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Research Article

Metaheuristic Approaches for Hydropower System Scheduling

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This paper deals with the short-term scheduling problem of hydropower systems. The objective is to meet the daily energy demand in an economic and safe way. The individuality of the generating units and the nonlinearity of their efficiency curves are taken into account. The mathematical model is formulated as a dynamic, mixed integer, nonlinear, nonconvex, combinatorial, and multiobjective optimization problem. We propose two solution methods using metaheuristic approaches. They combine Genetic Algorithm with Strength Pareto Evolutionary Algorithm and Ant Colony Optimization. Both approaches are divided into two phases. In the first one, to maximize the plant's net generation, the problem is solved for each hour of the day (static dispatch). In the second phase, to minimize the units' switching on-off, the day is considered as a whole (dynamic dispatch). The proposed methodology is applied to two Brazilian hydroelectric plants, in cascade, that belong to the national interconnected system. The nondominated solutions from both approaches are presented. All of them meet demand respecting the physical, electrical, and hydraulic constraints.

1. Introduction

Brazilian power generation system is predominantly hydroelectric. The operation planning/scheduling of this system is divided into three stages: long-term, medium-term, and short-term. In the long-term the horizon is up to five years with monthly time-step. In this stage, the plants are grouped by subsystems. In the medium-term the horizon is up to one year with monthly or weekly time-step. In this stage, the plants are treated individually. In the short-term the horizon is up to two weeks with hourly time-step. In this stage the generating units (GUs) of the plants are considered and the physical, electrical, and hydraulic aspects are taken into account.

Within the short-term stage is made the optimal dynamic dispatch (ODD) of the GUs, which is the focus of this paper. It consists of determining, for each hour of the day, which units should be operating and their generating level. The objective is to meet energy demand, optimally utilizing the available water resources and reducing the maintenance costs of the GUs.

Two equations are important for the ODD of the GUs: the hydraulic balance and production function, Hidalgo et al. [1]. The hydraulic balance determines the reservoir's final volume from the initial volume, water inflow, and water outflow. The production function relates the plant's generation with the turbines efficiency, generators efficiency, net head, and water discharged.

The optimal use of the available water resources is related to plant's efficient operation. Yi et al. [2] propose to maximize the system efficiency, Arce et al. [3] aim to minimize the power generation losses, Finardi and Scuzziato [4] suggest minimizing the total water released, and Catalão et al. [5] propose to maximize the value of the stored water in the reservoir.

The maintenance cost of the GUs is affected, among other things, by the number of startups and shutdowns during the operation. Each switching on-off of a unit is estimated to reduce its useful life by about 10 to 15 hours, Nilsson et al. [6]. Borghetti et al. [7] define a cost for the switching on-off of GUs. Chang et al. [8] propose a penalty for each of the status changes of the units. Chancelier and Renaud [9] determine a minimum time required between the startup and shutdown of the GUs.

As shown, in general, the ODD problem has two main objectives: to increase the net generation of the plant and reduce the number of times that status of the GUs is changed. System constraints related to this problem include meeting the load demand and respecting the physical, electrical, and hydraulic constraints. It has discrete variables for the selection of GUs and continuous variables for the loading dispatch of each online GU. The production function of a hydroelectric plant and the efficiency curves of the units are nonlinear. The ODD problem is usually nonconvex. The combinatorial nature of the problem makes it more complex.

Artificial Intelligence techniques have been applied to solve similar problems to ODD. Santos and Ohishi [10] apply Genetic Algorithm (GA) and Lagrangian Relaxation (LR) to three Brazilian hydroelectric systems. Muller [11] employs GA and Sequential Quadratic Programming (SQP) for the Unit Commitment (UC) problem in order to minimize losses in power generation. Colnago [12] employs GAs to solve the problem. Naresh and Sharma [13] present a model based on Artificial Neural Networks (ANNs) for hydrosystem scheduling. Huang [14] proposes an optimization approach based on Ant Colony System (ACS) to enhancement of hydroelectric generation scheduling. Villasanti et al. [15] employ Multi-Objective Evolutionary Algorithms (MOEAs) to dispatch hydroelectric generating units. Musirin et al. [16] apply Ant Colony Optimization (ACO) technique to solve the economic power dispatch problem with cost minimization as objective function. Columbus et al. [17] propose the Nodal Ant Colony Optimization (NACO) technique to solve the UC problem with profit maximization as objective function. Mo et al. [18] present a hybrid algorithm based on Multi-Ant Colony System (MACS) and Adaptive Differential Evolution (ADE) for solving the short-term hydrogeneration scheduling problem.

