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Research Article

Progressive IRP Models for Power Resources Including EPP

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In the view of optimizing regional power supply and demand, the paper makes effective planning scheduling of supply and demand side resources including energy efficiency power plant (EPP), to achieve the target of benefit, cost, and environmental constraints. In order to highlight the characteristics of different supply and demand resources in economic, environmental, and carbon constraints, three planning models with progressive constraints are constructed. Results of three models by the same example show that the best solutions to different models are different. The planning model including EPP has obvious advantages considering pollutant and carbon emission constraints, which confirms the advantages of low cost and emissions of EPP. The construction of progressive IRP models for power resources considering EPP has a certain reference value for guiding the planning and layout of EPP within other power resources and achieving cost and environmental objectives.

1. Introduction

Energy efficiency power plant (EPP) is a kind of "virtual power plants"; it points to the reduction of power consumption by a series of energy-saving measures in a region, so as to achieve the same aim of construction and expansion of entity power plant. Energy efficiency is a hot research topic in the field of energy [1–3]; as shown in the name, energy efficiency is the label of EPP; implementing EPP greatly contributes to the improvement of energy efficiency [4]. State Grid Energy Research Institute of China estimates that the generation capacity of EPP is 640.7 billion KWh in China of 2011–2015, and that of 2016–2020 is 1.3254 trillion KWh. It can reach 1.9661 trillion KWh during the "twelfth five-year" and "thirteenth five-year" period, equivalent to a reduction of 22,598 KWh in generation capacity and nearly 400 billion yuan in investment compared with the conventional power plants [5].

Compared with entity power plants, EPP has no extra occupation of land and no consumption of resources such as coal, which has great social benefits and economic benefits. Compared with dispersed demand side management measures, EPP has large scale, low cost of financing, and remarkable power-saving effect, which makes it easier to be incorporated in the electric power integrated resource planning (IRP). IRP takes demand as well as supply resources into planning content and makes synchronous optimization of supply and demand resources [6, 7]. The combination of IRP and DSM radically changed simply relying on the power construction to meet the power demand growth in the traditional thinking mode. At present scholars mainly focus on IRP for traditional power sector [8]. Pagnarith and Limmeechokchai [9, 10] include the IRP concept into the long-term power planning of GMS countries. Although in recent years researches develop from the traditional sector to smart grid [11] and microgrid [12], most literatures mainly discuss framework, implementation, and significance of IRP; some literatures focus on one or two aspects of demand forecast, the demand side, supply side analysis, and the resources optimization. However, integrated resource planning model, the objective function, and constraint conditions of modeling and quantification, especially how to include EPP into the planning model, all these problems need further research and improvement.

Progressive planning is to set up multiple planning models, add next planning constraints on the basis of a constraint condition, and at last adjust objective function of the programming model. Comparing the results of the progressive planning model, the advantages and disadvantages of different power supply and demand side resources are more highlighted. Given that most literatures create a single objective function and constraint for IRP model, no progressive constraints of planning model are established. This paper intends to establish progressive planning models combining EPP and other power supply and demand side resources and discuss the calculation results of different resources under different programming models. This work can guide the layout of EPP and other power supply and demand side resources, achieve coordinated regional supply and demand side resources optimization, and finally reduce the cost of economic and environmental protection because of energy conservation and emission reduction.

2. Progressive IRP Models Construction for Power Resources Including EPP

2.1. Model 1-IRP Model Only Considering Generated Output Constraints

2.1.1. The Objective Function. The objective function of "IRP model only considering generated output constraint" is to minimize resources cost of the planning stage. Total resource costs include the system capacity cost and system operation cost. The function is shown as follows:

$$C = \min\left[f_{npv}(c_1) + f_{npv}(c_2)\right]$$
$$c_1 = \sum_{i=1}^{n}\left(C_{ci}X_{is}, r, s\right) \tag{1}$$
$$c_2 = \sum_{j=1}^{J}\left(\sum_{i=1}^{I}\left(C_{Oi}P_{ijs}\cdot T_j, r, s\right)\right).$$

