XLI CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020 FOZ DO IGUAÇU PARANÁ – BRAZIL

SIMULATION OF A LONG-TERM OPTIMIZED OPERATION PLAN FOR A HYDROELETRIC PLANT

Tiago Lino Bello[1,3], Luiz Carlos Matioli[2], Ana Paula Oening[3], Débora Cíntia Marcílio[3], Klaus de Geus[4], Marcelo Rodrigues Bessa[5], Gilmar Edson Schewtschik Filho[1]

[1]*PPGMNE, Federal University of Paraná (UFPR) - Curitiba, Paraná, Brazil*
tiago.bello1@hotmail.com
[2]*Dept. of Mathematics, Federal University of Paraná (UFPR) - Curitiba, Paraná, Brazil*
[3]*Power Systems, Lactec - Curitiba, Paraná, Brazil*
[4]*Copel Geração e Transmissão S.A. - Curitiba, Paraná, Brazil*
[5]*Dept. of Hydraulics and Sanitation, Federal University of Paraná (UFPR) - Curitiba, Paraná, Brazil*

Abstract. The main goal of the hydrothermal operation plan is the computation of optimal use of water and thermal resources in order to attend a predicted demand in a defined time horizon. In order to reduce the computational cost, it is necessary to consider relaxation in hydrothermal operation plan modeling in terms of detailing the physical and operational characteristics of the system. Although the optimized system is very useful, certain characteristics are difficult to model mathematically and these will be treated in the simulation, which is the main purpose of this work. In this paper, we implemented a simulation tool for the Brazilian hydrothermal system focusing on the long-term planning, which includes constraints that are not considered in the optimization model. A case study with Foz do Areia hydro plant using real data indicates that the simulation tool refine and validate the results from the adopted optimization model, turning the optimized policy more adequate in operational terms.

Keywords: Simulation tool, Long-term hydrothermal dispatch, Non linear programming

1 Introduction

The planning operation of the Brazilian hydrothermal system is challenging, since there is a need for a range of operating strategies for electric power generation. With the purpose of minimizing costs, whether operational from thermoelectric power plants or economic caused by energy *deficit*, guaranteeing the supply of demand and helping the operators of the system to make decisions regarding the rational use of water resources and absorb the maximum of the productivity in the generating units.

The mathematical modeling of the operation planning leads to a large non linear problem, which is nonconvex, differentiable and with stochastic characteristics. It is a robust problem and difficult to solve [1]. As a result of the high number of reservoirs and hydroelectric predominance of the system, due to the natural characteristics, the problem is usually decomposed into long, short and very-short time stages of operation planning [2]. In this work, the long-term horizon will be investigated and explored.

For the purpose of find a feasible solution for long-term planning, it is useful to consider relaxation in hydrothermal dispatch modeling in terms of detailing the physical and operational characteristics of the system, motivating to adapt the problem to the existing optimization methods, which guarantee convergence. Thus, when hydrothermal dispatch optimization fails to encompass some elements with greater precision, it is necessary to improve the optimized operating policy to a closer technical and physical solution, which is more adequate to the reality in operational terms. The improvement of the optimized planning works toward to make more realistic modeling of the hydro and thermoelectric power plants. Therefore, it is important to elaborate a simulation tool of hydrothermal system of individualized plants whose purpose is to refine and validate the results from the adopted optimization model.

In this work, a simulation tool for the Brazilian hydrothermal system operation planning is developed. This tool includes constraints that are not considered in the optimization model adopted. The purpose is to refine and validate the results from the adopted optimization model and analyze how the specific details impact on the operation of power plants by a case of study with historic inflow data.

The structure of this paper is the following. In Section 2 we describe the notation of some variables utilized. In Section 3 we describe briefly the mathematical model of the operation planning adopted. In Section 4 we describe the the simulation tool and the aspects considered. In the Section 5 we present our results for a real hydro unit. Finally, in the Section 6 we close the paper by taking some conclusions.

