Research and Application of Fast and Elitist Non-Dominated Sorting Generic Algorithm in Coal Blending Optimization

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Abstract. In view of coal blending optimization in thermal power plants, a multi-objective coal blending optimization model is proposed. The model uses coal quality indexes as constraint condition to construct three objective functions of economy, environmental protection and safety. The fast and elitist non-dominated sorting generic algorithm is used as the algorithm of solving the model. Combined with actual coal blending problem in domestic thermal power plants, the Pareto solution set is obtained. Results of example show that the algorithm has a good optimization effect and provides effective technical support for actual coal blending technology.

1. Introduction

With the rapid economic development of our country, sustainability of energy is particularly important. As one of the most important energy sources in China's energy structure, coal has occupied a high proportion in the country's energy production in recent years. Aiming at how to use coal resources reasonably and efficiently, coal blending technology is proposed. Coal blending is defined that single coal of different quality and different type are mixed and processed into the mixed coal according to a certain proportion based on user's requirements for coal quality. The mixed coal not only has some characteristics of single coal, but also has new comprehensive performance, and is a new type of coal that meets need of users.

In recent years, research at home and abroad in the field of coal blending has yielded fruitful results. The foreign coal blending technology is mainly to make full use of the blending of medium, low calorific coal and high calorific value coal [1] to ensure low calorific value of coal combustion and to control ash content of coal combustion. The foreign research mainly involves coal blending system and mixing methods of coal blending. In addition, effects of the ignition performance of coal blending, slagging performance on combustion, and the use of blended coal combustion on the emissions of nitrogen dioxide and sulfur dioxide have also been studied. In China, research of coal blending is mainly divided into two directions: (1) Study the blending ratio of mixed coal from the combustion characteristics and coal quality characteristics of the mixed coal; (2) Based on basic research of computer technology, artificial intelligence method is used to solve the best ratio. Jianrong Qiu [2] studied coal fire ignition, stable combustion characteristics, and reduced boiler slagging, fouling, ash accumulation after coal blending, coal calorific value, generation and emission of NOx and SO2. Yongjiang Liu [3] proposed a study on optimizing coal blending in thermal power plants based on the particle swarm algorithm and established a coal blending model with optimization theory, and found that the particle swarm algorithm...
with inertia weight has a strong global search capability. It can quickly and accurately find the optimal proportion of single coal. Junhu Zhou [4] studied the coal blending scheme based on the genetic algorithm, furthermore, he added a penalty function and modified the mutation operator. Dongnan Chen established a coal blending optimization model based on genetic algorithm and exhaustion method, and obtained the optimal solution of coal blending.

In this paper, a multi-objective optimization coal blending model is proposed. The coal quality indexes are used as constraint condition to construct three objective functions of economy, environmental protection and safety. The coal ratio can be calculated by solving the fast and elitist non-dominated sorting generic algorithm.

2. Multi-objective Coal Blending Optimization Model

In this paper, thermal power plants' economic goal, environmental protection goal and security goal are taken as three objectives of coal blending optimization. A multi-objective optimization coal blending model is established. Objective functions and constraint conditions are determined based on three optimization objectives and coal quality indexes. A fast and elitist non-dominated sorting generic algorithm is used to solve the model, and optimal blending ratio and coal blending scheme are finally obtained.

2.1. Objective function

2.1.1. Economic goal. The economic goal of coal blending in this paper mainly consider the cost of burning coal, which is the unit price of coal. Therefore, the expression of economic goal is:

$$\text{min} f_1(x) = \sum_{i=1}^{n} C_i x_i$$

In the above formula, $x_i$ is the blending proportion of the $i$-th coal, $C_i$ is the price of the $i$-th coal, and $n$ is the number of the blended single coal.

2.1.2. Environmental goal. Environmental protection is mainly to control SO$_2$ and NO$_x$ in thermal power plants. At present, NO$_x$ does not contribute much to air pollution because of its low emission. And NO$_x$ is mainly achieved through optimization of combustion adjustment. But SO$_2$ is the main source of air pollution in thermal power plants. Therefore, the expression of the goal of environmental protection is:

$$\text{min} f_2(x) = \sum_{i=1}^{n} S_i x_i$$

In the above formula, $x_i$ is the blending proportion of the $i$-th coal, $S_i$ is the sulfur index value of the $i$-th coal, and $n$ is the number of the blended single coal.

2.1.3. Security goal. Safety is mainly aimed at safety of the boiler combustion process. Safety of the boiler combustion process refers to avoiding accidents during the boiler combustion process, including boiler fire extinguishing, slagging, and pipe bursting. However, in the process of power blending, it is difficult to consider many factors, and the main one is still research on coal quality indexes. The coal quality indexes considered in the safety objectives include: calorific value, volatile matter, ash content, and moisture content. The expression of the security goal is:
minf₃(x) = \frac{Q - Q_d}{Q_d} + \frac{V - V_d}{V_d} + \frac{M - M_d}{M_d} + \frac{A - A_d}{A_d} \tag{3}

In the above formula, \(Q_d, V_d, M_d, \text{ and } A_d\) are calorific value, volatile matter, moisture, and ash of the designed coal, \(Q, V, M\), and \(A\) are the predicting values of the mixed coal.