This paper presents a comparison of two metaheuristic approaches developed to solve the ODD problem of GUs. They are based on GA, Strength Pareto Evolutionary Algorithm (SPEA), and ACO. GA is used to create and diversify the solutions' search space. SPEA is employed to select the solutions that approach Pareto Frontier. ACO is applied to explore the search space using the experience accumulated by ants.

2. Objects of Study

The objects of study of this research are two Brazilian hydroelectric plants that operate in cascade: Jupiá (*Engenheiro Souza Dias*) and Porto Primavera (*Engenheiro Sérgio Motta*). According to the company that manages the operation of these plants, their head can be considered constant, during the day, and equal to 20 m. Figure 1 shows the operation schematic diagram of these plants. They are located at Paraná River.

Jupiá is a run-of-river plant, with 1,551 MW of installed power and 14 GUs. The first 12 units of Jupiá plant are connected to the 440 kV busbar and the last 2 units are connected to the 138 kV busbar. Its dam is 5,495 m long and its reservoir is 330 km^2.

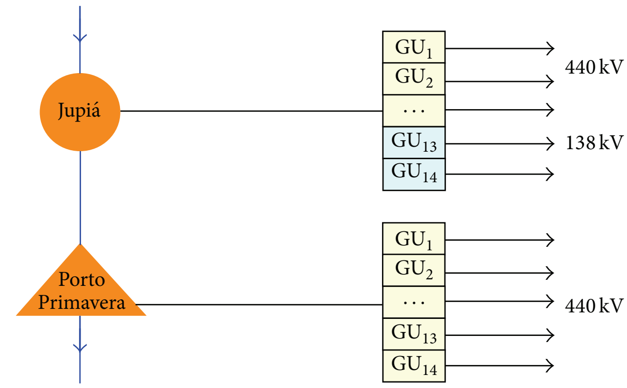

Figure 1: Diagram of the objects of study: Jupiá and Porto Primavera hydroelectric plants.

Porto Primavera has a small capacity of storage, 618 hm^3. For this reason, it is operated as a run-of-river plant. Porto Primavera plant has 1,540 MW of installed power and also 14 GUs. All of them are connected to the 440 kV busbar. Its dam, the largest in Brazil, is 10,186.20 m long and its reservoir is 2,250 km^2.

For Jupiá plant, the range of operating limits of GUs 1, 3, 5, 6, 7, 8, 9, 11, 12, and 14 is 25–110.8 MW; GU 2 range is 40–110.8 MW; GU 4 can only operate 100 MW. GUs 10 and 13 range is 50–100 MW. For Porto Primavera plant, all GUs have the same operating limits: the lower is 30 MW and the upper is 110 MW.

The characteristic curves of the GUs are represented by a fourth degree polynomial. They relate efficiency and power for head = 20 m. Table 1 shows the coefficients for Jupiá's GUs. Table 2 displays the coefficients for Porto Primavera's GUs.

3. Mathematical Formulation

3.1. Objective Functions. The proposed optimization model consists of two conflicting objectives. They are (1) maximizing the total net generation of the plant and (2) minimizing the number of times that the status of the GUs is changed. Jupiá and Porto Primavera are individually optimized, since they are operated as run-of-river plants:

$$\begin{gathered}\text{Max} \sum_{t=1}^{24}\sum_{u=1}^{U} g_u^t \eta_u^t\left(h_p, g_u^t\right),\\ \text{Min} \sum_{t=1}^{24}\sum_{u=1}^{U}\left|y_u^{t+1}-y_u^t\right|,\end{gathered} \tag{1}$$

where t = index of the time period; u = index of the GU; U = total number of GUs; g_u^t = generation of the unit u, in the time period t (MW); η_u^t = efficiency of the unit u, in the time period t; h_p = net head of the plant; and y_u^t = binary variable that indicates whether the unit u is active in the time period t (1 = active, 0 = inactive).