In formula (1), C is the total cost of planning period, $f(c)$ is the resource cost considering discount rate, r is discount rate, c_1 is system capacity cost, c_2 is system operation cost, and i is the ith power resource. $i = 1, 2, \ldots n, \ldots, I$; n is the number of new resources of planning period; s is the subperiod of planning period. $s = 1, 2, \ldots, S$; j is the time interval of subperiod. $j = 1, 2, \ldots, J$; T_j is the time span between periods $j-1$ and j; X_{is} is the maximum capacity of new resource i, unit: kW, the decision variable; C_{ci} is the average capacity cost of new resource i, unit: yuan/kW; C_{Oi} is the average power generation cost of electricity generated resource i, unit: yuan/(kW·h); P_{ijs} is the power output of power resource in time interval j of subperiod s, unit: kW, the decision variable.

2.1.2. The Constraints. "IRP model only considering generated output constraint" needs to consider the following constraints [13]:

(1) Load Demand Constraint. Power output of electricity generated resource must satisfy power load prediction of each time interval in the planning period.

$$\sum_{i=1}^{I}P_{ijs} \geq D_{js}. \tag{2}$$

In formula (2), D_{js} is the maximum power load forecast in time interval j of subperiod s, unit: kW.

(2) Electricity Demand Constraint. Generating capacity of electricity generated resource must satisfy electricity consumption in time interval j of subperiod s.

$$\sum_{i=1}^{I}P_{ijs}T_i \geq Q_{js}. \tag{3}$$

In formula (3), Q_{js} is the maximum power consumption forecast in time interval j of subperiod s, unit: kW·h, mW·h.

(3) The Reliability Constraint. This article uses the spare capacity as the reliability index of the whole system. System reserve capacity must achieve a certain proportion of maximum load demand to guarantee the power system reliability:

$$\sum_{i=1}^{n}X_{is} + \sum_{i=n+1}^{I}G_i = (1+R)\,D_s. \tag{4}$$

In formula (4), R is the system spare capacity coefficient, D_s is the maximum electricity demand of subperiod, unit: kW, and G_i is the installed capacity of existing resource i.

(4) Resource Operation Constraints. Resource capacity cannot exceed its rated capacity; namely, the resource generated output contribution cannot exceed its rated capacity:

$$P_{ijs} \leq X_{is}, \quad i = 1, 2, \ldots, n$$
$$P_{ijs} \leq G_i, \quad i = n+1,\ n+2, \ldots, I. \tag{5}$$

Resource power contribution cannot exceed its equivalent electricity; namely, resource generating contribution cannot exceed amount of equivalent electricity:

$$\sum_{j=1}^{J}P_{ijs} \leq n_{oi}JX_{is}, \quad i = 1, 2, \ldots, n$$
$$\sum_{j=1}^{J}P_{ijs} \leq n_{oi}JG_i, \quad i = n+1,\ n+2, \ldots, I. \tag{6}$$

n_{oi} is the equivalent availability factor of resource i.

(5) The Conventional Power Plant Size Constraint. Due to the limitation of technology, capital, and policy factors, in the short term a large scale of capacity cannot be installed, so annual installed size of all kinds of conventional power plants cannot exceed a certain limit, namely,

$$X_{is} \leq X_{is}^{\max}. \tag{7}$$

$X_{is}^{\max}$ is the biggest installed capacity limit of conventional power plant i in planning period s.

(6) EPP Size Constraint. Due to the limitation of energy conservation potential, annual installed size of EPP cannot exceed a certain limit, namely,

$$X_{is} \leq a_{is}L_{is}. \tag{8}$$

a_{is} is the energy-saving potential coefficient of EPP i in planning period s; $X_{is}{}^{\max}$ is the electric power load forecast value of electrical equipment i in planning period s.