2 Notation

The following notation is adopted. More variables will be explicit defined throughout the text.

- Index	**- Input data at stage** t (besides bounds for all variables)
$i = 1, \ldots, R$: hydro plants	gt_j^t: generation of thermal plant j $[MW\text{month}]$
$j = 1, \ldots, J$: thermal plants	v_i^t: volume of hydro i at the end of the period $[hm^3]$
$t = 1, \ldots, T$: stages/periods	sp_i^t: spillage of hydro plant i $[m^3/s]$
$s = 1, \ldots, S$: subsystems	q_i^t: discharge of hydro plant i $[m^3/s]$
- Index sets	def_s^t: *deficit* of subsystem s $[MW\text{month}]$
λ_t: discount factor at stage t	$int_{(s,n)}^t$: power interchange between subsystems s and n $[MW\text{month}]$
R_s: hydro plants of subsystem s	**- Energy costs functions**
U_i: plants immediately upstream of plant i	ct_j: thermal cost for the plant
J_s: thermal plants of subsystem s	cd_s: deficit cost for subsystem
M_s: interconnections of subsystem s	ipi: nterchange cost for branch
- Input data at stage	**- Other factors during the period of stage**
d_j^t: energy demand in subsystem	$\overline{evp}_i^t$: linear liquid evaporation of the hydro unit i $[hm^3]$
y_j^t: natural inflow of hydro plant	ρ_i^t: output energy of the hydro unit i $[MW\text{month}]$

3 Mathematical model for the operation planning problem

To perform the simulation of an optimized plan, an approach of operational plans optimization must be chosen according to the modeling of the adopted planning problem. The adopted model is based on Periçaro et. al [3] deterministic formulation, which given the demand and a serie of inflow, the model aims to minimize the sum of all costs for the thermal generation and the costs of the energy system *deficit*, with decisions taken at one-month intervals for a period of 60 months. This minimization will be constrained to the system's demand, hydro balance and bounds for the decision variables.

This model is realized individually for each unit of the system, noticing the nonlinearities of the problem and optimizing in a deterministic form. The hydro balance constraints – total of $R \cdot T$ – considers the liquid evaporation of the reservoirs. Due to the low nonlinear characteristic in the zone of operative volume of the hydro units presented in the Brazilian system, this phenomenon will be computed by a linear approximation of the fourth degree polynomial of flooded area [4] in the adopted optimization model. The demand constraints – total of $S \cdot T$ – contains much of the nonlinearities stemming from fourth degree polynomials relating head (and thus hydro energy) to reservoir volumes and to discharges and spillages.

In this work, we will define the output energy of the hydro unit i by

$$\rho_i^t = \underbrace{10^{-6} \cdot g \cdot \gamma \cdot \eta}_{=k} \cdot h_l \cdot q_i^t, \tag{1}$$

where g is the acceleration of gravity $[m^3/s]$, γ is specific weight of water $[kg/m^3]$, η is the efficiency of the turbine-generator set and h_l is the effective water head, which is given by

$$h_l = \phi(v_i^t) - \theta(q_i^t, sp_i^t) - h_{loss}, \tag{2}$$

where ϕ is the forebay level – dependent on the storage of the reservoir – and θ is the tailrace level – function of the water discharge and the spillage of the plant –, both calculated by a fourth degree polynomials $[m]$. The h_{loss} computates the penstock head losses [1]. It shall be noted that [3] use the k value in equation (1) as constant, which in the simulation tool will be different.

4 Methodology and implementation of the simulation tool

Given an optimized plan from the model adopted, the implemented simulation tool will include some high non-linear constraints of the hydro plants that are not considered by the optimization model due the computational costs. Thus, it is necessary to bring to reality the optimized operating policy found to a closer technical and physical solution which is more adequate in operational terms. The simulation tool can be divided in two parts, as synthesized in the flowchart in Figure 1. This parts will be described in the Subsections 4.1 and 4.2, respectively.

