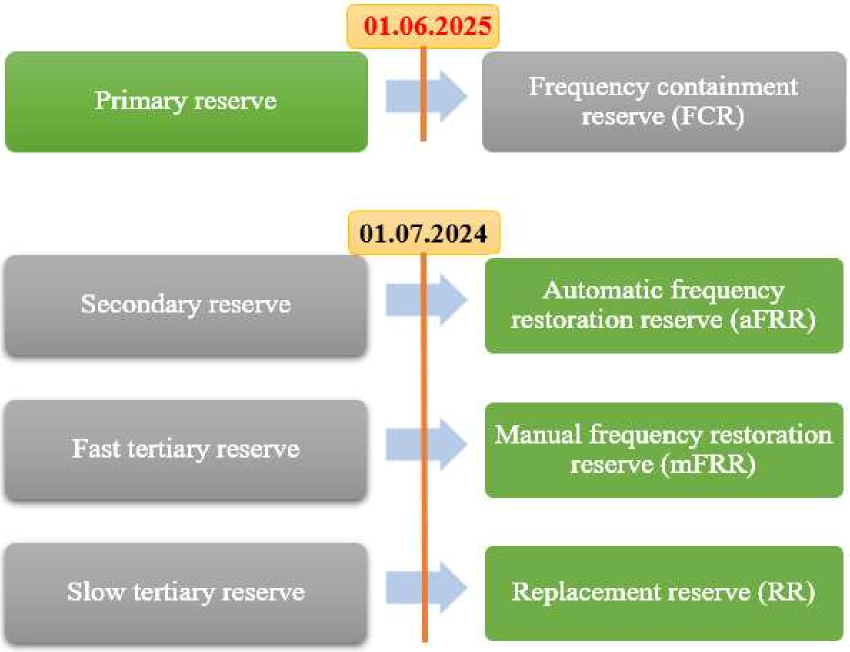


Figure 2.1. Types of balancing capacity reserves.

3 IDENTIFYING OPPORTUNITIES FOR IMPROVING THE DISPATCH ACTIVITY OF HYDROPOWER PLANTS

In order to improve the dispatching activity of generating units, it is necessary and appropriate to develop a high-performance IT system that simplifies the generation scheduling activity at the generating unit level and facilitates the estimation of water levels in reservoirs.

The technological advance in the last two decades has simplified the process of implementing numerical systems for remote command and control of power generation units.

Thus, it has become attractive for power producers to optimize operating expenses by remote management of production units with minimal intervention by operating personnel, or even operating these plants without permanent operating personnel.

Using a top-down approach, where balance at the production portfolio level is important, a system for the automatic generation control is proposed in **Figure 3.1**. Central power regulators of the producer, AGCs, are fully redundant systems, both hardware and software, and are functionally equivalent to the transmission system operator's central power-frequency regulator.

Thus, through the EMS-SCADA system and the DAMAS/DUROM web service (the IT system through which power reserves activations are carried out in the balancing market), the dispatcher can send instructions for loading or unloading of the power generation units, at aggregated level, to the power producer's AGC. Furthermore, the aggregated setpoint of active power is distributed to the units within each reserve providing group under its command, on the principle of proportionality with the scheduled active power or according to an merit order.

In addition to the control function of the power generation units, performed by the AGC (automatic generation control) modules, it is necessary to make generation schedules as precise as possible at the generation unit level.

An optimal solution that satisfies the required accuracy can only be obtained with the help of an optimization-simulation application of generation schedules.

Figure 3.1 shows the functional relationships between the different modules/activities in the generation scheduling activity, highlighting the proposed IT application.

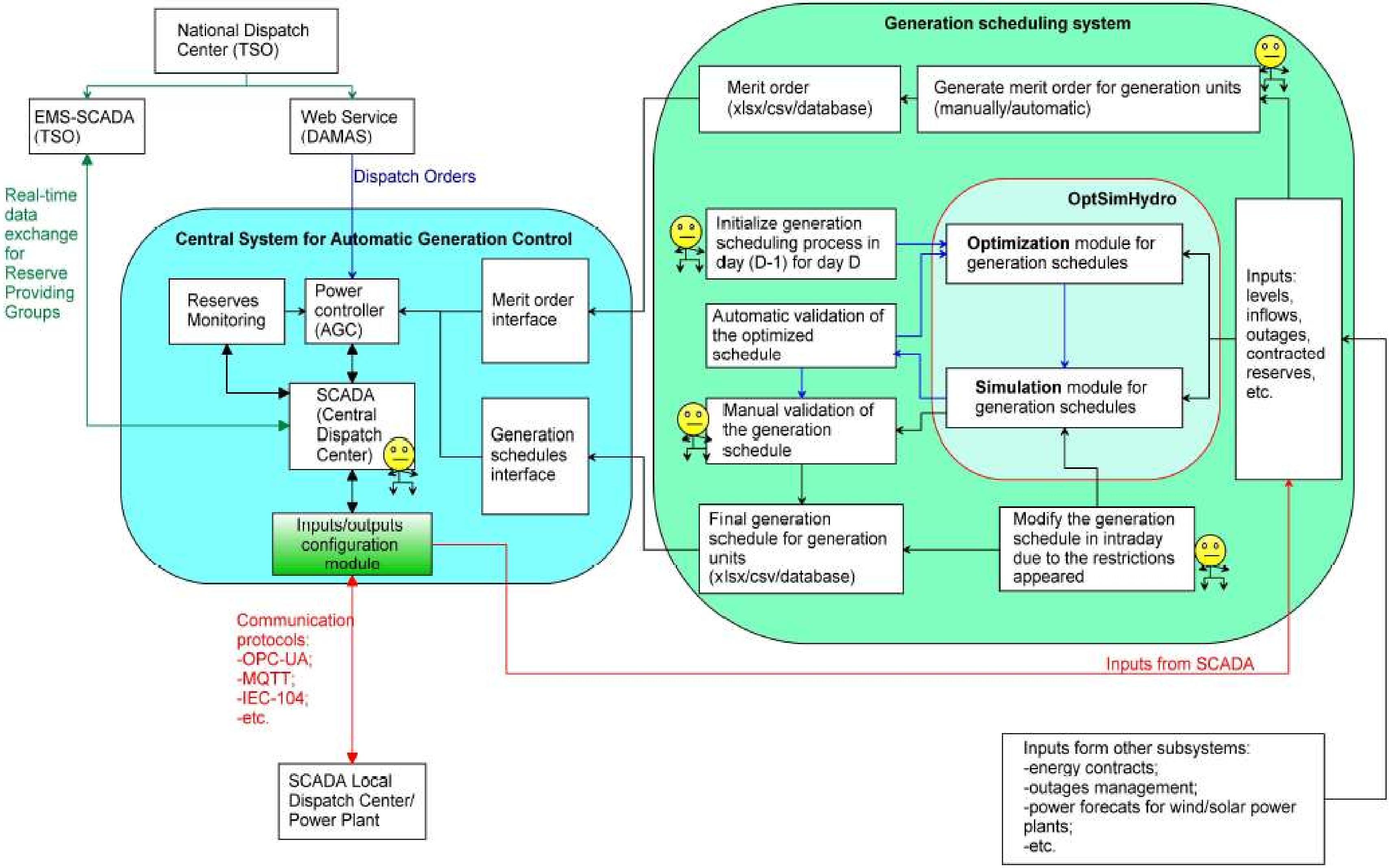


Figure 3.1. Diagram highlighting the central system for automatic generation control and the scheduling system of hydropower units.

4 ASSESSMENT OF FACTORS INFLUENCING THE GENERATION HYDROPOWER PLANTS

4.1 Identifying the factors that influence the variable operating costs of a hydropower unit

Determining the variation of generation costs according to the mode of operation of the hydropower units is a key factor in establishing the operation and bidding strategy, so that there is an optimum between profitability and the lowest possible wear and tear of the hydropower units.

Given the large variations in electricity geration over the course of a day, short-term generation scheduling is a key element in the operational management of hydropower plants. The flexibility offered by hydropower units comes with the disadvantage that efficiency and hourly operating costs vary considerably within the permitted operating range.

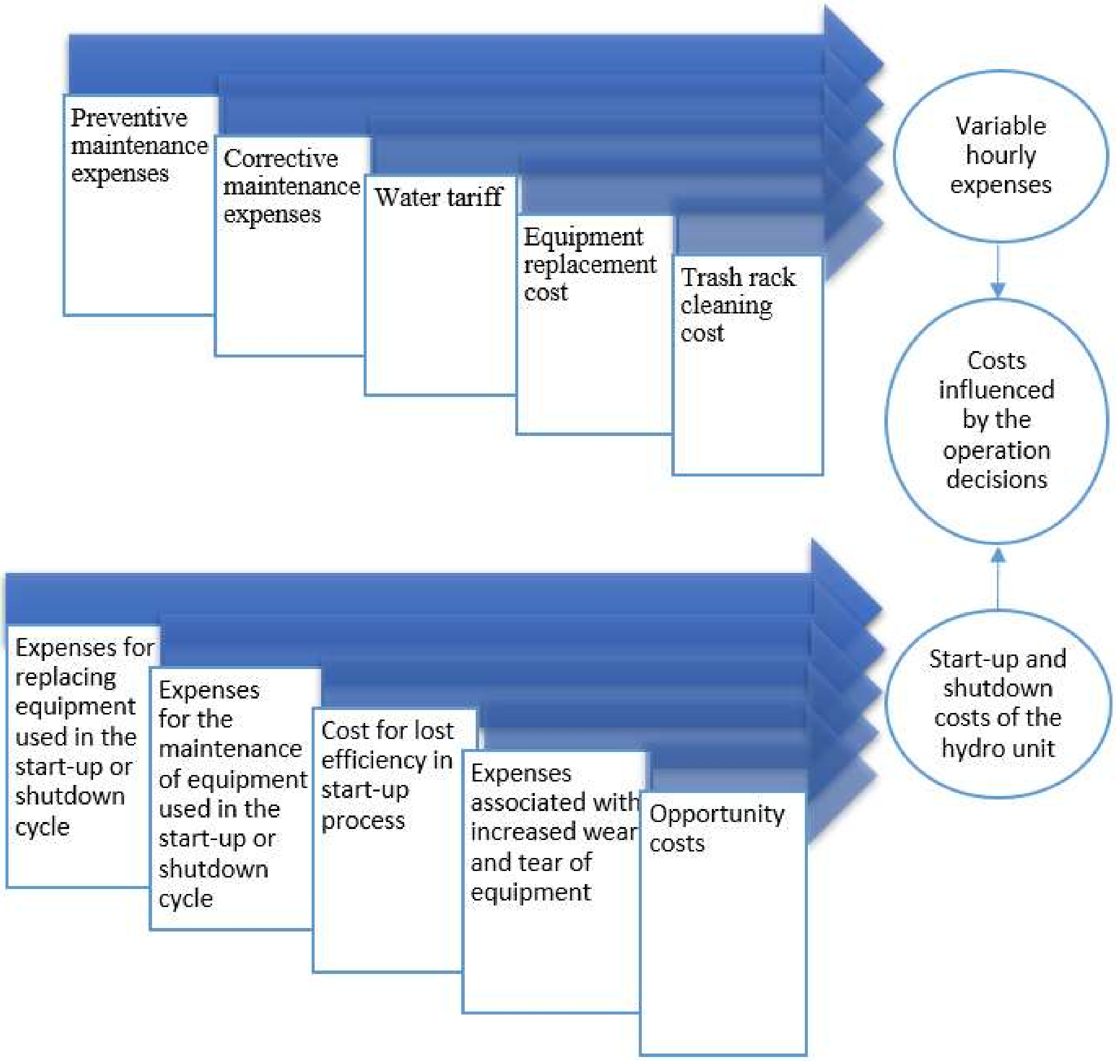


Figure 4.1. Diagram of expenses influenced by the operating decisions of the hydropower unit.