2.2. Model 2-IRP Model Considering Generated Output Constraints and Environmental Constraints

2.2.1. The Objective Function. The objective function of "IRP model considering generated output constraints and environmental constraints" is to minimize resources cost of the planning stage. Total resource costs include the system capacity cost, system operation cost, and pollutant discharge cost. The function is shown as follows:

$$
\begin{aligned}
C &= \min\left[f_{npv}(c_1) + f_{npv}(c_2) + f_{npv}(c_3)\right] \\
c_1 &= \sum_{i=1}^{n} \left(C_{ci} X_{is}, r, s\right) \\
c_2 &= \sum_{j=1}^{J} \left(\sum_{i=1}^{I} \left(C_{Oi} P_{ijs} \cdot T_j, r, s\right)\right) \\
c_3 &= \sum_{j=1}^{J} \sum_{i=1}^{I} \sum_{k=1}^{m} \left(C_{Eik} P_{ijs} \cdot T_j \cdot \theta_{Eik}, r, s\right).
\end{aligned} \tag{9}
$$

In formula (9), c_3 is the pollutant discharge cost, k is the kth pollutant, $k = 1, 2, \ldots, m, \theta_{Eik}$ is the kth pollutant discharge coefficient of resource i, unit: kg/(kW·h), and C_{Eik} is the kth pollutant discharge cost of resource i, unit: yuan/(kW·h). Other parameter interpretations are the same with formula (1).

2.2.2. The Constraints. "IRP model considering generated output constraints and environmental constraints" firstly should meet the constraints of "IRP model only considering generated output constraint"; in addition, the model still needs to meet annual pollutant emission constraint [14]; consider the following.

The pollutants emission of planning period should not exceed emission ceiling A allowed by laws, regulations, and standards:

$$
\sum_{j=1}^{J} \sum_{i=1}^{I} \sum_{k=1}^{m} \left(P_{ijs} \cdot T_j \cdot \theta_{ik}\right) \le A. \tag{10}
$$

Specifically during the planning period annual coal, oil, and natural gas emissions of sulfur dioxide and nitrogen oxides should not exceed allowed emission ceiling:

$$
\begin{aligned}
&\sum_{j=1}^{J} \sum_{i=1}^{I} \left(P_{ijs} \cdot T_j \cdot \theta_i^{\mathrm{SO}_2}\right) \le A^{\mathrm{SO}_2} \\
&\sum_{j=1}^{J} \sum_{i=1}^{I} \left(P_{ijs} \cdot T_j \cdot \theta_i^{\mathrm{NO}_x}\right) \le A^{\mathrm{NO}_x}.
\end{aligned} \tag{11}
$$

2.3. Model 3-IRP Model Considering Generated Output Constraints, Environmental Constraints, and Low Carbon Constraints

2.3.1. The Objective Function. The objective function of "IRP model considering generated output constraints, environmental constraints, and low carbon constraints" is to minimize resources cost of the planning stage. Total resource costs include the system capacity cost, system operation cost, pollutant discharge cost, and carbon emission cost. The function is shown as follows:

$$
\begin{aligned}
C &= \min\left[f_{npv}(c_1) + f_{npv}(c_2) + f_{npv}(c_3) + f_{npv}(c_4)\right] \\
c_1 &= \sum_{i=1}^{n} \left(C_{ci} X_{is}, r, s\right) \\
c_2 &= \sum_{j=1}^{J} \left(\sum_{i=1}^{I} \left(C_{Oi} P_{ijs} \cdot T_j, r, s\right)\right) \\
c_3 &= \sum_{j=1}^{J} \sum_{i=1}^{I} \sum_{k=1}^{m} \left(C_{Eik} P_{ijs} \cdot T_j \cdot \theta_{Eik}, r, s\right) \\
c_4 &= \sum_{j=1}^{J} \left(\sum_{i=1}^{I} \left(C_{Ti} P_{ijs} \cdot T_j \cdot \theta_{Ti}, r, s\right)\right).
\end{aligned} \tag{12}
$$

In formula (12), c_4 is the carbon emission cost, θ_{Ti} is the carbon emission coefficient of resource i, unit: kg/(kW·h), and C_{Ti} is the carbon emission cost of resource i, unit: yuan/(kW·h). Other parameter interpretations are the same with formulas (1) and (2).

