Optimization of the operation of Dokan hydropower development using Cuckoo Search Algorithm

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Abstract. In this paper one of the recently developed metaheuristic algorithms, the Cuckoo Search algorithm is used for the optimization of the operation of a large hydropower plant in Kurdistan, Iraq. The optimization problem is to realize an annual planned energy generation with monthly imposed fractions. The obtained results are excellent, nevertheless, there are some limitations of the algorithm determined by the initial level into the reservoir and a certain correlation between the type of the year, the starting level and the planned energy to be realized.

1. Introduction

The hydropower development (HPD) operation can be considered as an optimization problem that allows the achievement of the set objective by complying with a set of imposed restrictions [1]. The concept of “HPD management” or “operation” can refer to the following aspects:

- HPD size (one or more hydropower plants – HPPs);
- considered time horizon (online, daily schedule, medium or long term);
- hydrological conditions (known or probabilistic);
- concrete objective pursued (financial, technical, environmental, a combination of possibly contradictory requirements);
- internal (technological, maintenance) or external (legislative, market, etc.) restrictions.

According to the definition given by U.S. Bureau of Reclamation, the purpose of the hydropower management issue is related to the “selection of hydropower units and their loading so as to cover the demand for production and system services, using a minimum quantity of water for turbines” [2].

Regarding the optimization of the production of a single turbine, the aim is only to determine the used flow and not to cover a demand for services imposed for a given level in the reservoir. This leads to realize the maximum amount of energy from the turbined unit of water volume, to operate with optimal overall efficiency.

If the optimal operation of a HPP is analyzed, with all available units, the aim is to detect the configuration of units and their degree of load to cover the demand for services from HPP, with a minimum consumption of water from the reservoir.

An optimization problem involves defining a performance function, \( f(\mathbf{x}) \), depending on the vector \( \mathbf{x} = x_1, x_2, \ldots, x_d \) of unknowns (decision variables). This function can be maximized or minimized, in the presence of equations that describe the functioning of the physical system considered and of various constraints, relationships in which the components of the vector \( \mathbf{x} \) also appear. The solution of the
optimization problem consists in finding the vector that satisfies the performance function, in accordance with the system equations and respecting all the imposed restrictions [3].

In the last period there have been many stochastic algorithms classified into heuristic and metaheuristic [4]. The heuristics algorithms are of the “tests and corrections” type, based mainly on the analyst’s experience and the time available to find a satisfactory solution (not optimal guaranteed), by generating different solutions that explore the search space on its global scale, while metaheuristic algorithms (of higher level) have increased efficiency, due to the two characteristics: diversification and intensification, and by local search in the approach of better solutions. This leads to a multitude of convenient suboptimal solutions, with a much more limited search effort.

The most powerful metaheuristic algorithms are inspired by processes in the surrounding world and among them are evolutionary algorithms, which are algorithms that operate with populations of solutions. This, practically, began with the definition and use of genetic algorithms, between 1960 and 1970 (J. Holland, University of Michigan) and first papers related to it [5-7].

Other type of problems, than optimization of the operation related to hydropower, that can be addressed using optimization algorithms are:

- some studies can go, for example, from the determination of the impact of environmental flow on some small hydropower plants (SHPs) production [8], to the impact of climate change and distributions of precipitation on hydropower production for a large country [9];
- use of dedicated software for assess the possibility to model the attachment of a HPP to existing dams [10], or presenting innovative concepts applied to recent hydropower projects [11];
- analysis of past energy production for determination of hydropower share in total energy generation [12], or of different statistical parameters [13,14], or prediction of share of hydropower in total energy generation [15];
- assessment of hydropower potential [16], or of pumped storage plants potential at a country level [17], or of hidden hydro related to empowering non-powered dams at a country level [18].

Related to optimization of the operation of HPDs, complex problems where the as the optimization of the electricity production of a HPP powered from a multiple use reservoir [19], or estimation of performance of a complex HPD with more reservoirs and associated HPs and a pumped storage plant (PSP) [20] or the optimization of such complex HPDs [21], can be successfully addressed, where classical operational research methods can no longer face the complexity of the problem to be solved.

In this paper, the Cuckoo Search Algorithm (CSA) defined first time in 2009 [22] is applied for a large HPD from Iraq, Dokan, for the optimization of the operation of the related HPP.

2. Cuckoo search algorithm
To understand how the CSA was formulated, the following are some aspects that were Yang’s source of inspiration in [22]. CSA is based on the parasitic reproductive behavior of some cuckoo species.

In fact, females of these species lay their eggs in the nests of other host species, having the ability to produce eggs similar in shape and color to those of the host, and even choosing the time of their laying (with shorter hatching time) - immediately after the parasitized bird.