4.2 Considerations regarding the efficiency of hydropower units

Turbine efficiency is determined by field or model tests and depends on the type of turbine, the dicharge and the net head at which the turbine is operated. In the case of double-regulation turbines, the efficiency of the turbine is significantly influenced by the combinatorial cam implemented in the speed controller. **Figure 4.2** shows the efficiency of a Kaplan turbine [19].

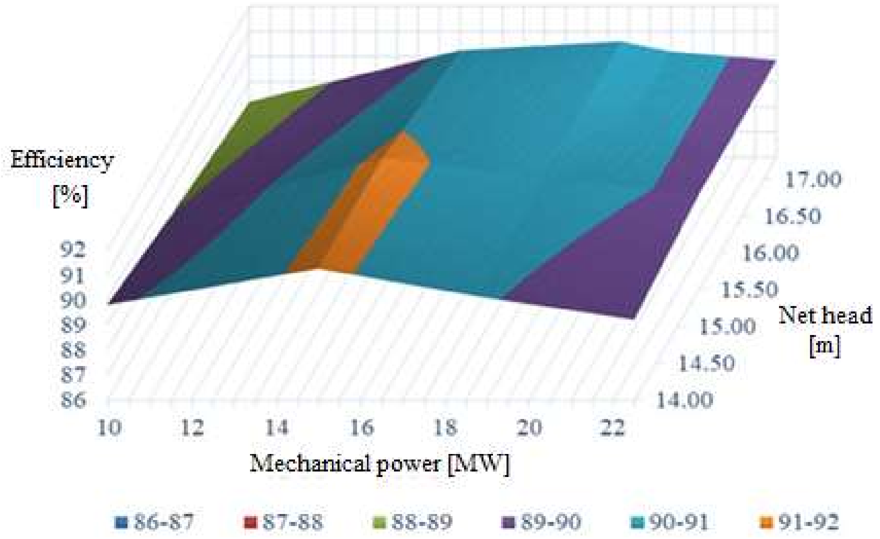


Figure 4.2. Efficiency of a Kaplan turbine [19].

Considering the turbine hill chart on optimal cam and the generator efficiency curve, the hydropower unit operation diagram will be obtained (**Figure 4.3**), which can be used to determine generation costs.

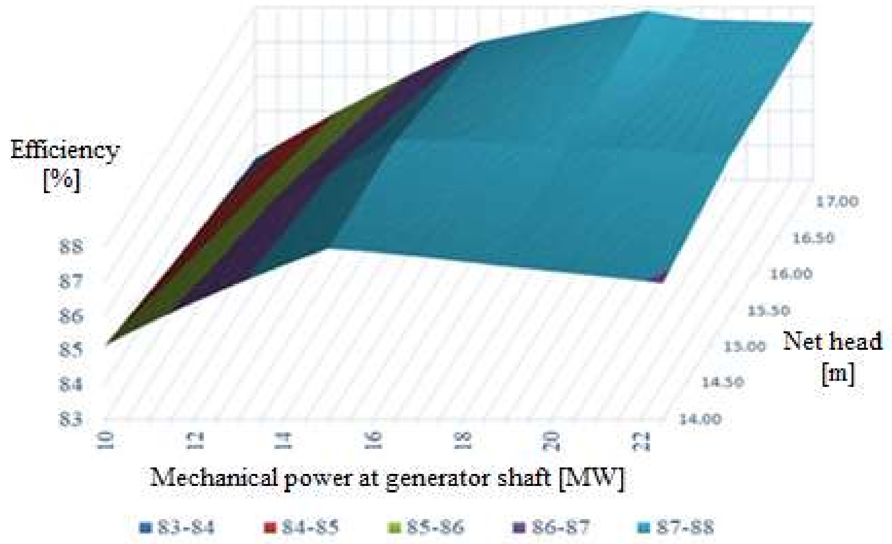


Figure 4.3. The total efficiency of a hydropower unit equipped with Kaplan turbine.

Analyzing **Figure 4.3** we can conclude that it is technically efficient to operate the hydropower unit at loads higher than 65% of the nominal power.

4.3 Variable hourly cost of the hydropower units

The variable hourly costs of a hydropower unit are:

- costs associated with the operating hours of the hydropower unit and include:
  - expenses for preventive maintenance;
  - expenses for corrective maintenance;
  - expenses for replacing equipments with a limited number of operating hours.
- expenses with discharged water;
- expenses for cleaning the trash racks of the water intake of the hydropower unit.

In order to evaluate the expenses associated with maintenance works, we analyzed the maintenance works from 2007-2017, carried out at 20 hydro units equipped with vertical axis Kaplan turbines and synchronous generator with apparent poles, with installed powers between 18.5MW and 35MW, and design net heads of the turbines between 13.25m and 24m.

From the complexity point, preventive maintenance works are divided into [19]:

- level 1 maintenance works (LN1);
- level 2 maintenance works (LN2);
- level 3 maintenance works (LN3);
- level 4 maintenance works (LN4).

In the analyzed period, 2007-2017, for hydropower units with Kaplan turbines and installed power greater than 15MW and an average annual number of operating hours greater than 2200 hours, the cycle of carrying out preventive maintenance works is the one shown in **Figure 4.4**.

Figure 4.4. Preventive maintenance work cycle for the analyzed hydropower units.

According to the analyzed data, the average expenses of the maintenance works were approximately 64 thousand Euros/hydropower unit and work for level 2 works, approximately 130 thousand Euros/hydropower unit and work for level 3 works and approximately 4.56 million Euros/hydropower unit and work for level 4 works.

For a complete cycle of preventive maintenance, result an average of 90 Euro/hour for a hydropower unit.

For the calculation of expenses related to corrective maintenance works, the period 2013-2017 was considered, mainly for reasons of calculation of the average annual hours of operation for the hydropower units under analysis. Thus, for an average of 4100 h/year and generating unit, resulted average expenses of 1.5 Euro/hour for a hydro unit, insignificant compared to the expenses of preventive maintenance. For the case analyzed, separate costs for replacing equipment with a limited number of operating hours cannot be associated because they are usually replaced as part of preventive maintenance works.

Discharged water costs are calculated depending on how the regulatory authority applies the turbine water tariff. Over the years, this rate has been applied as:

- tariff for 1000 m^3 of water;
- tariff applied to a volume of water equivalent to the nominal flow rate, regardless of the real discharge of turbine in the respective hour;
- tariff applied to the active energy produced at generator terminals.

Figure 4.5 shows the costs of discharged water for the generation of one MWh (in euros/MWh), depending on the hourly active energy produced at the generator terminals, considering the tariff for water equal to 0.244 euros/1000m^3.

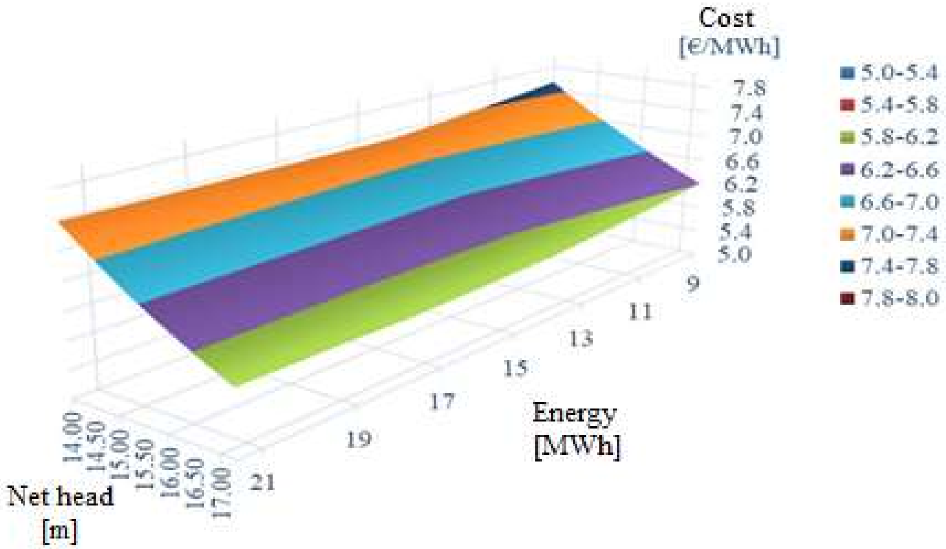


Figure 4.5. The variation of water costs for the production of one MWh of energy.

The costs for cleaning trash racks and evacuation of the resulting waste were on average about 220 Euro/cleaning and hydropower unit until 2017. Later, they increased to about 820 Euro/cleaning and hydropower unit. The values are inconsistent, require further analysis and were therefore not considered in the optimization algorithm.

4.4 Costs associated with start and stops of hydropower units

We can associate the processes of start and stops a hydropower unit with the increase in the degree of wear and tead of the hydropower unit and auxiliary installations [20, 21].

For the same set of hydropower units, we analyzed the corrective maintenance expenses associated with the start-up and shutdown processes for the period 2012-2017. We found that part of the used equipment is repaired or replaced as part of preventive maintenance works. For this reason, the resulting expenses for corrective maintenance are therefore minimal, with a value of approximately 0.3 Euro/start-up.

Based on the active power records, we determined the number of start-ups of the 20 hydropower units each year. Even if the number of units analyzed is large, we identify significant variations in the number of incidents associated with start-ups and shutdowns.

For the period 2015-2018, for the 20 hydro aggregates, 90 failed start-ups or shutdowns (with the unavailability of the unit) were identified, of which:

- 39 due to break of shear bolts, with a total of 51 bolts replaced and an average of 12 bolts/year;
- 51 from other causes, such as: automation sequence failure, generator circuit breaker mechanism failure, synchronization relay fault, Buchholz relay trip, etc

The average number of failed starts/stops is 22.5 per year, of which 9.75/year are due to shear bolts. The average time to replace a bolt is 45 minutes, resulting in an average annual downtime of 21.93 minutes/year and unit. For the other failed starts, we consider an average downtime of 90 minutes for the maintenance team to travel and carry out repairs, resulting in an average annual downtime of 57.37 minutes/year and unit.

Based on the average annual downtime associated with starts and stops, equal to 79.3 minutes per year and hydro aggregate, opportunity costs can be calculated.

The costs associated with reduced efficiency of hydropower unit in the start/stop cycle can be calculated with reference to the methodology described in [22].

Representative time intervals for the start-up process of a hydropower unit:

- speed increase time from 0% to 100%: 40s;
- time for synchronization: 65s;
- ramping-up time at 8MW: 105s.