Table 1: Coefficients of the fourth degree polynomial of each GU, Jupiá plant.

GU	a_4	a_3	a_2	a_1	a_0
01	$-8.22E-008$	$5.549E-005$	$-1.24E-002$	$1.03E+000$	$6.45E+001$
02	$5.33E-007$	$-1.14E-004$	$4.19E-003$	$3.74E-001$	$7.31E+001$
03	$4.37E-007$	$-7.60E-005$	$-2.87E-004$	$5.47E-001$	$7.21E+001$
04	$-4.92E-007$	$1.31E-004$	$-177E-002$	$1.24E+000$	$5.99E+001$
05	$8.12E-007$	$-1.93E-004$	$1.21E-002$	$3.53E-002$	$7.82E+001$
06	$3.08E-008$	$3.93E-005$	$-1.22E-002$	$1.08E+000$	$6.32E+001$
07	$3.124E-007$	$-5.12E-005$	$-2.38E-003$	$6.71E-001$	$6.82E+001$
08	$7.79E-008$	$3.04E-005$	$-1.18E-002$	$1.08E+000$	$6.30E+001$
09	$3.62E-007$	$-5.58E-005$	$-2.24E-003$	$6.27E-001$	$7.10E+001$
10	$7.58E-008$	$-4.47E-005$	$1.59E-003$	$3.66E-001$	$7.34E+001$
11	$3.70E-007$	$-5.96E-005$	$-1.70E-003$	$5.98E-001$	$7.14E+001$
12	$7.96E-007$	$-1.88E-004$	$1.16E-002$	$6.08E-002$	$7.78E+001$
13	$-6.03E-007$	$1.58E-004$	$-2.00E-002$	$1.33E+000$	$5.82E+001$
14	$3.53E-007$	$-5.17E-005$	$-2.81E-003$	$6.62E-001$	$7.01E+001$

Table 2: Coefficients of the fourth degree polynomial of each GU, Porto Primavera plant.

GU	a_4	a_3	a_2	a_1	a_0
01	$8.97E-007$	$-3.17E-004$	$3.44E-002$	$-1.31E+000$	$1.05E+002$
02	$-7.80E-007$	$1.41E-004$	$-1.05E-002$	$5.53E-001$	$7.74E+001$
03	$1.60E-006$	$-4.85E-004$	$4.82E-002$	$-1.77E+000$	$1.10E+002$
04	$6.74E-007$	$-1.58E-004$	$1.02E-002$	$-2.71E-002$	$8.43E+001$
05	$-9.19E-007$	$1.72E-004$	$-1.26E-002$	$5.88E-001$	$7.78E+001$
06	$7.99E-007$	$-2.20E-004$	$1.93E-002$	$-5.39E-001$	$9.39E+001$
07	$-3.00E-007$	$2.96E-005$	$-1.496E-003$	$2.49E-001$	$8.11E+001$
08	$1.11E-006$	$-3.02E-004$	$2.64E-002$	$-7.67E-001$	$9.52E+001$
09	$-3.93E-007$	$5.42E-005$	$-4.08E-003$	$3.81E-001$	$7.83E+001$
10	$7.47E-007$	$-2.05E-004$	$1.78E-002$	$-4.75E-001$	$9.29E+001$
11	$1.03E-006$	$-2.69E-004$	$2.27E-002$	$-6.31E-001$	$9.49E+001$
12	$1.22E-006$	$-3.37E-004$	$3.04E-002$	$-9.57E-001$	$9.82E+001$
13	$-5.56E-007$	$9.59E-005$	$-7.78E-003$	$5.11E-001$	$7.69E+001$
14	$-1.91E-006$	$4.67E-004$	$-4.49E-002$	$2.14E+000$	$4.95E+001$