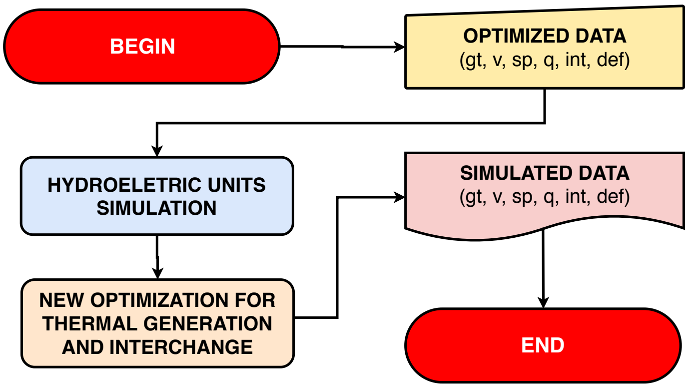

Figure 1. Simulation tool flowchart.

4.1 Hydroeletric units simulation

In the process of generating energy for hydro units, there are operational constraints of the plants that impact on its operation, such as liquid evaporation, maximal turbine water discharge at the penstock, turbine-generator set efficiency, maximal output constraints, among others. These details have strongly non linear mathematical characteristics, which prevent them from being considered during the computational planning of the operation of the plants. The implemented hydroelectric plants simulation includes most of the actual operating restrictions to the optimized plan.

The simulation of hydroelectric plants implemented operates in terms of the water balance, in which the initial volume for the simulation is considered the same as the optimized plan data, assuming the premise that the simulation outflow will be equal – or approximate – the outflow resulting from the optimized plan. The structure of the hydroelectric units simulation is divided in two main modules, as illustrated in Figure 2.

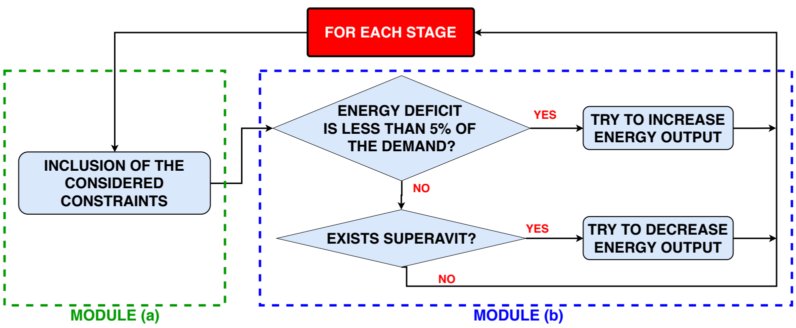

Figure 2. Hydroeletric units simulation flowchart.

The modules are:

(a) Initial estimates of v, q and sp including some physical phenomena not considered in the optimization model;

(b) When necessary, obtaining new estimates of the variables related to the hydroelectric plants via

- maximizing the output energy by subsystems in gradual way, without changing the total outflow;
- adjustment of the discharge rate for the cases where there is a *superavit* of the total energy generation of the system[1], reducing the hydraulic generation of the plants that have reservoir per subsystem.

[1] In the hydroelectric plant simulator, the total generation of the system is taken as the sum of the hydraulic generation ρ and minimum thermal generation gt_{min} for the respective stage.