It is known that the discharge flow at idle for the analyzed hydro unit is approximately 20m^3/s. The average turbine flow rate in the speed increase process (0-100%) is equal to 23.8m^3/s.

Approximating the turbine flow curve during the ramping-up period, a water volume of 4980m^3 was used in the loading process (105s). The energy produced in this interval was 0.136MWh, being obtained based on the active power measured in the start-up process.

In order to determine the volume of water turbined in steady state, the operation of the hydropower unit is considered optimal with a global efficiency of 87% at the net head of 16m, the resulting the discharged volume of 3589m^3.

The volume of water used ineffectively in the ramping-up interval is determined as the difference between the volume of water used in the ramping-up process and the previously determined water volume.

The total volume of water lost in the starting cycle is determined as the sum of the volumes of water used in the processes of speed increase, synchronization and part of the volume used in the ramping-up process.

The equivalent active energy lost in the start-up cycle is 0.135 MWh. At an average energy price of 80 Euro/MWh, results a loss of 10.8 Euro/start-up, comparable to the one in the paper [22].

5 PROPOSAL OF A DECISION SUPPORT SYSTEM TO FACILITATE THE AUTOMATIC GENERATION CONTROL – OptSimHydro

5.1 Notions about hydraulic head losses in hydrotechnical circuits

When a fluid flows through a circuit, with or without a free level, energy losses occur. They are divided into two categories [23, 24]:

- uniformly distributed hydraulic head losses;
- local hydraulic head losses.

5.1.1 Hydraulic head losses for pressured flow

In the case of pipes of circular section, linear hydraulic head losses can be determined based on the Darcy-Weisbach equation:

$$h_l = \lambda \cdot \frac{L}{D} \cdot \frac{w^2}{2g} \tag{5.1}$$

The Darcy coefficient is determined from the diagram in **Figure 5.1** and depends on the Reynolds number (Re) and the relative roughness of the pipe.

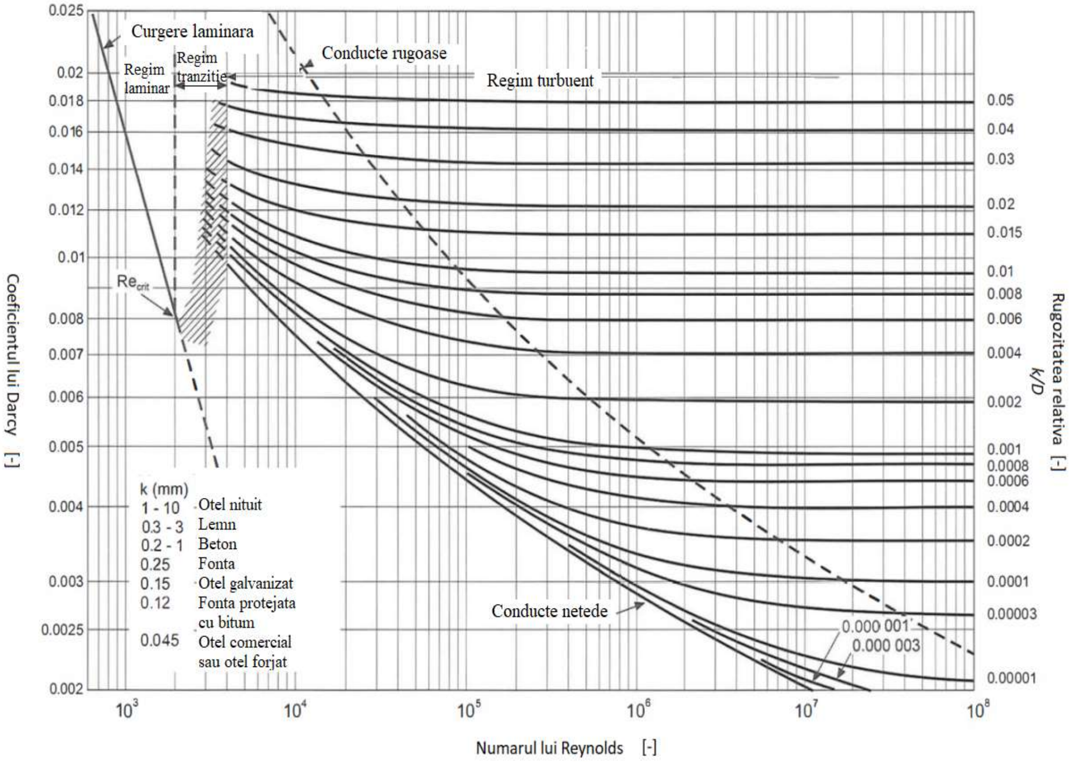


Figure 5.1. Moody's diagram for determining Darcy's coefficient [25].

In the absence of measurments, for pipes with a circular section, local pressure loss coefficients determined according to the work [23] can be used.

5.1.2 Hydraulic head losses for free surface flow

Like hydraulic losses in pressurized flow, for steady and non-uniform free surface flow can be applied Chezy's equation [26]:

$$w = C \cdot \sqrt{R_h \cdot s_f} \tag{5.2}$$

In the case of steady and uniform flow, the geometric slope of the channel (s_0) is equal to the energy slope (s_f) and the geometric slope can be used in the previous relation.

Chezy's coefficient has the meaning of Darcy's coefficient from pressured flow.

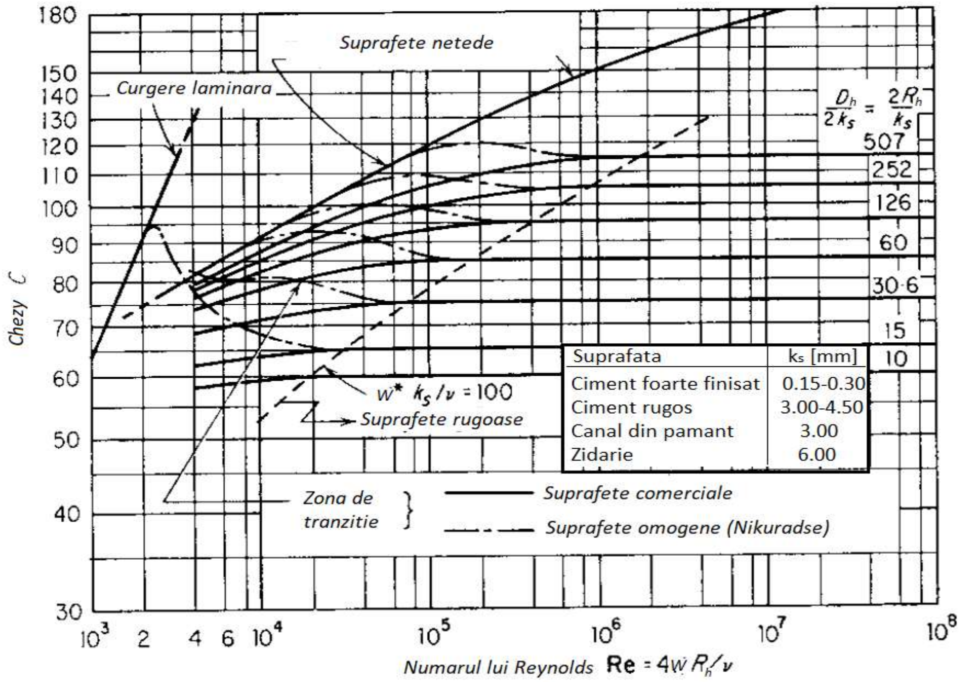
A modified Moody diagram can be used to determine hydraulic losses in channels according to [25, 26, 27].

The equivalent absolute roughnesses in **Figure 5.2** are from [28]. These can also be found in the paper [27].

For the rough zone, Manning's relation is used to determine Chezy's coefficient [23]:

$$C = \frac{1}{n} R_h^{1/6} \tag{5.3}$$

In the work [26], the ways to evaluate Manning's coefficient are presented, considering that this evaluation depends on the experience of the one who performs the calculations. The values of Manning's coefficient (n) can be found in table 4-7 of the work [29].



Suprafata	k_s [mm]
Ciment foarte finisat	0.15-0.30
Ciment rugos	3.00-4.50
Canal din pamant	3.00
Zidarie	6.00

Figure 5.2. Modified Moody diagram for free surface flow [27].

For the situation where the surface roughness of the section is not homogeneous (the case of natural beds), it is necessary to calculate an equivalent roughness coefficient. Also, the calculated equivalent coefficient will be used for a flow difference transited in the section. The methodology is presented in [29].

5.2 Development of a simulator for the generation schedules of hydropower units

A first step towards making generation schedules more efficient is the development of a schedules simulator.

The level error is used as an evaluation of the performance of the algorithm, mainly due to the fact that in the current operation of hydropower plants the aim is to avoid water spillage, which start at a certain level defined in the approved operating regulations.

The important steps of a simulation are shown in **Figura 5.3**, where t represents the simulation timestep number. Stages 1 and 2 are run only once, at the beginning of the simulation, for all hydropower plants. For a simulation step $t \geq 0$, steps 3-6 will be applied in turn to each hydropower plant.

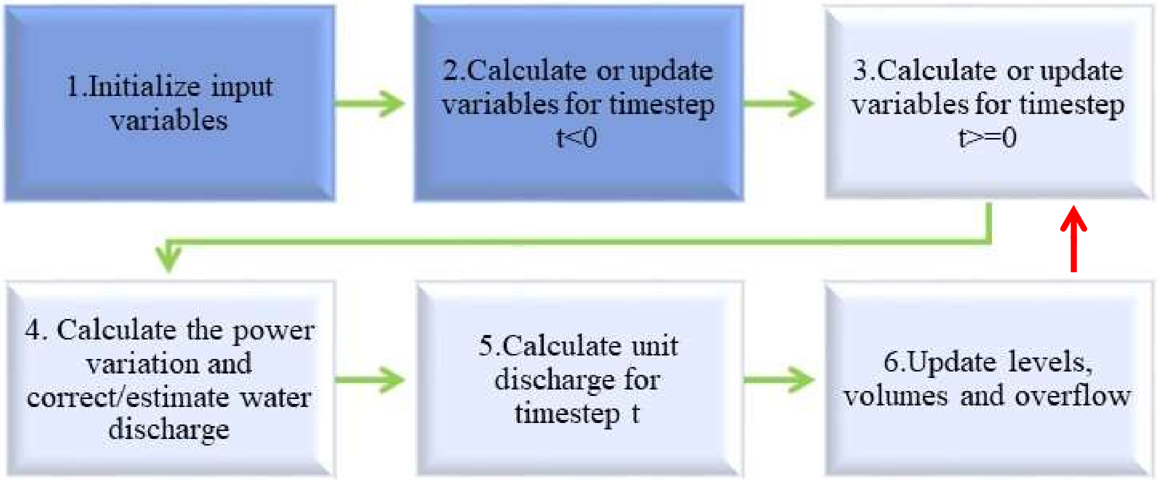


Figura 5.3. Etapele importante ale simulării.