3.2. Constraints. The optimization is subject to the following set of constraints, for each time period. Inequality (2) is the demand constraint by busbar, which states that the power generated must meet the specified load demand. According to (3), the sum of the water discharge of the units is equal to the total water discharge of the plant. Since the plants are run-of-river, the water inflow must be equal to the water outflow, water discharge plus water spillage (4). Inequalities (5) and (6) specify the lower and upper bounds of net generation, respectively:

$$\sum_{u=1}^{U} g_u^t \eta_u^t \left(h_p, g_u^t\right) \geq \mathrm{Dem}^t, \tag{2}$$

$$\sum_{u=1}^{U} d_u^t = D^t, \tag{3}$$

$$I^t = D^t + S^t, \tag{4}$$

$$g_u^t \eta_u^t \left(h_p, g_u^t\right) \leq (\min)\, g_u^t \eta_u^t \left(h_p, g_u^t\right), \tag{5}$$

$$g_u^t \eta_u^t \left(h_p, g_u^t\right) \leq (\max)\, g_u^t \eta_u^t \left(h_p, g_u^t\right), \tag{6}$$

where Dem^t = demand of the plant, in the time period t (MW); d_u^t = water discharge of the unit u, in the time period t (m^3/s); D^t = water discharge of the plant, in the time period t (m^3/s); I_p^t = water inflow of the plant, in the time period t (m^3/s); and S^t = water spillage of the plant, in the time period t (m^3/s).

3.3. Variables. The integer and continuous variables of the model are represented in integrity constraints (7) and (8), respectively. The integer variables are used for the selection of GUs and the continuous variables are employed for the loading dispatch of the selected GUs:

$$y_u^t \in \{0, 1\}, \tag{7}$$

$$g_u^t \in R. \tag{8}$$

Table 3: Solution strategy (GA + SPEA) and (GA + ACO).

Approach 1	Approach 2		Objective(s)	Dispatch
GA + SPEA	GA + ACO	Phase 1	Max plant's generation	Static (for each hour)
		Phase 2	Max plant's generation Min GUs' on/off	Dynamic (for all day)

Table 4: Parameters of the algorithms: GA, SPEA, and ACO.

GA		GA + SPEA		ACO	
Selection	Roulette	Selection	Elitism	α	2
Crossover	One point	Crossover	One point	β	5
Cross rate	0.9	Cross. rate	0.9	Pheromone	0.0001
Mutation	Inversion	Mutation	Inversion	Evap. rate	0.5
Mut. rate	0.1	Mut. rate	0.1	Ants	2000
Individuals	100	Individuals	100	Iterations	50
Iterations	50	Iterations	50	—	—
—	—	Ext. archive	40	—	—

4. Methodology

We propose two solution strategies using metaheuristic approaches. The first one combines GA, Holland [19], with SPEA, Zitzler et al. [20]. The second approach relates GA with ACO, Dorigo and Stüzle [21]. Table 3 shows the main characteristics of these approaches.

Both approaches are divided into two phases. In Phase 1, to maximize the plant's net generation using GA, the problem is solved for each hour of the day (static dispatch). The resulting population consists of a set of individuals containing dispatch solutions for each hour of the day. These solutions are randomly combined to compose the individuals of the initial population for Phase 2.

For the first approach, Phase 2 employs SPEA. In our problem, this multiobjective algorithm searches a tradeoff between maximizing the plant's net generation and minimizing the GUs' switching on-off. The day is considered as a whole (dynamic dispatch). As a result the algorithm saves the nondominated solutions in an external archive.

For the second approach, ACO is used in Phase 2. Ants exploit the search space based on accumulated experience by them. In this approach, the dynamic dispatch is solved as a minimal cost path problem. The main objective in this phase is to minimize the GUs' switching on-off using a state transition rule. The first objective function is also taken into account since the search space consists of suboptimal solutions from Phase 1. Trade-off curve is employed to deal with both objective functions simultaneously.

5. Case Studies

The parameters used for GA, SPEA, and ACO, chosen according to literature, are shown in Table 4. In this table, α = relative importance of pheromone trail and β = relative importance of heuristic function.