If the host identifies eggs, either remove the foreign eggs from the nest, or leave it permanently and build another one. Otherwise, when the cuckoo's chick hatches first - it has the reflex to throw the host's eggs out of the nest, and if there are “stepbrothers” next to it - it adapts its chicks to theirs - to be favored for feeding by “adoptive parents”.

This improved behavior of cuckoos in nature ensured the perpetuation of those species and suggested the schematization of CSA according to the following idealized rules:

- each cuckoo produces one egg at a time and lays it in a randomly selected nest;
- the nests with the most valuable eggs (solutions) are transferred to the next generations (iterations);
the number of available nests is fixed, but a host can discover the foreign egg with a probability, \( p_a \in [0; 1] \), in which case the host bird may either remove the egg from the nest or abandon it to build a completely new one in another location [22].

For simplification, the third rule can be approximated by a fraction, \( p_a \), of those, \( n \) nests that can be replaced with new ones (containing new random solutions). The quality or adjustment of a solution in a maximization problem can be admitted as proportional to the objective function.

The basic equation of CSA by which a solution (cuckoo), \( i \), is transferred from the current generation, \( t \), to the next, \( t+1 \), is:

\[
x_i^{t+1} = x_i^t + \alpha \cdot L,
\]

where the second term in the right part corresponds to a random “flight” of the Lévy type, \( \alpha \) is a parameter in the range \([0…1]\). This is a special type of distribution, with infinite average and variance, and the generation of implementation steps is done with Mantegna algorithm, [23], according to which:

\[
s = \frac{u}{|u|^{1/\beta}},
\]

where \( u \) and \( v \) are normally distributed random numbers and \( \beta \) a parameter in the range \([1…2]\).

The CSA provides that the fraction \( p_a \) of the total positions reached by equation (1) can be replaced by completely new solutions, randomly generated from the allowed domains for variables, avoiding convergence to local optima. As iterations are in progress, the initial solutions (nests) improve their content and tend towards the overall optimum of the problem.

3. Case study
For materializing this study performed as related to the long-term optimization of a HPD, considering the probabilistic nature of the inflows, it was chosen one of the most important hydropower developments in Iraq, on Little Zab river, Dokan HPD, presented in figure 1.

Figure 1. Hydropower development Dokan.

Dokan development project has been initiated by the Council for Reconstruction and the General Directorate for Irrigation from the Ministry of Agriculture, at the end of years 1930. In year 1940, a British institute of consultancy has proposed to be realized a reservoir on Little Zab river; the institute also proposed several potential sites for dam location.

Although the project also foreseen the energetic use, the performance of a hydropower plant has been started only in 1975, the last of the 5 units being started for tests on 20th of November 1979. Equipment
and installation have been carried out by the Technoprom company from USSR, but the construction part has been performed by a Yugoslavian company.

It results from the above mentioned that the completion of the whole project took 25 years and involved the participation of specialists from at least 5 countries of the world.

Under the design stage, the objectives for the project performance, were:

- protection against floods;
- use of water for irrigation;
- electric energy generation;
- pisciculture development;
- providing of favorable conditions for recreation.

The hydropower potential is turned to account through a hydropower plant, having an installed capacity of 400 MW in 5 identical units and generating, after commissioning, about 950 GWh/year.

Hydropower plant is built at the dam toe, being equipped with 5 Francis similar turbine with vertical axis, of 80 MW capacity, at net head of over 82 m and a flow rate between 95 and 111 m$^3$/s. The plant operates at a net head range between 60 and 95 m, with flow between 50 and 111 m$^3$/s. Maximum efficiency is achieved at heads over 77 m and flows over 90 m$^3$/s.

Within the initial project and upon the dam performance, in the dam body there were provided 4 penstocks for the HPP and one for irrigation. Subsequently it was assigned to the fifth unit, being constructively like the other ones. Each penstock has a diameter of 3.65 m and the maximum flow of 111 m$^3$/s. Access to the turbine is controlled by means of a butterfly valve weighing 76 t. The main housing is made of steel, with the spiral angle at over 350 degrees. The turbine runner has 16 blades, a diameter of 3.3 m and rated speed of 200 rot/min. Draft tube is also made of steel with a diameter increasing gradually from 3.3 m.

The turbined flow is discharged into a stilling basin provided at the downstream end with a sharp-crested spillway, over which the water is returned to the riverbed.

Dokan dam is a concrete arch dam, with a maximum height of 116.5 m and a crest length of 360 m. The base elevation is 399.5 masl, and the crest elevation is 516 masl. The upstream face is vertically built, and the thickness at main section varies according to third-degree equation, between 8.35 m at the crest and about 44 m at the base.