5.2.1 Stage 1. Initialize input variables

In the first stage, the input variables are initialized (**Figure 5.4**).

a) • Estimate natural inflow for simulated period.

b) • Initialize reservoir levels for *t=0*.

c) • Initialize power units water discharge, natural inflow, reservoir levels and spillway gates openings for *t=0* that affects the simulation.

d) • Initialize power schedule for each unit.

e) • Initialize controlled water release through spillways (as flow or gate opening).

f) • Initialize water discharge for utility.

g) • Initialize unavailable or under maintenance spillway gates.

h) • Initialize trash rack clogging.

Figure 5.4. Operations in stage 1.

The moment t=0 of the simulation represents the last moment of time for which all the input required in the process are known. In this stage, the order in which the operations are performed is not important.

To simplify the input data entry process and to reduce the risk of human error, the algorithm uses the levels at time t=0 as a reference for the calculation of the turbine flows prior to time t=0.

5.2.2 Stage 2. Calculate or update variables for timestep t<0

In the second stage (**Figure 5.5**) the variables required in the simulation are determined or updated.

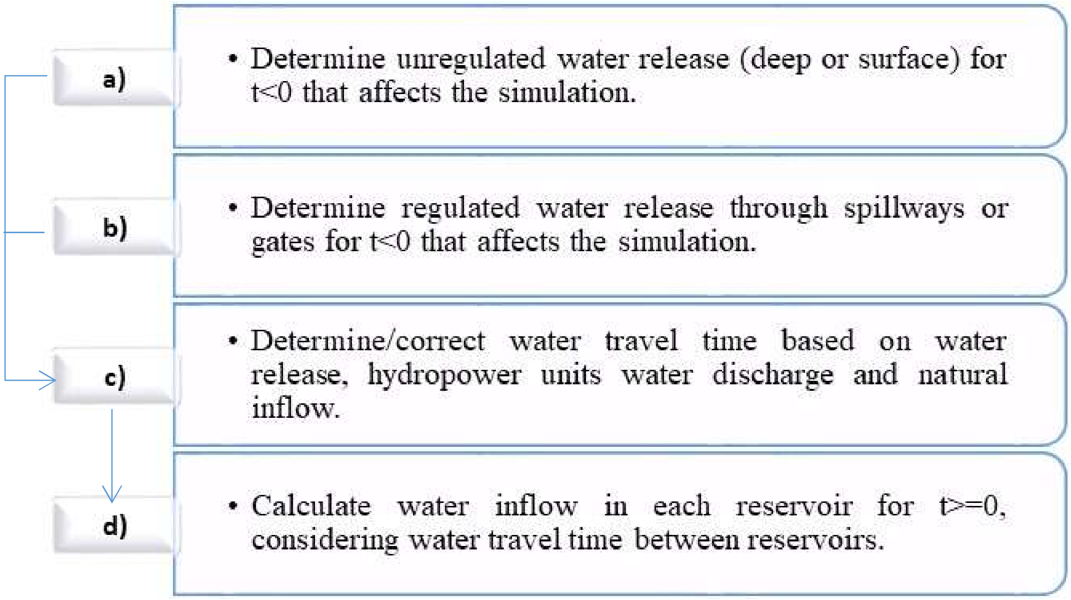


Figure 5.5. Operations in stage 2.

5.2.3 Stage 3. Calculate or update variables for timestep t≥0

In the third stage (**Figure 5.6**) the variables that influence the turbined flow calculation at moments t>=0 are updated or determined.

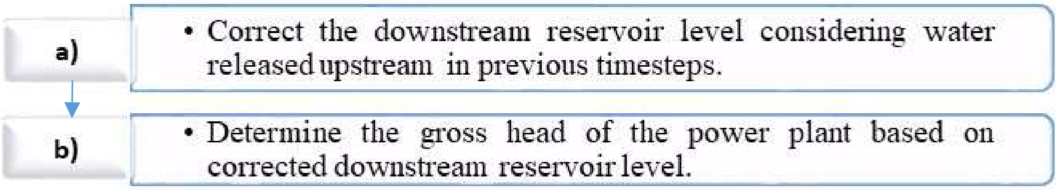


Figure 5.6. Operations in stage 3.

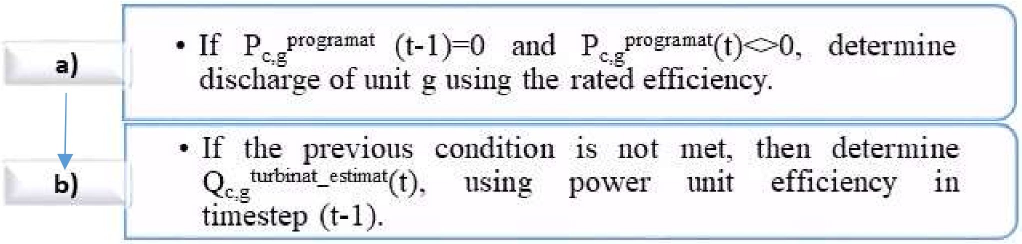
The correction of the level of the reservoir downstream of a power plant, from point 3.a, is done to include in the calculation the encroachement in the case of large spilled flows. The downstream level is considered at the reference point.

For example, in the case of a tailrace separated from the high water channel, the downstream reference level will be considered at the end of the tailrace. In this way, the hydraulic head losses in the tailrace can be estimated more precisely.

The gross head determined at point 3.b is used in step 4.b

5.2.4 Stage 4. Calculate the power variation and correct or estimate water discharge

In the fourth stage (**Figure 5.7**) the active power variation is checked and the turbine flow is estimated..


a)
- If $P_{c,g}^{programat}(t-1)=0$ and $P_{c,g}^{programat}(t)<>0$, determine discharge of unit g using the rated efficiency.

b)
- If the previous condition is not met, then determine $Q_{c,g}^{turbinat\_estimat}(t)$, using power unit efficiency in timestep (t-1).

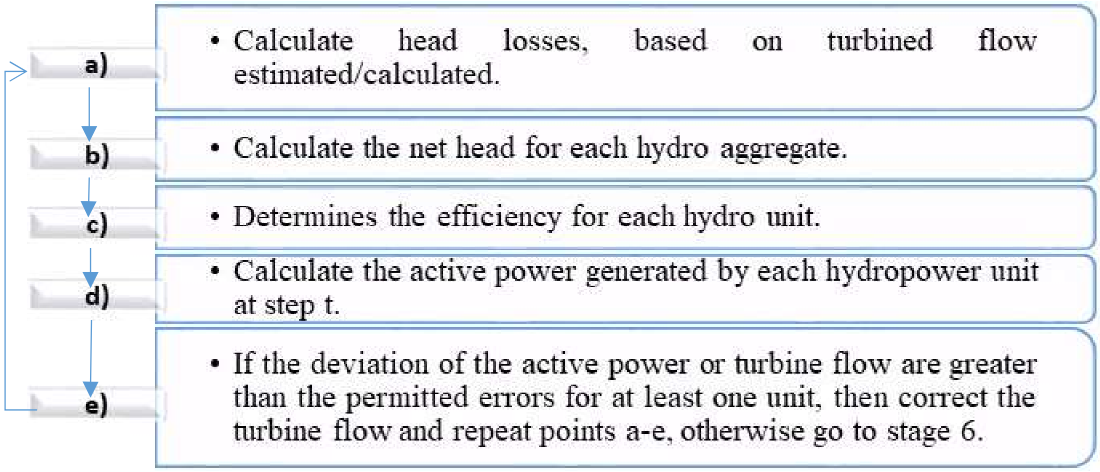
Figure 5.7. Operations in stage 4.

The estimation in stage 4 is carried out for each group of hydropower units that have at least one primary hydraulic circuit common between the reference sections. Thus, if the programmed power for a hydro unit within the group changes compared to the previous step, then the turbine flow estimation must be determined for the entire group of generating units.

The reference sections for common circuits can be: the water intake at the entrance to a channel or pipe, the outlet of a tailrace.

5.2.5 Stage 5. Calculate unit discharge for timestep t

In the fifth stage (**Figure 5.8**), the iterative calculation of the turbine flow is performed, starting from the flow estimated in the fourth stage.


a)
- Calculate head losses, based on turbined flow estimated/calculated.

b)
- Calculate the net head for each hydro aggregate.

c)
- Determines the efficiency for each hydro unit.

d)
- Calculate the active power generated by each hydropower unit at step t.

e)
- If the deviation of the active power or turbine flow are greater than the permitted errors for at least one unit, then correct the turbine flow and repeat points a-e, otherwise go to stage 6.

Figure 5.8. Operations in stage 5.

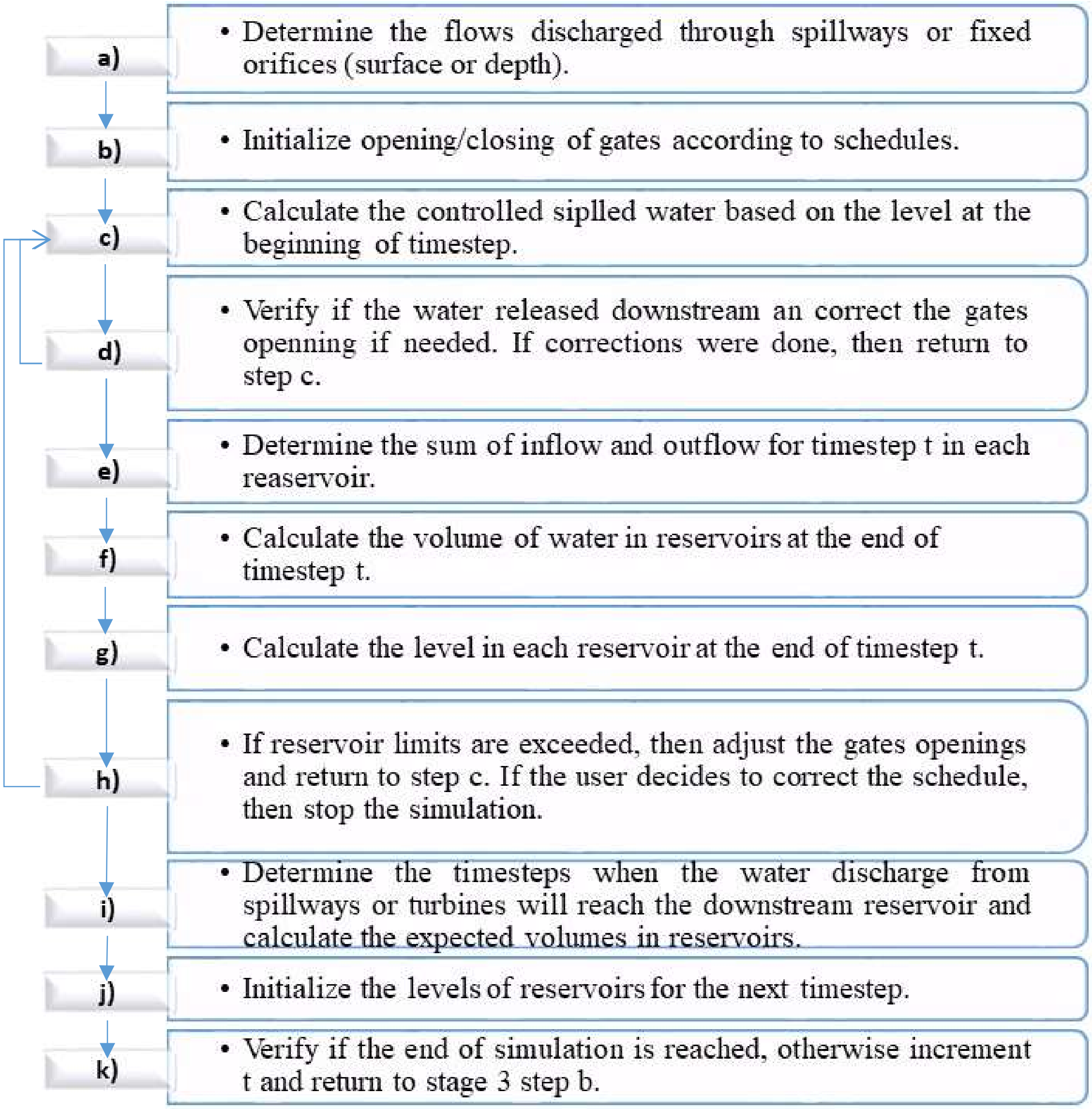
Stage 5 is executed for a group of units that have at least one common primary hydraulic circuit between the reference sections.