2.2. Constraint conditions

The blending ratio of single coal is also one of constraint condition. The blending ratio of single coal cannot be greater than one, and the sum of all single coal blending proportions is equal to one. The expression of the constraint condition is:

\[ \sum_{i=1}^{n} x_i = 1 \tag{4} \]

The technical requirements of coal quality indexes in thermal power plants are taken as the basic constraint condition of coal blending. Coal quality indexes include heat \(Q\), moisture \(M\), volatile matter \(V\), sulfur \(S\), and ash \(A\). The constraint condition of coal quality indexes are as follows:

\[ Q_{\min} \leq \sum_{i=1}^{n} Q_i x_i \leq Q_{\max} \tag{5} \]

\[ V_{\min} \leq \sum_{i=1}^{n} V_i x_i \leq V_{\max} \tag{6} \]

\[ M_{\min} \leq \sum_{i=1}^{n} M_i x_i \leq M_{\max} \tag{7} \]

\[ S_{\min} \leq \sum_{i=1}^{n} S_i x_i \leq S_{\max} \tag{8} \]

\[ A_{\min} \leq \sum_{i=1}^{n} A_i x_i \leq A_{\max} \tag{9} \]

In the above formula, the meaning of each variable is shown in Table I.
Table 1. Variable meaning table

| coal quality index | lower limit | upper limit | content of i-th raw material |
|--------------------|-------------|-------------|-----------------------------|
| heat               | $Q_{\text{min}}$ | $Q_{\text{max}}$ | $Q_i$                      |
| volatile matter    | $V_{\text{min}}$ | $V_{\text{max}}$ | $V_i$                      |
| moisture           | $M_{\text{min}}$ | $M_{\text{max}}$ | $M_i$                      |
| sulfur             | $S_{\text{min}}$ | $S_{\text{max}}$ | $S_i$                      |
| ash                | $A_{\text{min}}$ | $A_{\text{max}}$ | $A_i$                      |

3. Multi-objective Coal Blending Optimization Based On Nsga-ii Algorithm

Indian scientist Deb improved NSGA algorithm in 2002 and proposed the fast and elitist non-dominated sorting generic algorithm [5] (NSGA-II). The specific improvements are as follows:

- A fast and non-dominated sorting method was proposed.
- Congestion degree and congestion degree comparison operators were proposed instead of a fitness sharing strategy that requires the sharing radius to be specified.
- Elite strategy was introduced.

3.1. Fast and non-dominated sorting method

The size of population $P$ is setted to $N$, two parameters $n_i$ and $S_i$ are setted in advance for population $P$. Among them, $n_i$ is the number of individuals that dominate individuals in the population, and $S_i$ is the set of individuals that are dominated by individuals in the population [6]. Steps of fast and non-dominated sorting are:

1) For all individuals with $n_i=0$ in the population and save them in the current set $F_1$.
2) For each individual $i$ in the current set $F_1$, the set of individuals $S_i$ dominated by it traverses each individual $l$ in $S_i$, and executes $n_l=n_l-1$. If $n_l=0$, it will be stored in set $H$.
3) Individuals in $F_1$ is the first non-dominating individuals, and use $H$ as the current set. Repeat the above operation until the entire population is stratified.

3.2. Computation of congestion degree and congestion degree comparison operators

Congestion degree refers to density of surrounding individuals of given individuals in the population. Intuitively, it can be expressed as the length of the largest cuboid around the individual $n$ containing only the individual $n$ itself. Congestion degree is represented by $n_d$, and its calculation procedure is as follows:

1) Let $n_d=0$, $n=1$, 2,..., $N$.
2) For each objective function:
   a) Sort the population based on the objective function.
   b) Make congestion degree of two individuals at the border infinite.
   c) Calculate $n_d=n_d+(f_m(i+1)-f_m(i-1))$, $n=2,3,...,N-1$.
3) After fast and non-dominated sorting and calculation of congestion degree, each individual $n$ gets two attributes in the population: non-dominant rank and congestion degree $n_d$. Through these two attributes, the dominated and non-dominated relationships of any two individuals in the population can be distinguished. The definition of congestion degree comparison operator is $\geq n$. The basis for comparison of individual advantages and disadvantages is: $i \geq n_j$, that is, individual $i$ is better than individual $j$, if and only if $i_{\text{rank}}<j_{\text{rank}}$ or $i_{\text{rank}}=j_{\text{rank}}$, and $i_d=j_d$.

The congestion degree is shown in Fig.1.
3.3. Elite strategy

Elite strategy preserves the superior individuals in the father’s generation and directly enters the offspring. It is a necessary condition for the genetic algorithm to converge with a probability of 1. The calculation steps of elite strategy are:

1) Combine all the parents $P_t$ and offspring $Q_t$ into a statistical population $R_t=P_t \cup Q_t$, the number of individuals in $R_t$ is $2N$.