We conduct case studies to the days 02/11/2012 and 01/16/2013 (chosen by the company that holds the concession of the plants), for Jupiá and Porto Primavera plants, using GA + SPEA and GA + ACO approaches. In the total there are eight case studies grouped in Frames I, II, III, and IV.

For all studies, the net generations at least meet demand; the physical, electrical, and hydraulic constraints are satisfied. Tables 5 and 6 show the results for the studies of 02/11/2012 and 01/16/2013, respectively. For each day, plant, and approach two variables are presented: number (#) of GUs' switching on-off and plant's total net generation (MW).

The better results have lower number of GUs' switching on-off and higher plant's total net generation. It is possible to compare the results just focusing on the first line (highlighted) of these tables.

In Frame I, the better results are presented by GA + SPEA, in relation to the number of startups and shutdowns of the GUs (2) and net generation of the plant (32,512.59 MW). In Frame II, although both strategies avoid GU's on-off in a perfect way (0), GA + SPEA exhibits better net generation values (33,774.55 MW). In Frame III, GA + SPEA yields higher plant's net generation value (31,949.96 MW), whereas GA + ACO yields lower number of startups and shutdowns (5). In Frame IV, again both strategies avoid GU's on-off in a perfect way (0), but GA + SPEA exhibits better net generation values (36,426.65 MW).

6. Summary and Conclusions

This paper presents metaheuristic approaches to optimize the dynamic dispatch of hydropower systems. The mathematical model consists of two conflicting objectives. It is formulated as a dynamic, mixed integer, nonlinear, nonconvex, and combinatorial optimization problem.

The solution strategies that employ GA, SPEA, and ACO consist of two phases. The first one solves the static problem for each hour of the day, in order to maximize the total net generation of the plant. The second phase is concerned with the linking hour-by-hour of the statics solutions throughout the day, setting the dynamic dispatch. Its objectives are to

Table 5: Results from the case study of day 02/11/2012.

Solution	Jupiá (Frame I)				Porto Primavera (Frame II)			
	GA + SPEA		GA + ACO		GA + SPEA		GA + ACO	
	# on-off	Generation (MW)	# on-off	Generation (MW)	# on-off	Generation (MW)	# on-off	Generation (MW)
1	**2**	**32,512.59**	**2**	**31,770.43**	**0**	**33,774.55**	**0**	**32,168.20**
2	3	32,626.50	3	32,247.92	2	33,777.07	2	32,219.96
3	4	32,970.51	5	32,324.27	—	—	4	33,313.23
4	5	32,976.89	—	—	—	—	—	—

Table 6: Results from the case study of day 01/16/2013.

Solution	Jupiá (Frame III)				Porto Primavera (Frame IV)			
	GA + SPEA		GA + ACO		GA + SPEA		GA + ACO	
	# on-off	Generation (MW)	# on-off	Generation (MW)	# on-off	Generation (MW)	# on-off	Generation (MW)
1	**10**	**31,949.96**	**5**	**30,212.20**	**0**	**36,426.65**	**0**	**35,147.76**
2	12	31,978.13	6	30,463.18	—	—	2	35,187.10
3	14	31,986.00	9	30,528.50	—	—		—
4	—	—	10	30,819.07				

maximize the total net generation of the plant and to reduce the number of startups and shutdowns of the units.

The proposed approaches are applied to two hydroelectric plants that operate in cascade: Jupiá and Porto Primavera plants. Eight case studies are carried out for two days of these two plants, comparing GA + SPEA and GA + ACO strategies.

For the case studies of this research, on the whole, GA + SPEA approach shows better results for both objectives functions of the problem. This can be seen in Frames I, II, and IV where the higher net generation values and lower number of startups and shutdowns are in GA + SPEA column. Besides, in general, GA + SPEA presents better result in terms of plant's net generation and GA + ACO exhibits better performance in relation to GU's switching on-off, as shown in Frame III. That probably occurs because, in Phase 2, SPEA deals with both objectives of the problem in a simultaneous way, since it is a multiobjective algorithm, whereas ACO focuses on the second objective, minimizing GU's on-off, although the first objective is also taken into account in a preemptive way.