2.3.2. The Constraints. "IRP model considering generated output constraints, environmental constraints, and low carbon constraints" firstly should meet the constraints of "IRP model considering generated output constraints and environmental constraints"; in addition, the model still needs to meet annual carbon emission constraint [15]; consider the following.

The carbon emission of planning period should not exceed emission ceiling B allowed by laws, regulations, and standards:

$$
\sum_{j=1}^{J} \left(\sum_{i=1}^{I} \left(P_{ijs} \cdot T_j \cdot \theta_{Ci}\right)\right) \le B. \tag{13}
$$

3. The Example Analysis

3.1. Data Source and Assumptions. To verify the validity of models, we used the above three different programming models and GAMS software to plan supply and demand side resource in certain planning period and then compared calculation results and put forward the related conclusions. Assuming that planning period is divided into four subplanning periods, each subplanning period includes six time intervals. Table 1 shows electric power demand forecasting data every plan year in planning period.

Table 1: Load forecast in each planning level year.

Plan year	Load forecast of different time intervals/MV					
	1	2	3	4	5	6
0	2231	2415	2357	2674	2254	2247
1	2758	2632	2686	3043	2438	2746
2	3272	3054	3117	3786	3017	3321
3	4052	3867	3947	4471	3583	4034

Table 2: Resource parameters in each planning level year.

	Resource type	Resource ID	Capacity/MV	Amount	Unit operation cost yuan/kWh	Unit initial investment yuan/kWh	Equivalent available coefficient
Existing resources	Coal-fired unit	1	520	1	0.129	0	0.75
	Coal-fired unit	2	160	2	0.154	0	0.83
	Coal-fired unit	3	100	2	0.149	0	0.73
	Gas turbine	4	280	2	0.122	0	0.77
	Gas turbine	5	100	2	0.14	0	0.84
	Fuel-fired unit	6	300	2	0.125	0	0.78
	Fuel-fired unit	7	100	2	0.134	0	0.83
New resources	Coal-fired unit	A	300	4	0.135	4010	0.75
	Coal-fired unit	B	150	5	0.137	4500	0.75
	Gas turbine	C	150	4	0.17	3200	0.75
	Fuel-fired unit	D	150	4	0.14	3600	0.75
	Wind power	E	100	3	0.4	6400	0.3
	EPP1	F	50	1	0.005	1500	0.19
	EPP2	G	30	1	0.004	2670	0.9
	EPP3	H	50	2	0.004	2700	0.4
	EPP4	I	100	2	0.004	4000	0.7
	EPP5	J	50	1	0.005	2000	0.5

Data source: Hebei Province Development and Reform Commission (NDRC), DSM Center in Hebei Province (URL: http://www.hbdsm.com/html/dlyxkb/).

Table 2 shows relevant data of existing resources and new resources. Among them, EPP1 is packed by air conditioner load and water heater load; EPP2 is packaged by power-saving technology aiming at raising household refrigerator energy efficiency; EPP3 is packaged by power-saving technology aiming at raising household air-conditioning energy efficiency; EPP4 is packaged by upgrading energy intensive transformer and promoting efficient transformer; EPP5 is constituted by promoting efficient motor technology.

To mainly highlight the difference of EPP with conventional power generation resources, this article regards the same type of resources with the same emission factor. Table 3 shows the emission factor parameters of various resources during the planning period.

Set system backup rate $R = 20\%$, and the discount rate $r = 10\%$; the number ceiling of the new resources is shown in Table 2, total capacity of all the launch of new resources is up to 4000 MW, in planning stage, CO_2 emission is up to 70 million t, SO_2 emission is up to 500000 t, and NO_x emission is up to 200000 t.

3.2. Calculation Process and Results. Based on the above data, the objective function, decision variables, and constraint number of three different optimization models with different constraint conditions are shown in Table 4.