Module (a) has the purpose, for each stage, of making the refinement at the variable related to hydro units, which consists of including topics such as:

- *Liquid evaporation*: water volume of the power plant that is lost naturally. According to [4], the evaporation evp is defined at any month in the reservoir of the hydro plant as

$$evp = area \cdot \xi \cdot c, \tag{3}$$

  where $area$ is obtained by the fourth degree polynomial of flooded area $[km^2]$, ξ is the monthly evaporation rate of the hydro unit $[mm]$ and c is a constant equal 10^{-5} to turn the evaporation in physical quantities of volume;
- *Maximal turbine water discharge at the penstock*: the maximal discharge quantity to obtain the maximal power given the water head, with the mathematical definition related to the a plant as

$$\overline{q} = \sum_{k=1}^{N_c} (N_k \cdot \overline{q_k}), \tag{4}$$

  where N_c is the total of units in the plant, N_k is the number of generation unit of the k-unit of the plant and $\overline{q_k}$ is the hydro unit maximal turbine water discharge, which depends the effective turbine water discharge, effective water head and the type of turbine utilized in the hydro unit [5];
- *Turbine efficiency*: this constraint bring the output energy of the plant to a more realistic way. Therefore, the specific productivity for the output generation for hydro units is defined as

$$k = 10^{-6} \cdot g \cdot \gamma \cdot \eta; \tag{5}$$

- *Power output constraints*: its verified the environmentally adequate outflow aiming at downstream and maximum hydraulic output constraints.

All the constraints described were implemented in a heuristic form. Due the complexity of obtaining the turbine efficiency, the long-term planning operation optimizer usually treats this coefficient as constant, basing this value on an average for all sets of generating units of the plant, something replicated in [3]. To the simulation tool implemented, we will represent the turbine efficiency η with the "Curva Colina Conjunta" technique [6], which unifies each turbine curve efficiency of the plant in a unique curve. The refinement of the optimized plan will be realized to each hydro unit i at the stage t is the same as discussed at [7, 8]. Also is noteworthy that this constraints will be analyzed at both modules.

Regarding module (b), its execution will depend on the need of increase or decrease of power generation in the system. An increase in power generation will be indicated when the difference in total system power generation with the demand for the period is less than 5% of the system demand – adopted empirically. The signaling for decreasing power generation will be performed as soon as there is energy *superavit*.

In case of signaling to increase the power generation of the system, the discharge of the power plants of each subsystem will be gradually changed according to a per_a percentage, which will be defined, for a given stage t, by the ratio between the energy *deficit* and the generation, namely

$$per_a = \left| \frac{\sum\limits_{i=1}^{R} \rho_r^t + \sum\limits_{j=1}^{J} gt_j^t - \sum\limits_{s=1}^{S} d_s^t}{\sum\limits_{r=1}^{R} \rho_r^t} \right|. \tag{6}$$

Thus, the attempt to increase energy for the plants of a subsystem will be carried out in those plants that have spillage ($sp > 0$) and that do not have their maximum discharge at the penstock $\overline{q}$, or maximum power generation ρ_{max} reached/satisfied. The signaling of the energy requirement for the subsystem s will be given by the following conditions:

- for the "Sudeste/Centro-Oeste" and "Sul" subsystems, the maximum values of the respective energy interchange lines of the "Itaipu" subsystem:

$$\rho_s^t < d_s^t - gt_s^t - int_{max_{(Itaipu,s)}};$$

- the other subsystems use the following condition:

$$\rho_s^t < d_s^t - gt_s^t.$$

The stopping criterion, analyzed at each increment, will be the interruption of the generation increase in the system when the following condition is satisfied.

$$\sum_{s=1}^{S} d_s^t - \Big(\sum_{i=1}^{R} \rho_i^t + \sum_{j=1}^{J} gt_j^t \Big) < 5\% \cdot \sum_{s=1}^{S} d_s^t. \tag{7}$$

When the left side of the inequality (7) is negative, the increase process is also terminated.