In conclusion, both solution strategies, GA + SPEA and GA + ACO, are good alternatives to solve the optimal dynamic dispatch in the short-term operation of hydroelectric plants. As future work, the authors propose to run the models several times to collect an expressive number of case studies. The goal will be to apply statistical analyses in a bigger sample to compare the models in a more accurate way.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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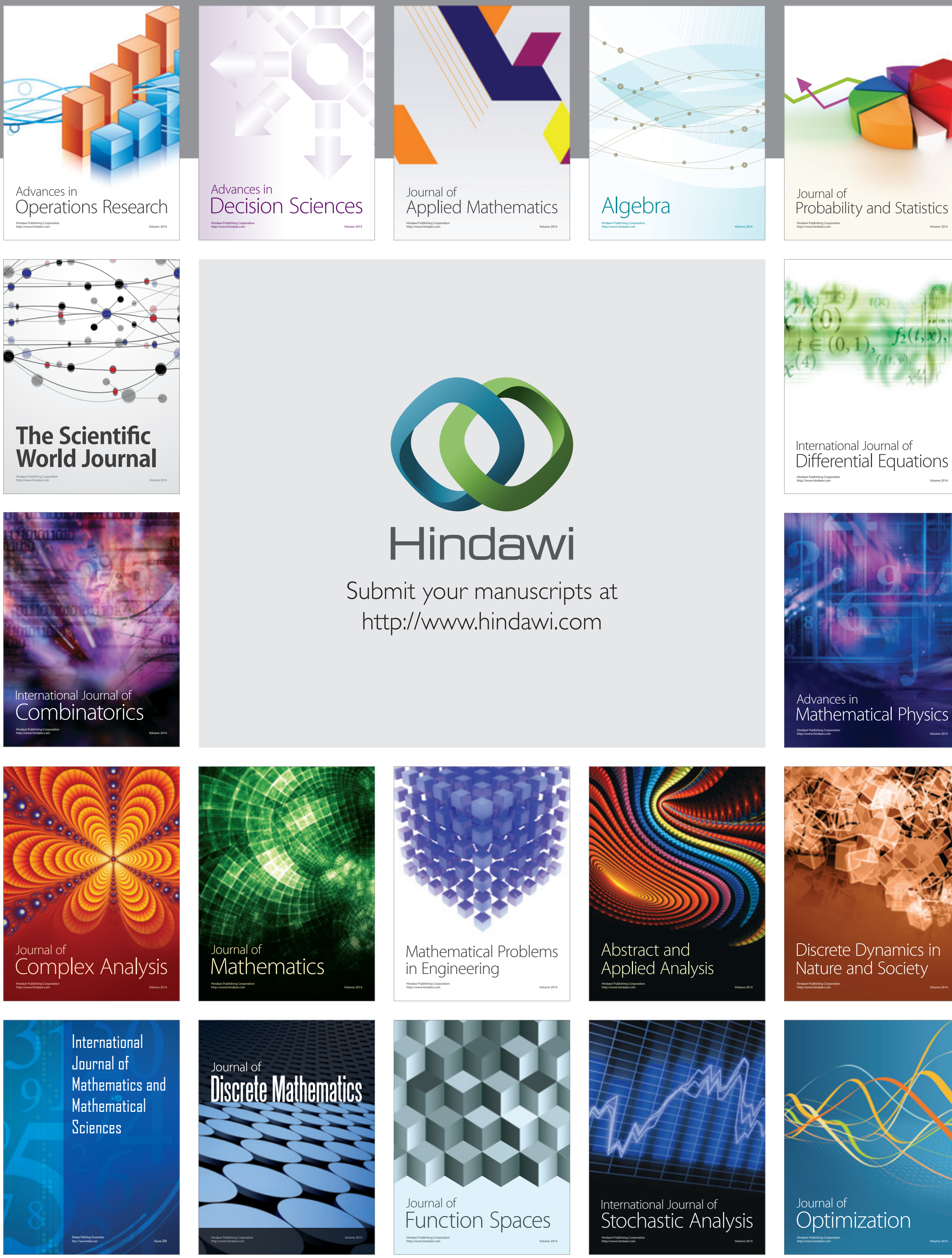
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