For hydraulic circuits under pressure and trash racks of water intakes, hydraulic head losses vary with the square of the flow through the circuit. In the case of free surface flow, they must be determined by measurements or by simulations associated with control measurements, an example of determination being exemplified in chapter **Error! Reference source not found.**.

In the first iteration, the turbine flow will be equal to the flow estimated in stage 4.

5.2.6 Stage 6. Update levels, volumes and overflow

In stage 6 (**Figure 5.9**) the discharged flows are updated, the opening of controllable dischargers is initialized and the level in each reservoir is calculated.



a)
- Determine the flows discharged through spillways or fixed orifices (surface or depth).

b)
- Initialize opening/closing of gates according to schedules.

c)
- Calculate the controlled siplled water based on the level at the beginning of timestep.

d)
- Verify if the water released downstream an correct the gates openning if needed. If corrections were done, then return to step c.

e)
- Determine the sum of inflow and outflow for timestep t in each reaservoir.

f)
- Calculate the volume of water in reservoirs at the end of timestep t.

g)
- Calculate the level in each reservoir at the end of timestep t.

h)
- If reservoir limits are exceeded, then adjust the gates openings and return to step c. If the user decides to correct the schedule, then stop the simulation.

i)
- Determine the timesteps when the water discharge from spillways or turbines will reach the downstream reservoir and calculate the expected volumes in reservoirs.

j)
- Initialize the levels of reservoirs for the next timestep.

k)
- Verify if the end of simulation is reached, otherwise increment t and return to stage 3 step b.

Figure 5.9. Operations in stage 6.

The activities performed in step 6.a are identical to those in step 2.a.

In the primary data of the simulator it is necessary to implement the opening sequence of the gates and the total controllable discharged flows related to the normal retention level of the reservoir.

5.3 Facts regarding the optimization of the generation schedules of the generation units in a hydropower development scheme

In order to determine an generation schedule for the generating units in the portfolio of an energy producer, it is considered that the contractual obligations of energy and ancillary services are known, and the goal is to cover them with minimum expenses.

For the development of a mathematical model, in this work we used mixed-integer programming, being also used in the works [2, 30, 31, 32].

In the present case, the aim is to minimize the production expenses, taking into account that the execution of the application and the generation schedule optimization are carried out after knowing the contractual energy obligations.

Thus, the objective function is of the form:

$$\begin{aligned}[MIN]\,\mathrm{C} = \sum_{t\in T}\sum_{c\in Cj}\sum_{g\in Gc} \Big[& \mathrm{TF}^{apa\_mc} * Q_{c,g}^{turbinat}(t) * \theta^{simulare} * ST_{c,g}(t) \\ & + \mathrm{TF}^{apa\_Qi} ** Q_{c,g}^{instalat} * \theta^{simulare} * ST_{c,g}(t) + C_{c,g}^{orar} * ST_{c,g}(t) \\ & + CSS_{c,g} * SS_{c,g}(t)\Big] \\ & + \sum_{j\in J}\left(Pr_j^{E\_viitor} * \left[V_j(0) - V_j(T) - V_{j,T+}^{asteptat}\right]/csp_j\right)\end{aligned} \tag{5.4}$$

The sets associated with the mathematical model are:

J –set of reservoirs *j;*

Cj –set of power plants *c;*

Gc –set of generation units *g;*

T –set of optimization steps *t.*

In the situation where the tariff for turbined water is paid according to the active energy produced at the generating unit terminals, the objective function will not take these expenses into account, the reason being that the contractual obligations are firm. For this reason, the associated term in the objective function would always be constant.

The restrictions that must be respected are determined by the topology of the development schemes, the conservation of water volume [33], the technical limitations of the equipment and constructions, the production of the contracted energy, the provision of the contracted ancillary services (supplemented with the power reserve that must be provided depending on energy production forecast in wind power plants), as well as water requirements for non-energy uses.

The objective function in equation (5.4) is subject to restrictions:

RESTRICTION 1. Water balance:

$$\begin{aligned} V_j(t+1) = V_j(t) + \theta^{simulare} * \\ * \left(Q_j^{afl}(t) + Q_j^{asteptat}(t) - Q_j^{utilitati}(t) - Q_j^{deversat}(t) \right. \\ \left. - Q_c^{turbinat}(t)\right), \forall t \in T, \forall j \in J, \forall c \in Cj \end{aligned} \tag{5.5}$$

RESTRICTION 2. Technical limitations of equipments and constructions:

$$0 \leq P_{c,g}^{calculat}(t) - P_{c,g}^{minim} * ST_{c,g}(t), \forall t \in T, \forall c \in Cj, \forall g \in Gc \tag{5.6}$$

$$0 \leq P_{c,g}^{maxim}(t) * ST_{c,g}(t) - P_{c,g}^{calculat}(t), \forall t \in T, \forall c \in Cj, \forall g \in Gc \tag{5.7}$$

$$Q_{c,g}^{turbinat}(t) \leq Q_{c,g}^{turbinat\_maxim}(t),\ Q_{c,g}^{turbinat\_maxim}(t) = f\left(H_{c,g}^{net\_calcul}(t)\right) \tag{5.8}$$

$$H_j^{am}(t) \geq NmE_j, \forall t \in T, \forall j \in J \tag{5.9}$$

$$H_j^{am}(t) \leq NNR_j, \forall t \in T, \forall j \in J \tag{5.10}$$

$$Q_j^{dev}(t) \geq 0, \forall t \in T, \forall j \in J \tag{5.11}$$

$$Q_j^{dev}(t) \leq Q_j^{deversat\_maxim}, \forall t \in T, \forall j \in J \tag{5.12}$$

RESTRICTION 3. Covering the load obligations:

$$\left| P^{contractat}(t) - \sum_{c \in Cj} \sum_{g \in Gc} \left[P_{c,g}^{calculat}(t)\right] \right| \leq \varepsilon^{P\_contractat\_admisibil}, \forall t \in T \tag{5.13}$$

The topology of the development schemes can be represented in matrix form: a matrix for hydraulic connections between reservoirs and a matrix for hydraulic connections between reservoirs and hydropower plants.

Also, to represent the dependence of the turbine flow on the active power and the net head [34], the equation was linearized:

$$P_{c,g}^{calculat} = f\left(Q_{c,g}^{turbinat}, H_{c,g}^{net\_baza}\right) \tag{5.14}$$

In **Figure 5.10** are represented, for a hydro unit, the active power based on the turbine flow, respectively the efficiency of the hydro unit based on the turbine flow.

In the implementation of the application, the dependence of the efficiency according to the turbine flow was not used, mainly because the linearization of the efficiency curve required more segments and implicitly an increased calculation time, but also because of the larger deviations from the initial curve.

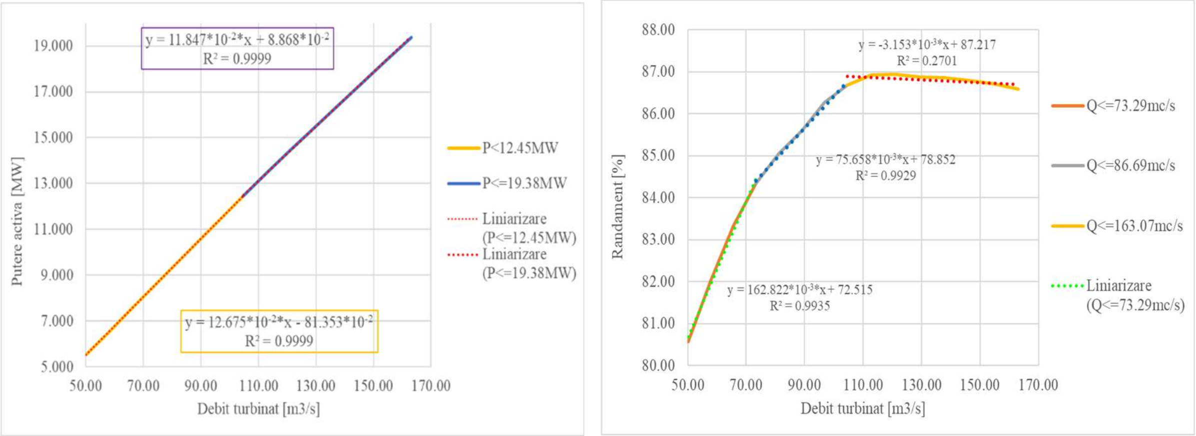


Figure 5.10. The net active power according to the turbine flow rate and the efficiency of the hydro unit according to the turbine flow rate.

5.4 The proposal of OptSimHydro

In order to develop a computer application that eliminates the deficiencies caused by the simplification of the optimization model, it is proposed to integrate the simulation algorithm with the optimization algorithm of one hydropower development, so that the solution obtained in the optimization process is accurately enough to be used in real power generation process, the bottom-up strategy being used.

The proposed solution is called OptSimHydro and it keeps the main simulator functionality of generation schedules, improving and providing additional validation to the solution obtained in the optimization process.

The immediate functionality of the proposed simulation application ((**Figure 5.11**) is to support the dispatcher in the process of operating the hydropower plants by calculating the levels in reservoirs based on the generation schedules and to provide a tool for validating any changes in the generation schedules and to verify if that they are feasible and do not lead to energy losses through spillage.

The output data from the simulation application (levels) will also be used in the re-optimization process if necessary. Thus, it is proposed that within the optimization process:

- to carry out the initial optimization;
- to simulate the generation schedule so as to obtain the evolution of levels in reservoirs;
- to identify any differences between the levels calculated in the optimization process and the levels resulting from the simulation algorithm, and in the case of level deviations greater than a certain value
  - to fix the resulting operating program up to timestep t^{limita_opt} for which the deviation is under limit;

- to enter in the optimization application the input data for the timestep previous to t^{limita_opt}, these being output data from the simulation process;
- to run the optimization process for the rest of the optimization steps;
- to simulate the resulting operating schedule again;
- the deviation condition between the level resulting from the optimization application and the level resulting from the simulation application should be checked again;
- to resume the optimization-simulation-reoptimization process until the complete optimization and simulation of the analyzed time interval, usually 24 hours, with differences between the levels in the optimization application and in the simulation application falling within a predetermined deviation, usually 10 cm. Level deviation is preferred as a reference of simulation application performance, as it is much easier for operating personnel to identify reservoirs where there is a risk of spillage, otherwise valuable time would be wasted calculating levels associated with volumes resulting from the simulation.