Using mixed integer programming solver BDMLP of GAMS to solve the model, the production order of new resources and the output of all resources each time in planning period are gotten; thus generating capacity, new unit capacity, the initial investment, operating cost, and pollutant emission data of optimal decision under the three models are calculated.

Table 5 shows resource production number of the best solution under the three models.

Table 6 shows relevant parameters of calculated results of the best solution under the three models.

3.3. Results Analysis. (1) As shown in Figure 1, from the point of unit operating quantity, types and quantities of installed units under three models are quite different. "Model 1" has the biggest quantities of installed coal-fired units

Table 3: Emission factors for various resources.

Resource type	CO_2 emission factor (g/kW·h)	SO_2 emission factor (g/kW·h)	NO_x emission factor (g/kW·h)
Coal-fired unit	980.1	5.577	2.562
Gas turbine	498.8	0.045	0.747
Fuel-fired unit	731.4	5.283	1.782
Wind power	0	0	0
EPP1	0	0	0
EPP2	0	0	0
EPP3	0	0	0
EPP4	0	0	0
EPP5	0	0	0

Data source: Energy Statistics Yearbook 2015 of Hebei Province.

Table 4: Parameters volume of three models.

Model	Objective function	Decision variables	Constraint number
Model 1-IRP model only considering generated output constraints	1	231	332
Model 2-IRP model considering generated output constraints and environmental constraints	1	321	441
Model 3-IRP model considering generated output constraints, environmental constraints, and low carbon constraints	1	386	487

Table 5: Result of plants' installation for each model.

Planning year	A	B	C	D	E	F	G	H	I	J
Model 1-IRP model only considering generated output constraints										
0	0	1	0	0	0	0	0	0	0	0
1	0	2	0	0	0	0	0	0	0	0
2	1	1	0	1	0	0	0	0	0	0
3	3	0	0	1	0	0	0	0	0	0
Model 2-IRP model considering generated output constraints and environmental constraints										
0	0	0	1	0	0	0	0	0	0	0
1	0	0	1	0	1	0	0	0	0	0
2	0	0	2	0	2	0	0	0	0	0
3	2	0	1	0	3	0	0	0	0	0
Model 3-IRP model considering generated output constraints, environmental constraints, and low carbon constraints										
0	0	0	0	0	0	0	0	1	1	0
1	0	0	0	0	0	1	0	2	0	1
2	0	0	0	0	1	1	1	0	2	1
3	2	0	0	0	2	0	0	1	1	1

Table 6: Result of some parameters for each model.

Models	Average annual output/GWh	New installed electricity capacity/MW	Total cost/billion yuan	Initial investment/billion yuan	Average annual running costs/billion yuan	Average annual SO_2 emission/thousand t	Average annual NO_x emission/thousand t	Average annual CO_2 emission/thousand t
Model 1	15471	2100	5.75	3.12	0.79	48.1	18.9	6734.1
Model 2	13245	2050	5.01	2.77	0.68	20.2	7.2	5628.6
Model 3	10480	1780	4.56	2.26	0.56	15.7	4.2	2623.5

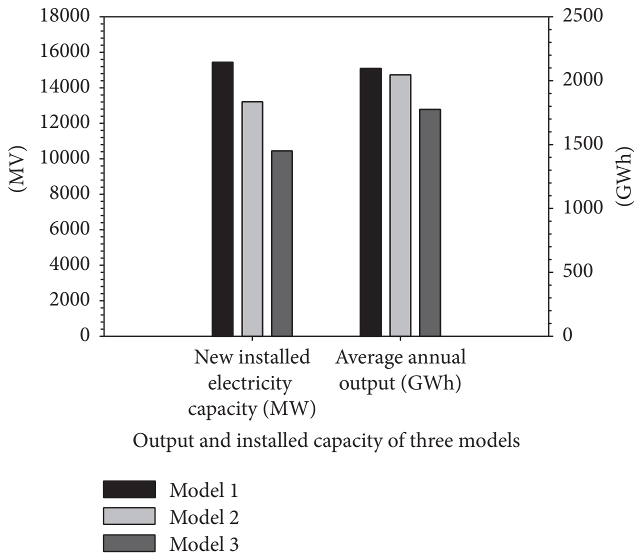

Figure 1: Comparison of output and installed capacity of each model.