If the total power generation of the simulation at the period t is above the demand, the hydraulic generation of the plants with subsystem reservoir is reduced, since they can store water and avoid unnecessary spillages. In this case, in order to estimate the generation value that needs to be reduced, we compute the power energy of the period with the hydraulic generation of the reservoir plants, both in the system and in the subsystem, thus obtaining the participation percentage of plants with reservoir in the generation surplus per_d of the stage, that is,

$$per_d = \left| \frac{\sum_{i=1}^{R} \rho_i^t + \sum_{j=1}^{J} gt_j^t - \sum_{s=1}^{S} d_s^t}{\sum_{s} \rho_{res_s}^t} \right|. \tag{8}$$

Thus, the percentage of participation in the discharge of all plants with reservoir of the system is deducted. After the discount, the total generation of the system is again compared to the demand. The signaling of the energy decrease requirement for the subsystem s will be given by the following condition:

$$int_{max_s} + \rho_s^t > d_s^t - gt_s^t.$$

The stopping criterion, analyzed at each discharge decrease, will be the exemption from the decrease of generation in the system, namely

$$\Big(\sum_{i=1}^{R} \rho_i + \sum_{j=1}^{J} gt_j \Big) - \sum_{s=1}^{S} d_s > 0. \tag{9}$$

It is remarkable that these attempts to increase or decrease hydraulic generation will be carried out by subsystems, and the highest demand is taken as the priority.

4.2 Optimization of the thermal generation and energy interchange

Based on results of the hydroeletric plants simulation, it is necessary to obtain new values for gt, int and def. For this purpose, we have decided to optimize again the dispatch problem with the fixed hydraulic generation, considerably reducing the scale and difficulty of the problem.

In this simulation tool, we consider the variable *superavit* (sup) for subsystems in order to guarantee the feasibility and convergence. For a control of its value in this new optimization, a penalty will be included in the objective function of the problem for each generated unit, minimizing such value. This penalty value will not be included in the total cost of planning the simulator operation.

Therefore, the new non-linear problem to be solved is given as follows.

$$\begin{aligned} \underset{gt,int,def,sup}{\text{minimize}} \quad & \sum_{t=1}^{T} \lambda_t \left[\sum_{j=1}^{J} ct_j^t + \sum_{s=1}^{S} cd_s^t + \sum_{s=1}^{S} ps_s^t \right] + \sum_{t=1}^{T} \sum_{s=1}^{S} \sum_{n \in M_s} ip_{(s,n)}^t \\ \text{subject to} \quad & \sum_{j \in J_s} gt_j^t + \sum_{i \in R_s} \rho_i^t(x) + \sum_{n \in M_s} (int_{(n,s)}^t - int_{(s,n)}^t) = d_s^t - def_s^t + sup_s^t \\ & gt_{min_j}^t \le gt_j^t \le gt_{max_j}^t \\ & int_{min_{(s,n)}}^t \le int_{(s,n)}^t \le int_{max_{(s,n)}}^t, \end{aligned} \tag{10}$$

where ps_s is the penalty function associated to the sup variable decision.

5 Numerical Experiments

The simulation tool was implement in MATLAB®, version R2011a. The simulation tool was performed in a laptop with Intel(R)®Core(TM) i5-3337U CPU @ 1.80GHz, 3.8GB of usable RAM and Windows®7 operational system. The stochasticity of the inflows is treated implicitly, since the implicit stochastic models do not consider uncertainties directly in the problem. Thus, one scenario of inflow was generated based on [9], but it should be noted that any inflow scenario could be chosen. For each inflow data, the deterministic operational plan model [3] was optimized by a SQP-Filter method and then was later simulated at the simulation tool.

To facilitate the comprehension and the display of the results, the hydrothermal test system is initially discussed.

5.1 Hydrothermal system considered

The system considered consists of 142 hidro units and 106 thermal units distributed in four geoeletrical regions considered by ONS: Norte (N), Sul (S), Nordeste (NE) and Sudeste/Centro-Oeste (SE/CO) [2]. In addition, we are considering a subsystem composed only by Itaipu plant besides a fictitious node, that does not contain any plants [3]. As for the connections between the subsystems, it was considered 14 lines of energy interchange.