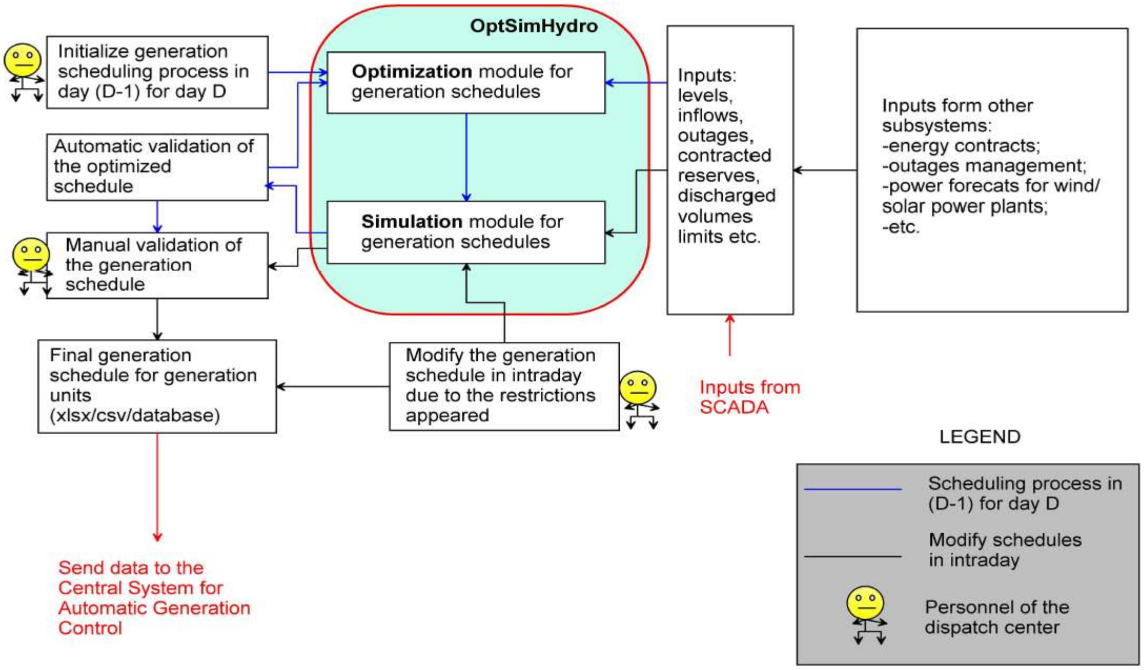


Figure 5.11. Proposed computer application, OptSimHydro

6 RESULTS USING OptSimHydro TO IMPROVE THE DISPATCHING OF A SET OF POWER GENERATION UNITS. CASE STUDY

6.1 Description of the analyzed hydropower development scheme

For the validation of the proposed algorithm, a hydropower plants section was selected (***Figure 6.1***)) consisting of 5 hydroelectric plants each equipped with 2 hydropower units with Kaplan turbines. The hydro units in each plant have independent water intakes.

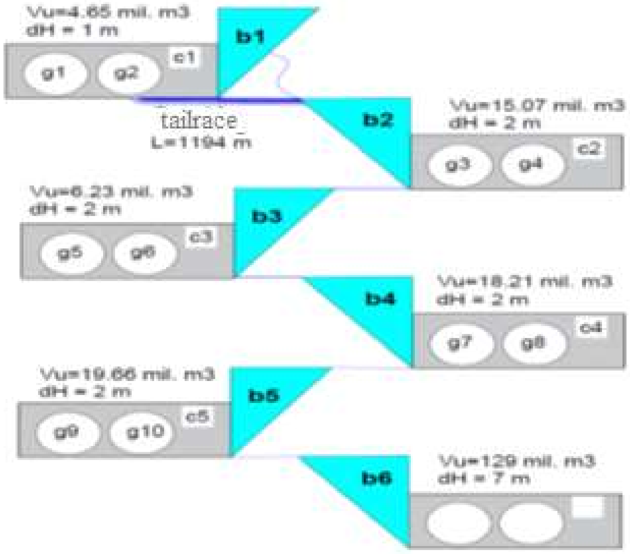


Figure 6.1. Simplified scheme of the studied hydropower development section.

6.2 Input data used in the case study

The model is a multiple inputs-multiple outputs (MIMO) type..

Input data required to configure the simulation application [23] [35] [29] are:

A. **Reservoirs data**:

a) Normal retention level (NNR), minimum operation level (NmE) and maximum level (NME) ;
b) Volume curves, in Excel files: levels and related volumes;
c) Water travel time of spilled water, to the downstream reservoir [29];
d) Level at which spillage occurs;
e) Water flow taken for non-energy use;
f) Continuous servitude flow depending on the turbined flow;
g) Matrix of hydraulic connections between reservoirs.

B. Hydropower plants and units data:

a) If the HPP do not have reservoir and is connected directly to another powerplant upstream;
b) Downstream level, if it is not the downstream reservoir level;
c) Water travel time to the downstream reservoir (in minutes);
d) The upstream/downstream hydraulic resistance module, in the form of a value or table (matrix in Excel file) [26], on the hydraulic circuits shared with other hydropower units;
e) Matrix of hydraulic connections with the upstream/downstream reservoirs;
f) Rated active power of hydropower unit (Pn);
g) Rated discharge of hydropower unit (Qn);
h) Design net head of turbine (Hc);

i) Reference efficiency of hydropower unit (Eta_ref), used for the initial estimation of the discharge;
j) Maximum active power of unit (Pmax), considering the real operation;
k) Maximum active power of unit, for long-term operation;
l) Net heads: minimum (Hmin) and maximum (Hmax), between which the turbine operation is allowed;
m) The hydraulic resistance modules independent of the operation of the other hydro units in the plant;
n) The overall efficiency of hydro unit, represented as table in Excel file.

C. **Input data required to simulate a generation schedule:**

a) For reservoirs:

i. Natural inflows;
ii. Flows for irrigation taken on the route between the current reservoir and the downstream reservoir;
iii. Levels in reservoirs at the start of simulation.

b) For hydropower units:

i. Active power scheduled for each step of simulation, în MW;
ii. Scheduled or measured active power prior to the start of simulation, that affects the simulation because of the water travel time;
iii. The hydraulic head losses at the trash racks and the associated flow at which they were measured, as well as possible corrections for measurement errors (corecție_dh).

6.3 Data processing methodology

The input data required for the simulation algorithm are represented in the form of tables in Excel files. These are:

- tables with volume curves of reservoirs;
- matrices related to hydraulic head losses on the intake channels or tailrace of hydropower developments;
- matrix associated with hydro units efficiency.

Data processing is minimal in the case of volume curves of reservoirs.

To eliminate errors when running the algorithm, the 0 mdM level and the 10000 mdM level are added, in particular not to stop the simulation for the rest of the reservoirs in the situation where one of the solutions would be infeasible.

The matrix of hydraulic head losses on the tailrace channels of the plants is determined based on the hydraulic head loss curves for different levels in the downstream reservoir. The data for their representation can be determined according to the methodology presented in [36], by simulation in HEC-RAS [37]. It is recommended that the matrix determined by simulation be extended outside the operation range, so that no errors occur in the iterative calculation process of the turbine flow. A graphical representation of such a matrix can be found in **Figure 6.2**.

Hydropower units efficiency matrices are determined based on hill charts. For the case study in this paper, these were available as images or PDF files.

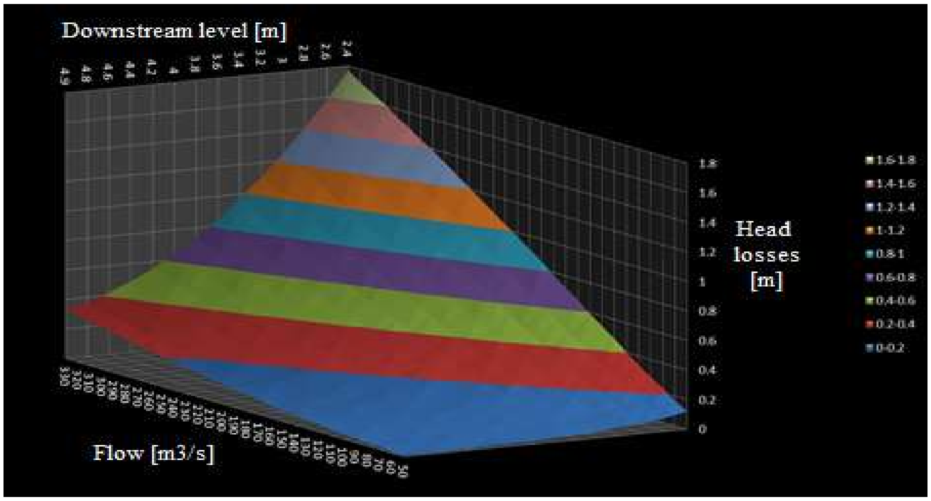


Figure 6.2. Head losses in the tailrace of power plant c1. [36]

The efficiency of the electrical generators are usually related to the active power at their terminals. Since the mechanical powers at the turbine shaft are represented in the hill chart of the turbines, for the representation of the hill charts according to the active powers at the terminals of the hydro unit, it is necessary to determine the efficiency of the generators related to the mechanical powers at the turbine coupling [19]. An example of a graphical representation of hydropower unit efficiency can be found in **Figure 6.3**.

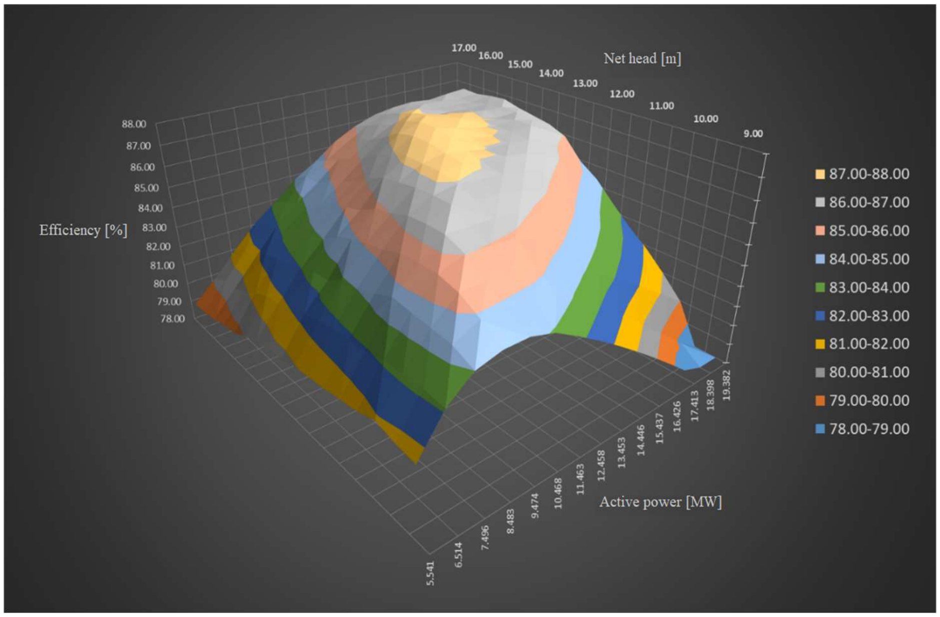


Figure 6.3. Efficiency of hydropower unit g3.