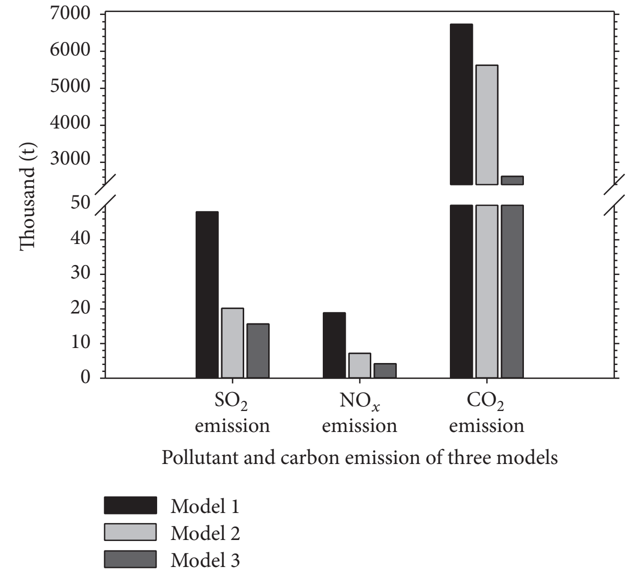

Figure 2: Comparison of pollutant and carbon emission of each model.

and gas turbines, while no wind power unit and EPP are installed, which shows coal-fired units and gas turbines with high power output are the best choice ignoring pollutant emission and carbon emission constraint. In "Model 2," quantity of wind power unit has a certain increase, and coal-fired units (gas turbines) together with wind power units are the optimum allocation, which illustrates the advantage of wind power unit under the environmental restriction; at the same time due to the weakness of the generation output of EPP, EPP is not an option for this kind of situation. In "Model 3," the wind power unit and EPP become the best power configuration, the advantage of zero discharge of EPP reflected considering three kinds of constraints at the same time, and EPPs become the primary choice of this case.

(2) From the perspective of the related parameters of the calculation results, the total cost, average annual power generation, new installed power capacity, total capacity, installation cost, and operation cost decrease progressively of the three models, which illustrates the fact that since constraint conditions are more strict, the installed capacity, power generation, and related costs are gradually reduced. At the same time, pollutant and carbon emission of "Model 3" are significantly reduced compared to the other two models (shown in Figure 2).

(3) From the point of time sequence, as the electricity demand and load gradually increase, weakness of equivalent available coefficient (average used hours) of wind power (hours), as well as the weakness of EPP output, was gradually exposed; at this time it has no option but to enable conventional power generation resources with high power output. Under the condition of high electric power demand, new energy power generation and EPP resources may not be able to meet the demand for electricity.

Above all, considering the combination of meeting the generator output and environmental constraints optimization scheme has better economic and environmental benefits, taking EPP projects into IRP can greatly reduce the installed capacity, cost, pollutant emissions, and carbon emissions.