For a case study, we selected one plant of this test system in order to observe the operational constraints implemented in the simulation tool. The selected hydroelectric plant, Foz do Areia hydro plant, is located on the Iguaçu River in the state of Paraná. The operational data of the hydrothermal system considered was adopted from NEWAVE [10], being: initial volume of the hydro units; minimum and maximum values of volume, discharge, hydraulic and thermal generation; coefficients of monthly evaporation of the reservoirs; coefficients of forebay, tailrace and flooded area polynomials; composition of the generating units of each plant, such as quantity of turbines, effectives power, water head and maximal water discharge at the penstock; limits of energy interchange between subsystems; and energy demand of each subsystem.

5.2 Case study

About the evolution of water storage in Foz do Areia reservoir plant during the operation horizon, there was no big differences between the optimized data and the respective simulation. Even so, the more realistic water storage plan, more reasonable operation plan can be assumed. The results of this case study indicate, for that plant, that the liquid evaporation in the water balance in its linear form during the elaboration of the optimized planning of the operation – by the deterministic model [3] – reduces the impact on the planning of these plants when the liquid evaporation is included in its non-linear form in the simulation tool, once the planning model becomes more operationally realistic. Figure 3 highlights this conclusion.

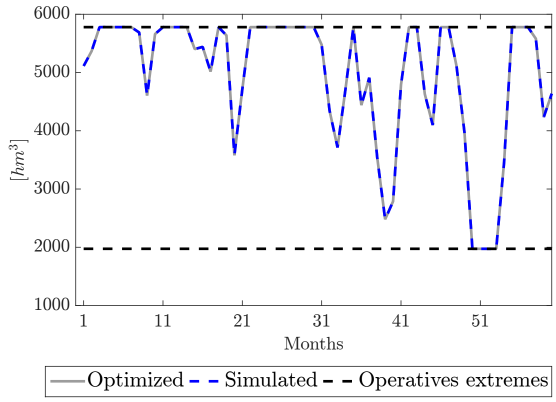

Figure 3. Volume v of Foz do Areia hydro plant.

In this scenario, the output generation ρ of the analyzed hydro plant undergoes variability during the simulation with the "Curva Colina Conjunta" (C.C.C.), while maintaining the optimized generation characteristic during the simulations. The evolution of the specific productivity of the hydro plants of the Foz do Areia hydro unit is represented in Figure 4, comparing to the average specific productivity considered in NEWAVE [10].

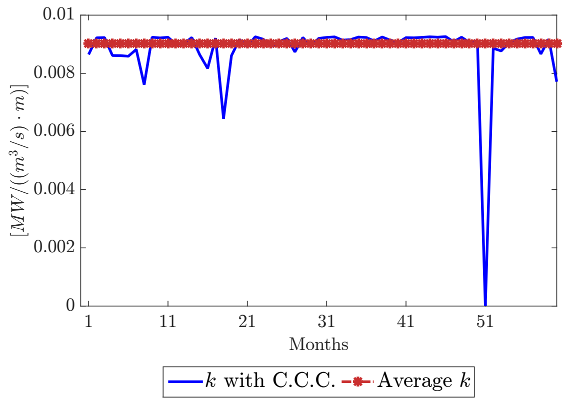

Figure 4. Specific productivity k of Foz do Areia hydro plant.

Although the specific productivity are around the average for a large part of the horizon in Figure 4, the specific productivity considering the "Curva Colina Conjunta" is efficient since it demonstrates, mainly in the low inflows period, that the productivity of the hydro plants falls due to operating in regions that would be harmful to the turbines of the plant, thus generating lower values of efficiency in order to avoid any damages to the machines.

Figure 4 shows the specific productivity k of the Foz do Areia hydro plant obtained by the simulation with a "Curva Colina Conjunta": in the period 51, k is zero, which in theory means that the operating condition of the Foz do Areia hydro unit is harmful to the turbine equipment. In practice, specifically this event does not have such justification, as this null value of efficiency is explained due to the non-convexity of the "Curva Colina Conjunta" of Foz do Areia [6]. The variability of specific productivity in this hydro unit reflects in the difference obtained in the hydraulic generation of the plants, even if this deviation occurs around the average specific productivity.