6.4 Results and challenges in integrating OptSimHydro into practical applications

For the extended validation of the simulation algorithm implemented in Python [38], a day from January 2024 and later a period of one week from May 2024 was chosen in the first stage, the criterion being the variations of the generation schedules and the changes in the configuration of the hydropower units.

The simulation step was chosen with a time resolution of 300 seconds, as it provides a good accuracy and leads to small simulation times. In the simulations carried out for 10 hydro units, the solution is obtained in approximately 7-10 seconds for 24 simulated hours.

The active powers produced by the hydro units at the generator terminals, with 5-minute resolution, were entered as data in the input data file.

Since, in the current scheme, upstream of the power plant c1 is another hydropower plant, the turbine flow of this power plant was entered in the table as a natural inflow in the reservoir b1.

Also, downstream of the b6 reservoir is a hydropower plant equipped with 2 hydro units with Pn=25MW. The discharge of this plant was entered in the table as natural inflow with a negative sign (outflow).

Since the longest water travel time is 50 minutes, between the power plant c5 and the reservoir b6, the active power produced by the hydro units for 60 minutes before the start of the simulation were entered as input data.

Based on the aforementioned data, the algorithm iteratively calculates the units discharge and associated hydraulic head losses.

The results of the simulations are saved in Excel files and represent:

- water discharge of each unit for each simulation step;
- water balance in each reservoir for each simulation step;
- levels in reservoirs at the end of each simulation step.

We analyze the performance of the simulator based on the difference between the actual level and the level obtained in the simulation. The choice of the level and not of the volume as a reference has practical applicability, as it is important for operating personnel to know quickly, without further calculations, whether it is at the limit of the spill level or there is a risk of reaching the level minimum operation level. **Figure 6.4** shows the actual and simulated levels, the actual inflow and the discharge resulting from the simulation for reservoir b1 and one of the simulated days.

The obtained results correspond to the expectations and confirm that the simulator can be applied to a real system. Thus, the differences between the actual levels of the reservoirs and the levels resulting from the simulation algorithm at the end of the 24 hours of simulation are shown in the table below.

Table 6.1

Synthesis of simulation results

Day	Data	Reservoir					
		b1	b2	b3	b4	b5	b6
02.01.2024	H_simulated [mdM]	212.89	197.38	181.98	169.64	155.72	139.68
	H_measured [mdM]	212.93	197.3	182.08	169.7	155.69	139.7
	Deviation_H [m]	**-0.04**	**0.08**	**-0.1**	**-0.06**	**0.03**	**-0.02**
01.05.2024	H_simulated [mdM]	213.09	197.35	183.55	169.43	155.8	139.37
	H_measured [mdM]	213.12	197.38	183.5	169.44	155.74	139.34
	Deviation_H [m]	**-0.03**	**-0.03**	**0.05**	**-0.01**	**0.06**	**0.03**
02.05.2024	H_simulated [mdM]	213.19	197.63	183.52	169.64	155.71	139.37
	H_measured [mdM]	213.12	197.66	183.57	169.6	155.65	139.36
	Deviation_H [m]	**0.07**	**-0.03**	**-0.05**	**0.04**	**0.06**	**0.01**
03.05.2024	H_simulated [mdM]	213.03	197.49	183.45	169.5	155.72	139.41
	H_measured [mdM]	213.07	197.38	183.55	169.52	155.63	139.39
	Deviation_H [m]	**-0.04**	**0.11**	**-0.1**	**-0.02**	**0.09**	**0.02**
04.05.2024	H_simulated [mdM]	213.08	197.41	183.52	169.47	155.73	139.42
	H_measured [mdM]	213.01	197.39	183.55	169.5	155.66	139.4
	Deviation_H [m]	**0.07**	**0.02**	**-0.03**	**-0.03**	**0.07**	**0.02**
05.05.2024	H_simulated [mdM]	213.01	197.29	183.66	169.41	155.73	139.49
	H_measured [mdM]	212.97	197.3	183.6	169.43	155.67	139.48
	Deviation_H [m]	**0.04**	**-0.01**	**0.06**	**-0.02**	**0.06**	**0.01**
06.05.2024	H_simulated [mdM]	213.02	197.55	183.5	169.42	155.82	139.42
	H_measured [mdM]	213.04	197.63	183.51	169.4	155.76	139.39
	Deviation_H [m]	**-0.02**	**-0.08**	**-0.01**	**0.02**	**0.06**	**0.03**
07.05.2024	H_simulated [mdM]	213.07	197.51	183.35	169.31	155.88	139.42
	H_measured [mdM]	213.01	197.49	183.4	169.32	155.82	139.38
	Deviation_H [m]	**0.06**	**0.02**	**-0.05**	**-0.01**	**0.06**	**0.04**

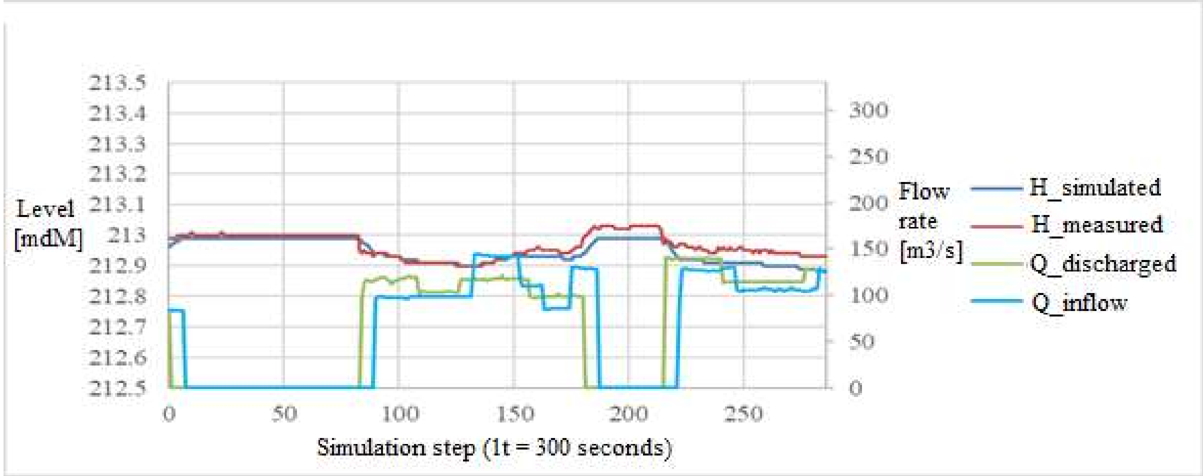


Figure 6.4. Levels in reservoir b1 in 2.01.2024.

Next, the full functionality of optimization and simulation algorithm was tested, on generation schedules for 02.02.2024. As input data to the optimization program were entered:

- the sum of the active powers of the 10 hydro units, equal to the contractual obligations for a normal optimization case;
- the gross volumes of each reservoir at the beginning of the optimization;
- the active powers of hydro units prior to the optimized period;
- the expected water flows in the reservoirs, as a result of the operation previous to $t^{optimizare}=0$.

To identify possible dysfunctionalities of the proposed system:

a) I performed the simplified optimization, without taking into account the variable hourly expenses of the hydro units;

b) I performed the optimization proposed in this paper, taking into account the variable hourly costs of hydro units, with a value of 90 Euro/hour.

Thus, for the simplified optimization, a feasible solution was obtained in 2 simulation optimization iterations. The resulting generation schedule led to the realization of energy production with 111 operating hours of the hydro units, compared to 109 operating hours in the actual schedule, this represents a 1.8% increase in operating hours per 24-hour interval. Also, the optimized program led to the avoidance of using a volume of water with an equivalent energy of 9.49 MWh. Compared to the scheduled energy over the 24-hour interval, equal to 1553.2 MWh, it represents an energy production gain of approximately 0.6%. The results are presented in Table 6.2.

Table 6.2

Synthesis of optimization-simulation results, without considering variable hourly expenses

		Reservoir					
Simulated schedule	**Data**	**b1**	**b2**	**b3**	**b4**	**b5**	**b6**
Actual generation	**H [mdM]**	213.19	197.63	183.52	169.64	155.71	139.37
	V_gross [mil.m3]	11.04	37.20	19.18	49.83	63.90	197.56
Optimized generation	**H [mdM]**	213.34	197.88	184	168.65	155.95	139.47
	V_gross [mil.m3]	11.74	39.27	20.70	40.48	66.31	199.67
Specific consumption [m3/kWh]		24.15	24.15	24.95	24.88	26.42	23.64
Volume difference [mil.m3]		-0.37	0.70	2.07	1.52	-9.34	2.40
Equivalent energy [MWh]		-15.40	28.88	82.84	60.96	-353.70	101.71

Considering the expenses equal to 90 Euro/hour of operation with a hydro unit, the result is an increase in expenses of 180 Euros/24 hours if it had been operated according to the optimized generation schedule. Considering an energy price equal to 80 Euro/MWh, the energy equivalent to 9.49 MWh, gained in the optimization process, represents 759 Euro.

We then performed the full optimization, taking into account variable hourly operating costs. To obtain a feasible solution, four optimization-simulation iterations had to be performed.

The optimized generation schedule led to the realization of energy production with 90 hours of operation of the hydro units, compared to 109 hours of operation in the actual schedule, this representing a 17.4% reduction in operation hours per 24-hour interval. Also, the optimized program led to the avoidance of using a volume of water with an equivalent energy of 18.55MWh. Compared to the scheduled energy over the 24-hour interval, equal to 1553.2 MWh, it represents an energy production gain of approximately 1.2%.

Table 6.3

Synthesis of optimization-simulation results

		Reservoir					
Simulated schedule	**Data**	**b1**	**b2**	**b3**	**b4**	**b5**	**b6**
Actual generation	**H [mdM]**	213.19	197.63	183.52	169.64	155.71	139.37
	V_gross [mil.m3]	11.04	37.20	19.18	49.83	63.90	197.56
Optimized generation	**H [mdM]**	213.11	197.53	183.92	169.55	155.95	139.31
	V_gross [mil.m3]	10.67	36.38	20.44	48.98	66.31	196.29
Specific consumption [m3/kWh]		24.15	24.95	24.88	26.42	23.64	23.76
Volume difference [mil.m3]		-0.37	-0.83	1.26	-0.85	2.40	-1.27
Equivalent energy [MWh]		-15.40	-33.13	50.80	-32.15	101.71	-53.27

Considering the cost equal to 90 Euro/hour of operation with a hydro unit, it results in a saving of 1710 Euro/24 hours if it would have operated according to the optimized generation schedule. Considering an energy price equal to 80 Euro/MWh, the energy equivalent to 18.55MWh, gained in the optimization process, represents 1484 Euro.