4. Conclusion

Research purpose of this article is to include EPP in power integrated resource planning, to provide the basis for coordination and optimization of all regional kinds of supply and demand resources and to achieve objectives such as cost and environmental benefits. In order to highlight the advantages of EPP in cost, pollutant emission, and carbon emissions, this paper established three different IPR models including EPP with gradually progressive constraints, namely, "Model 1-IRP model only considering generated output constraints," "Model 2-IRP model considering generated output constraints and environmental constraints," and "Model 3-IRP model considering generated output constraints, environmental constraints, and low carbon constraints," and then designed examples to verify the validity of the models. From the point of the calculation results of the model, including EPP into IRP can significantly lower installed cost, operation cost, and emissions, and "Model 3-IRP model considering generated output constraints, environmental constraints, and low carbon constraints" has the best economic and environmental benefits.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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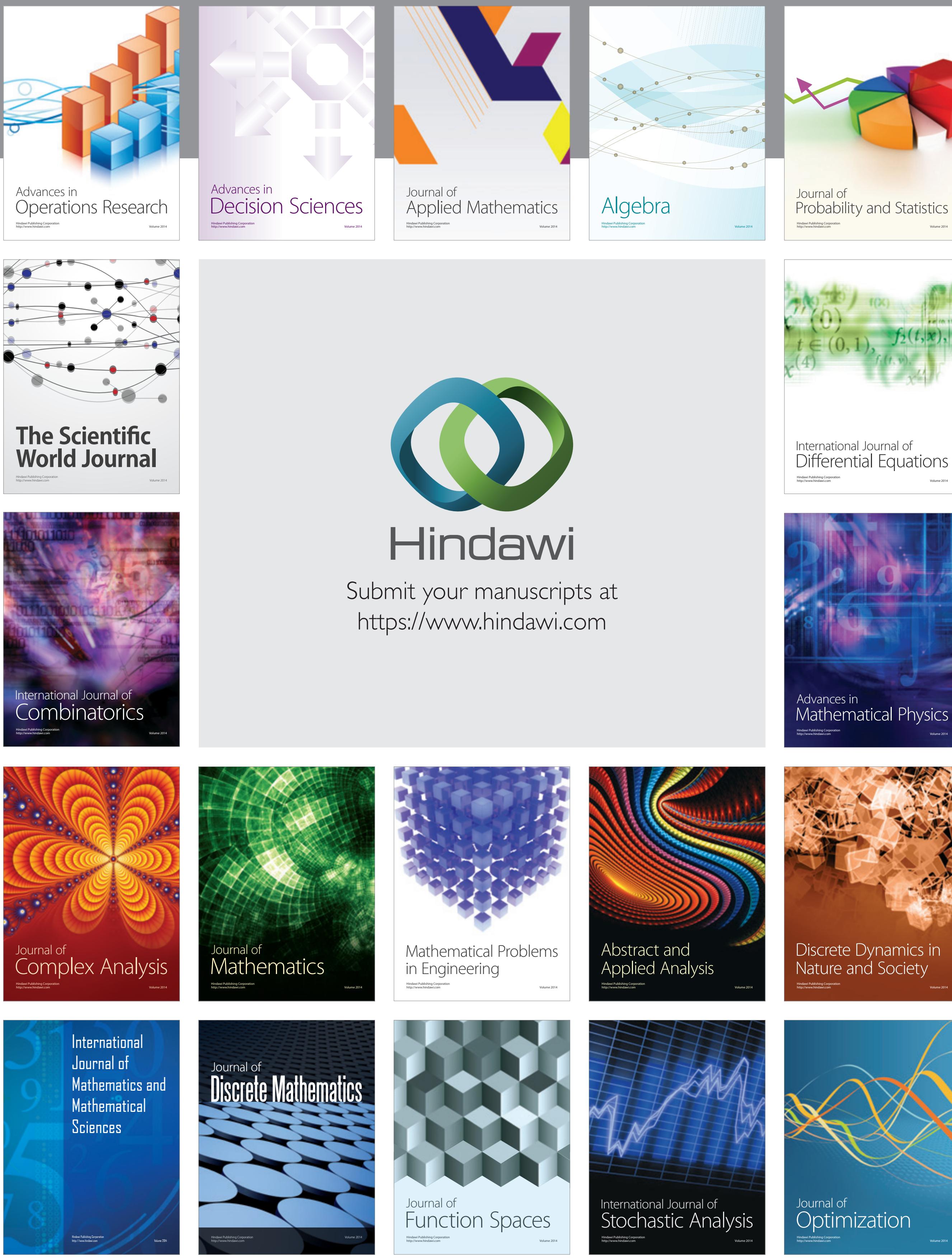
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