Though of rather low dimensions (height, crest length), Dokan dam achieves a huge reservoir, with a maximum level, under normal conditions, at elevation 511 masl and a minimum operating level at elevation 480 m masl, respectively. It is noticed that at elevation 511 masl the volume of water into the reservoir is of about 7 billion m$^3$.

At the elevation corresponding to the minimum operating level, 480 masl, the volume of water into the reservoir is still 1.45 billion m$^3$ and the surface exceeds 72.3 km$^2$. It results a live storage of about 5.4 billion m$^3$ achieved on a level difference of only 31 m.

The dead storage capacity is of 700 million m$^3$ and is situated under elevation 469 masl, where the water surface reaches 48 km$^2$.

Water supply for irrigation was the main objective upon the project drawing up and three tunnels were first carried out, with a total discharge of over 300 m$^3$/s. After the HPP construction, only a part of this arrangement remained as distinct work.

This supply system consists in a bank intake, a gallery that goes around the dam body and where two steel pipes of 2.28 m diameter and of about 160 m length each. The maximum flow likely to be conveyed is of 110 m$^3$/s. Each tunnel is provided with 3 safety and control valves, one at the upstream end and two at the downstream end. The water taken over from the reservoir is returned to the riverbed downstream of the stilling basin of the HPP, at an elevation of about 415 masl.

To apply CSA, the following were considered:

- capacity curve that was approximated with interpolation function “spline”;
specific energy production through \( e(z_k) = 0.002107(z_k - 416) \), in [GWh/million m\(^3\)], where the coefficient of the right part is obtained considering the overall efficiency 77%, \( z \) represents free water level surface and 416 masl is the downstream level;

the annual energy production from the project phase was admitted at \( E_p = 950 \) GWh/year, with the monthly productions imposed, \( E_k^* \), \( k = 1, 12 \) and the average monthly multiannual inflows into the reservoir \( Q_{in,k} \) (m\(^3\)/s), as in table 1;

stored volumes at the end of each month \( k \) were limited: lower at \( V_{\text{min}} \) and upper at \( V_{\text{max}} \), respectively, so that there is a reserve of water in the reservoir for the dry months and the possibility of flood control for the wet months (at the values in table 1);

we also considered the driest year, and the wettest year, data presented in table 1: monthly inflows in Dokan reservoir, \( Q_d \) and \( Q_w \), and monthly imposed energy generations in Dokan HPP, \( E_d \) and \( E_w \), for driest year and wettest year, respectively.

Assuming that the initial volume, \( V_0 \), is known in the reservoir at the beginning of the year, the aim was to find the final monthly volumes in the reservoir \( x_k \), so that monthly energy production, \( E_k \), be as close as possible to those required, \( E_k^* \), if all the monthly effluent stock is processed.

The steps in CSA are: generation of new solutions keeping the current optimal solution, evaluation of new solutions, identification of weakest solutions and randomly replacing it, evaluation of new set of solutions and finding the optimal solution for each generation.

The performance function was chosen as:

\[
\min \left\{ f(x) = \sum_{k=1}^{12} (E_k - E_k^*)^2 \right\},
\]

where the energy generation is:

\[
E_k = e(z_k) \cdot D_k,
\]

with \( z_k = (x_{k-1}, x_k) \) the average monthly reservoir level and \( D_k(x_{k-1}, x_k) \) monthly stock for HPP operation:

\[
D_k = x_{k-1} - x_k + V_{\text{in},k},
\]

where \( x_0 = V_0 \) for the first month, when \( k = 1 \).