If we transpose the results obtained to the operation for one year, it follows that the savings would be approximately 1.16 million Euros for the 5 hydropower plants. The proposed system proves its efficiency, but it needs to be tested further to be able to make a more reliable estimate of the results.

It is found that taking into account the variable hourly expenses of the hydro units in the optimization process leads to considerable savings.

7 CONCLUSIONS AND PERSONAL CONTRIBUTIONS

7.1 General conclusions

In order to evaluate the expenses associated with the preventive maintenance works, we analyzed the maintenance works from 2007-2017, carried out at 20 hydro units equipped with vertical axis Kaplan turbines and synchronous generator with apparent poles, with rated powers between 18.5MW and 35MW and design net heads between 13.25m and 24m.

Based on the study for maintenance expenses, for a complete cycle of preventive maintenance, result an average costs of 90 Euro/hour of operation for a hydro unit. These values must be updated according to the maintenance regulations of each energy producer, as they can be significantly different from the values obtained in the study presented in this research.

For the calculation of expenses related to corrective maintenance works, the period 2013-2017 was analyzed, mainly for reasons of calculating the average annual operating hours. Thus, for an average of 4100 hours/year and generating unit, average expenses of 1.5 Euro/hour for a hydro unit resulted, insignificant compared to the expenses of preventive maintenance.

The expenses for trash rack cleaning and waste transport were on average about 220 Euro/clening and unit until 2017. Later, they increased to about 820 Euro/cleaning and hydropower unit. The values are inconsistent and require further analysis. For this reason, they were not included in the optimization model.

For the same set of hydro units, we analyzed the corrective maintenance expenses associated with the start-up and shutdown of hydro units for the period 2012-2017. We found that part of the weared equipment is repaired or replaced as part of preventive maintenance works. The resulting expenses for corrective maintenance are therefore minimal, with a value of approximately 0.3 Euro/start-up

For the period 2015-2018, for the 20 hydro units, 90 failed start-ups or shutdowns (with the unavailability of the unit) were identified. It turns out that the average number of failed starts/stops is 22.5/year, of which 9.75/year are due to broken shear bolts.

The costs associated with start-ups and shutdowns are significant but not as high as those mentioned in other studies [22, 39, 40], which have values of about $3/MW and start-up only for maintenance and equipment replacement. Partially, these differences can be caused by the predominantly preventive maintenance carried out at hydro units during the analyzed period.

The equivalent active energy lost in the start-up cycle, due to the low-efficiency, is 0.135 MWh. At an average energy price of 80 Euro/MWh, a loss of 10.8 Euro/start-up results. The equivalent energy lost in the start-up cycle was determined considering a total efficiency of the hydro unit of 87% and a net head of 16 m.

The use of a simulator like the one designed in this paper is essential to increase the flexibility in the Balancing Market and possibly in the Intraday Market. Thus, within a few minutes it is possible to analyze whether the change in the generation schedule will lead to spillage or the impossibility of generating the scheduled production. The accuracy of the simulator is very closely related to the accuracy of the input data and the accuracy of the hydraulic circuit modeling.

The integration of such a simulator in an optimization program avoid the errors caused by linearizations. Thus, the levels and volumes resulting from the simulator can be used as input data for the optimization process.

The optimized generation schedule led to the realization of the scheduled energy with 90 hours of operation of the hydro units, compared to 109 hours of operation in the actual schedule, this representing a 17.4% reduction in operating hours per 24-hour interval. Also, the optimized program led to the avoidance of using a volume of water with an equivalent energy of 18.55MWh. Compared to the scheduled energy over the 24-hour interval, equal to 1553.2 MWh, this represents an energy production gain of approximately 1.2%.

It is found that taking into account the variable hourly expenses of the hydro units in the optimization process leads to considerable savings.

If we transpose the results obtained to the operation for one year, it turns out that the savings would be approximately 1.16 million Euros for the 5 hydroelectric plants. The proposed system proves its efficiency, but it needs to be tested further to be able to make a more reliable estimate of the results.

The use of the simulator is essential for the successful and timely completion of the optimization process. The combined use of these applications will lead to lower operating costs and shorter response times. Thus, within 15-20 minutes it is possible to analyze whether the change in the operating schedule will lead to spillage or the impossibility of realizing the scheduled production, as well as whether a certain spillage can be avoided.

From the obtained results it can be seen that the deviations of the simulated levels compared to the levels measured in the reservoirs fall within the limit of [-10;10] cm, except for one reservoir, b2, which had a deviation of +11 cm for the date 3.05.2024. This deviation is considered to be acceptable and the exceeding of the 10 cm limit was caused by the variation of the natural inflow.

7.2 Synthesis of original contributions

As a result of the research during the doctoral stage, the following contributions resulted:

- Contributions regarding the identification and evaluation of preventive maintenance expenses of hydropower units, by performing an analysis that included a study period of 11 years, respectively 2007-2017, study carried out for 20 hydro units equipped with vertical axis Kaplan turbines and synchronous generator with apparent poles, with rated power between 18.5 MW and 35 MW and design head between 13.25 m and 24 m. Average operating hourly costs of 90 Euro/hour for a hydro unit resulted, only for maintenance associated with a complete preventive maintenance cycle.
- Contributions regarding the identification and evaluation of corrective maintenance expenses associated with long-term operation, by performing an analysis that included a study period of 5 years, respectively 2013-2017. Thus, for an average of 4100 hours/year

and generating unit, average expenses of 1.5 Euro/hour for a hydro unit resulted, insignificant compared to the expenses of preventive maintenance. The analyzed 5-year period was chosen to have an almost equal number of operating hours of the 20 hydropower units analyzed.

- Contributions regarding the evaluation and presentation of the corrective maintenance expenses associated with the start-up and stop-down processes of the hydro units for the period 2012-2017. I found that some of the weared equipment was repaired or replaced as part of preventive maintenance work. For this reason, the resulting expenses for corrective maintenance are minimal, with a value of approximately 0.3 Euro/start-up.
- Contributions regarding the evaluation and presentation of the unavailability times of the hydro units as a result of the start-up and shutdown processes, by analyzing a period of 4 years, respectively 2015-2018:
  - Thus, for the 20 hydro units, 90 failed start-ups or shutdowns (with the unavailability of the unit) were identified;
  - The average number of failed starts/stops is 22.5/year, of which 9.75/year are due to broken shear bolts. This results in an average annual downtime of 57.37 minutes/year and unit;
  - The impact of starts and stops is found approximately 1-2 years after the increase in the number of start-stop cycles.
- Contributions regarding the development and presentation of an algorithm for simulation of the generation schedules of hydropower units, with the presentation of the particularities necessary for its implementation in a software application for simulation;
- Contributions regarding the identification and analysis of the practical aspects related to the optimization of the generation schedules of the hydro units and the formulation of certain restrictions with practical applicability, especially for defining the restrictions associated with the water travel time between reservoirs. The references in the specialized technical literature to the practical way of implementing the restriction associated with the travel time are vague, not because it was not taken into account in computer applications, but because of the protection of implementation details in the commercial applications;
- Contributions regarding the definition of a systemic concept capable of facilitating the automatic generation control of the generation units for an energy producer. The concept is presented in detail in Figure 3.1.
- Proposing an essential tool for increasing the flexibility of hydropower units, OptSimHydro, which will ease the generation scheduling activity for hydropower units. This is a decision support system that provides to the dispatcher all the information to modify the generation schedules of the hydro units and identify possible infeasibility or associated spill risks.

- Contributions regarding the implementation of the proposed simulation algorithm in the Python programming language, providing practical implementation details and modeling of hydropower plants, including hydraulic head losses. The implementation of the algorithm was made so that the modeling of the behavior and restrictions of the hydropower plant can be done by personnel who do not have programming skills. Thus, the system can be used for any hydropower development scheme and any set of hydropower units by simply defining the input data in Excel files.

7.3 Research development perspectives

The current research opens up a new research direction, namely that of defining the requirements and implementation details of a system for automatic generation control, as it is conceptually defined in **Figure 3.1**.

Carrying out the necessary studies for the evaluation of power generation costs for other categories of hydropower units is a topic of interest, able to bring benefits both to the producer who applies the results of the study and to the scientific community interested in the optimization of generation schedules.

Optimizing the algorithm code and including new functionalities such as automatic data importing and exploring the possibilities of using other optimization solvers such as CPLEX [41] require further research.

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APPENDIX

List of publications for the dissemination of research results

A paper presented during my studentship at a WoS rated international conference was published and marked the beginning of my research activity and an important milestone in choosing my master's specialization and the topic of my future thesis:

- **I.B Stoenescu**; S. Costinaș; G. Chicco, "*Symulations of the Axial-Flux Permanent Magnet Synchronous Generator în no-load condițion*", 16th International Conference On Harmonics And Quality Of Power, Bucharest, Romania, 25-28 May, 2014, În: Book Series: International Conference on Harmonics and Quality of Power, pages: 375-379, Publisher IEEE, ISBN:978-1-4673-6487-4, ISSN: 2164-0610, ISI Proceedings, DOI: 0.1109/ICHQP.2014.6842802, WOS:000343776100078.

The research carried out during the doctoral stage was disseminated through the publication of 5 articles/4 first author. Among them, one is IEEExplore and the others are WoS:

- **I.B Stoenescu**; S. Costinaș; G. M. Marius Deaconu, "*A multi-objective approach to improve hydropower dispatching*", 2018 International Conference and Exposition on Electrical And Power Engineering (EPE), Iasi, Romania, October 18-19, 2018. Electronic ISBN: 978-1-5386-5062-2, USB ISBN: 978-1-5386-5061-5, Print on Demand (PoD) ISBN: 978-1-5386-5063-9, DOI:10.1109/ICEPE.2018.8559671. WOS:000458752200042
- **I.B Stoenescu**; S. Costinaș; G. M. Marius Deaconu, "*Assessment of Hydropower Plants Energy Production Cost Influenced by Operational Decisions and Control Strategy*", 22nd International Conference on Control Systems and Computer Science (CSCS), Bucharest, Romania, Year: 2019, Publisher: IEEE, INSPEC Accession Number: 18793023, DOI: 10.1109/CSCS.2019.00062. WOS:000491270300055
- G. G. M. Deaconu, S. Costinaş, **I. B. Stoenescu** and I. Opriş, "*The Testing of Digital Substation - an Important Issue în Power Engineering Education*", 2021 12th International Symposium on Advanced Topics în Electrical Engineering (ATEE), 2021, pp. 1-6, DOI: 10.1109/ATEE52255.2021.9425295. WOS:000676164800136
- **I.B. Stoenescu**, S. Costinas and G. M. Deaconu, "*Case Study for Validation of Hydropower Schedule Simulation Algorithm*", 2021 23rd International Conference on Control Systems and Computer Science (CSCS), Bucharest, 2021, pp. 381-385, doi: 10.1109/CSCS52396.2021.00069. [IEEExplore, Scopus].
- **I. B. Stoenescu**, S. Costinas, *"Improving Hydropower Generation Scheduling And Dispatching Decisions With Python Simulator*“, University POLITEHNICA of Bucharest Scientific Bulletin, Series C, Vol. 86, 2024, (*in progress of publishing WoS)*.