2) The population $R_t$ is sorted by the fast and non-dominated sorting method and the local congestion distance is calculated for each individual. Then select individuals according to grade level. At last a new parent population $P_{t+1}$ is formed until the number of individuals reaches $N$.

3) On this basis, a new round of selection, crossover, and mutation begins to form a new offspring population $Q_{t+1}$.

To sum up, the flow chart of multi-objective coal blending optimization with NSGA-II algorithm is shown in Fig.2.
4. Analysis of Example

According to the above proposed model and algorithm, coal blending is performed in domestic power plants. The coal quality indexes of single coal are shown in Table II.

| No. | \( Q \) Mg/kg | \( M \) % | \( A \) % | \( V \) % | \( S \) % | \( P \) yuan |
|-----|----------------|--------|--------|--------|--------|----------|
| 1   | 15.95          | 0.94   | 43.78  | 22.68  | 2.04   | 539.1    |
| 2   | 23.09          | 0.76   | 24.71  | 17.07  | 0.35   | 623.9    |
| 3   | 20.28          | 0.51   | 32.27  | 22.26  | 2.99   | 515.1    |
| 4   | 18.50          | 1.72   | 38.88  | 13.2   | 0.57   | 506.0    |
| 5   | 18.38          | 2.09   | 36.28  | 12.35  | 0.72   | 487.4    |
| 6   | 20.69          | 1.14   | 30.58  | 16.18  | 0.4    | 638.2    |
| 7   | 21.29          | 0.94   | 28.98  | 17.45  | 1.24   | 734.0    |
| 8   | 16.83          | 2.51   | 41.17  | 10.47  | 0.62   | 506.0    |
| 9   | 16.78          | 1.82   | 33.24  | 35.15  | 3.66   | 405.5    |
| 10  | 16.01          | 0.8    | 44.64  | 33.70  | 2.14   | 575.7    |
| 11  | 21.04          | 2.39   | 29.52  | 9.18   | 0.42   | 493.9    |
| 12  | 18.45          | 3.23   | 33.49  | 14.29  | 1.91   | 519.5    |
| 13  | 15.16          | 2.07   | 47.23  | 19.69  | 1.14   | 409.8    |
| 14  | 17.15          | 4.33   | 34.61  | 42.41  | 1.21   | 595.8    |
| 15  | 16.81          | 3.07   | 36.62  | 13.68  | 1.06   | 579.1    |

Through coal quality indexes of single coal, combined with the model proposed in this paper, a fast and elitist non-dominated sorting generic algorithm is used for solving. MATLAB is used for simulation calculations, distribution of Pareto solutions of initial population of 100 individuals after 500 iterations is shown in Fig.3.

**Figure 3.** Distribution of Pareto solutions.
From the objective function values in Fig. 3, it is not straightforward to see the coal blending scheme for each individual, and it is necessary to “decode” individuals. Fig. 4 shows the decoded partial Pareto solutions.

From the above figure, we can conclude that solution 2 is the best choice when the lowest cost is pursued; solution 1 is the best choice when sulfur content is the lowest; solution 5 is the best when safety of the boiler is best. The Pareto solutions obtained by NSGA-II algorithm is not necessarily optimal, but the solutions can satisfy various requirements, giving coal-mixing personnel certain choice space, and avoiding the extreme solution obtained by the single-objective optimization algorithm.

5. Conclusion
In this paper, a multi-objective coal blending optimization model is studied. With the goal of economy, safety and environmental protection, the fast and elitist non-dominated sorting generic algorithm is used for multi-objective coal blending optimization model. Pareto optimal solutions can be obtained in one run, facilitating coal blending. The personnel choose according to actual needs and achieve multi-objective optimization. In addition, the fast and elitist non-dominated sorting generic algorithm is used to analyze the actual example, and results verify validity and rationality of the algorithm. It shows that the algorithm has more practical application prospects in multi-objective coal blending optimization.

References
[1] Ch. Gone, S.Helle, X. Garcia. Coal blend combustion: fusibility ranking from mineral matter composition, Fuel, vol. 83, pp. 2087 - 2095, 2003.
[2] J. R. Qiu, H. C. Zeng, J. Guo, Comprehensive experimental study on the characteristics of blended coal, Power Engineering, vol. 13, pp. 32 - 36, 1993.
[3] Y. J. Liu, Z. P. Gao, Y. Han, Research on optimal coal blending for thermal power plant based on particle swarm optimization, Boiler Technology, vol. 43, pp. 18 - 24, 2015.
[4] J. H. Zhou, C. J. Ping, J. Z. Liu, Dynamic coal blending model based on genetic algorithm, Chinese Journal of Coal, vol. 28, pp. 547 - 551, 2003.
[5] Deb K, Pratap A, Agarwal S, A fast and elitist multi-objective genetic algorithm: NSGA-II [J], IEEE Transaction on Evolutionary Computation, vol. 6, pp. 182 - 197, 2002.
[6] H Li, Q. F. Zhang, Multi-objective optimization problems with complicated pareto sets, MODE/D and NSGA-II [J], IEEE Transaction on Evolutionary Computation, vol. 13, pp. 284-302, 2009.