6 Conclusions

In the proposed methodology, the main characteristics of the Brazilian electricity sector were respected, where the hydro and thermoelectric plants were considered individualized, both in the optimization planning of the operation adopted and in the simulation tool. In addition, in the simulation tool the constant of nonlinearities in the energy production equations were considered explicitly. The numerical experiments to validate the simulator methodology were performed in a test system that has the essence of the Brazilian system, which the results were discussed from the point of view of the system planner. The case study of the simulation with the energy *deficit* planning scenarios show the maintenance of the optimal characteristics of the variables, but adjusting them to the reality of the plant operation. Although most of the operational aspects of the hydro and thermal plants was implemented, there are some others that can be considered for futures works. Even so, the results presented here are considered coherent and promising.

Acknowledgements

This work has been developed by the Lynx Energy Research Group within the R&D project PD-6491-0307/2013 proposed by Copel Geração e Transmissão S.A., under the auspices of the R&D Programme of Agência Nacional de Energia Elétrica (ANEEL).

References

[1] Fortunato, L. A. M., Araripe Neto, T. A., Albuquerque, J. C. R., & Pereira, M. V. F., 1990. *Introdução ao planejamento da expansão e operação de sistemas de produção de energia elétrica*. Universidade Federal Fluminense, EDUFF, Niterói.

[2] Maceira, M. E. P., Terry, L. A., Costa, F. S., Damázio, J. M., & Melo, A. C. G., 2002. Chain of optimization models for setting the energy dispatch and spot price in the brazilian system. In *Proceedings of the Power System Computation Conference-PSCC*, volume 2, pp. 24–28.

[3] Periçaro, G. A., Karas, E. W., Gonzaga, C. C., Marcílio, D. C., Oening, A. P., Matioli, L. C., Detzel, D. H., de Geus, K., & Bessa, M. R., 2019. Optimal non-anticipative scenarios for nonlinear hydro-thermal power systems. *Applied Mathematics and Computation*, pp. 124820.

[4] ONS, 2004. Evaporações líquidas nas usinas hidroelétricas.

[5] Cicogna, M. A., 1999. Modelo de planejamento da operação energética de sistemas hidrotérmicos a usinas individualizadas orientado por objetos. Master's thesis, Universidade Estadual de Campinas.

[6] Vallejos, C. A. V., Detzel, D. H. M., Mainardes, S. C., Marcilio, D. C., Oening, A. P., Bessa, M. R., Mine, M. R. M., Bloot, M. L., Carneiro, C. D. B., & Estrócio, J. P. F., 2012. Modelagem da eficiência de turbinas hidráulicas para o planejamento da operação em médio-longo prazo. In *Anais do VIII Congresso Brasileiro de Planejamento Energético*, Curitiba, Brazil.

[7] Bello, T. L., Matioli, L. C., Oening, A. P., & Marcilio, D. C., 2017. Desenvolvimento de um simulador de despacho de usinas hidroelétricas. In *Anais do II Simpósio de Métodos Numéricos em Engenharia*, Curitiba, Brazil.

[8] Bello, T. L., 2019. Simulador da operação a médio prazo para o sistema hidrotérmico brasileiro. Master's thesis, Universidade Federal do Paraná.

[9] Detzel, D. H. M., Mine, M. R. M., Bessa, M., & Bloot, M., 2014. Cenários sintéticos de vazões para grandes sistemas hídricos através de modelos contemporâneos e amostragem. *RBRH: Revista Brasileira de Recursos Hídricos*, vol. 19, n. 1, pp. 17–28.

[10] CEPEL, 2013. Manual de referência do programa newave.