| 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 |
|----|----|----|----|----|----|----|----|----|----|----|----|
| \( V_{\text{min}} \) [mil.\( m^3 \)] | 1350 | 926 | 892 | 834 | 1159 | 1381 | 1932 | 2251 | 2302 | 2176 | 1978 | 1781 |
| \( V_{\text{max}} \) [mil.\( m^3 \)] | 4300 | 3789 | 3303 | 4127 | 4940 | 5624 | 6737 | 7135 | 7043 | 6695 | 5816 | 4832 |
| \( Q_{in} \) [m\(^3\)/s] | 67 | 123 | 195 | 217 | 321 | 471 | 497 | 304 | 135 | 75 | 56 | 54 |
| \( \alpha_k \) [-] | 0.1 | 0.1 | 0.09 | 0.09 | 0.08 | 0.07 | 0.07 | 0.06 | 0.07 | 0.08 | 0.09 | 0.1 |
| \( E_k^* \) [GWh] | 95.05 | 85.5 | 80.75 | 76 | 66.5 | 66.5 | 66.5 | 66.5 | 71.25 | 85.5 | 95 | 95 |
| \( E_m \) [GWh] | 83.05 | 61.64 | 62.01 | 55.06 | 47.18 | 47.17 | 37.46 | 53.71 | 76.56 | 118.89 | 150.18 | 116.25 |
| \( Q_d \) [m\(^3\)/s] | 16 | 23 | 39 | 108 | 125 | 146 | 162 | 88 | 31 | 16 | 12 | 13 |
| \( E_d \) [GWh] | 19.43 | 18.59 | 21.06 | 20.45 | 18.33 | 17.8 | 17.58 | 23.23 | 25.01 | 31.08 | 37.75 | 30.55 |
| \( Q_w \) [m\(^3\)/s] | 73 | 112 | 618 | 400 | 554 | 1510 | 814 | 515 | 256 | 162 | 84 | 91 |
| \( E_w \) [GWh] | 134.4 | 83.87 | 72.16 | 55.9 | 76.88 | 63.95 | 103.07 | 105.22 | 168.79 | 232.75 | 249.27 | 236.71 |

4. Results and discussions

To begin with, it was verified if CSA obtains the required energy of 950 GWh (the one from the project phase) for the mean hydrological year. The monthly values for the energy produced in HPP were calculated using monthly fractions, \( \alpha, E_k^* = \alpha_k \cdot E_p \), presented in table 1.

For verification, 10 runs were performed, and the results obtained can be seen in figure 2, a), with the variation of the volume in the reservoir at the end of each month. For these 10 runs were considered: \( E_p = 950 \) GWh, \( Q_{in} \) (from table 1) and the level at the beginning of the year was set up at 495 masl (correspond to the center of gravity of the reservoir as it split the live storage into two equal parts).
It can be observed that annual energy generation vary between 949.794 GWh/year (achieved after 896 generations) and 950.253 GWh/year (after 951 generations). For the graphical representation of realized energy generation, were chosen results from the 7th run, because of the smallest difference between the planned and realized energy generation. In this case, after 948 generations, energy generation was 950.023 GWh/year, the relative error being 0.0024%. Also, it can be observed that the planned energy and produced energy are very close, figure 2, b).

**Figure 2.** a) CSA results for 10 runs for the mean hydrological year, b) planned and produced energy.

There were computations for monthly energy generation for mean hydrological year for three different water levels, respectively known volumes at the beginning of the study period, namely: $Z_{01} = 480 \text{ masl}$, the minimum operating level (mOL), an intermediate level, $Z_{02} = 495 \text{ masl}$ and $Z_{03} = 500 \text{ masl}$, the maximum operating level (MOL). The obtained results are presented in figure 3.

**Figure 3.** Results for the mean hydrological year, for three imposed levels.

It can be easily observed that for the intermediate level planned energy is achieved month by month. Starting with the mOL, only in first month it was not possible to achieve the planned energy as it was no available water in the reservoir. Starting with the MOL, due to upper limitations of volumes into the reservoir, produced energy is larger than the planned one as it was compulsory to turbine more water than for realizing the imposed energy.

The results of the computations for the driest and for the wettest years are presented in figure 4 and figure 5.
For the driest year, planned energy can be realized starting with the intermediate level; very close starting with mOL and exceeded for the first 3 months and realized for the rest starting with MOL.

For the wettest year, planned energy can be realized in all alternatives of starting level for the last four months. Excepting the alternative of starting with mOL where energy generation in first month was well below and in the second month close to the planned energy, for first eight months, energy production was greater than the planned energy and relatively close one from the other.

5. Conclusions

Many papers demonstrates that metaheuristic algorithms can be successfully used for the optimization of the operation of HPDs. In this paper, CSA was used at an impressive HPD, for realizing a planned annual energy generation, month by month.

There were 10 computations for an intermediate level in the reservoir for the mean hydrological year and the obtained results were excellent. Then, for three levels at the beginning of the year, there were computations for the mean hydrological year, for the driest and for the wettest year. Concluding the discussion from the previous section: all volumes variations respected the imposed min and max limits and the planned monthly energy was realized excepting the situations when starting from the MOL it was compulsory to turbine more than for realizing the planned energy (first three months for the driest year) and the situations when the inflows correspond to the wettest year when for energy production was larger than the planned one, excepting last four months where it was equal for all starting level alternatives.

The overall conclusion of the paper is that, for the optimization of the operation of a HPD defined in terms of realizing a planned energy generation with monthly imposed fraction, CSA gives good results.

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