

Research Article

Study on Optimization of Coal Truck Flow in Open-Pit Mine

Haiming Bao ¹ and Ruixin Zhang^{1,2}

¹College of Energy and Mining, China University of Mining and Technology, Beijing 100083, China

²North China Institute of Science and Technology, Langfang 065201, China

Correspondence should be addressed to Haiming Bao; 952577029@qq.com

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A semicontinuous process system consisting of a single-bucket excavator, truck, crushing station, and belt conveyor is the main coal mining process system of a large-scale hard coal open-pit mine. Through analyzing the coal mining production process, the key issues of coal mining truck flow optimization are obtained. Statistical method of using triangular fuzzy numbers analyzes the key time parameters of coal mining truck flow. Taking one shift, the minimum expected value of number of trucks, as the objective function, the fuzzy expectation of the coal mining semicontinuous process system is established with the constraints of the truck flow continuity at the loading and unloading point, the production capacity of the electric shovel, the production capacity of the crushing station, coal quality, and coal mining production tasks. The truck flow planning model is solved using particle swarm intelligence algorithm. The simulation results show that the result of truck flow planning can effectively reduce truck number, truck dispatching number, transportation costs, and truck queuing. The fuzzy expected truck flow planning model established by the study is suitable for solving the problem of optimizing and matching the production capacity in the process which links electric shovel, truck, and crushing station. It can effectively improve the production efficiency of electric shovel mining, truck transportation, and crushing station.

1. Introduction

According to statistics, in 2018, there were about 450 open-pit coal mines in China. The production scale of the largest open-pit coal mine was 35 million tons/year, and over 20 large-scale open-pit coal mines' production was over 10 million tons/year. The total capacity of China's surface coal mines is about 950 million tons/year, accounting for about 25% of the total capacity of coal mines. China coal production and open-pit coal production from 2003 to 2018 are shown in Figure 1. The annual stripping and mining amount were about 10 billion tons, and the output of open-pit coal mines has reached the world's first [1].

At present, most of the coal mining processes of medium- and large-scale open-pit coal mines use the semicontinuous process system with a single-bucket excavator, truck, semifixed crushing station, and belt conveyor. This mining process system has gradually become the preferred mining process system for raw coal transportation in

Chinese open-pit coal mines. The specific process of this mining process system is as follows: a single-bucket excavator loads the coal in the stope to the truck to complete the mining and loading operation, and the truck transports coal to the designated semifixed crushing station according to the dispatch instruction to complete the transportation operation. The crushing station crushes the coal and transfers it to the belt conveyor. The coal is eventually transported to the coal preparation plant or loading station. Open-pit mining uses trucks as the main transportation equipment. With the increasing depth and scale of open-pit mining, the transportation distance of mining operations is also increasing. The reasonable transportation distance of truck transportation is generally only between 2 and 4 km. If this distance is exceeded, the cost of truck transportation will rise sharply. In order to reduce transportation costs and improve operating efficiency, open-pit mines choose coal mining semicontinuous process system to achieve coal mining operations. The coal mining semicontinuous process system

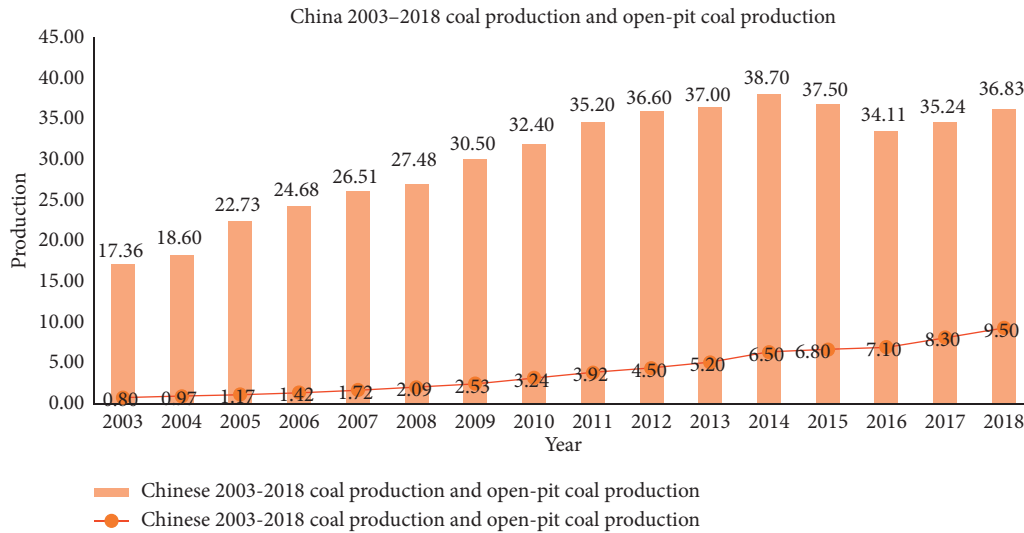


FIGURE 1: China 2003–2018 coal production and open-pit coal production.

has many advantages such as large production capacity, high transportation efficiency, energy saving, and environmental protection [2–4]. About 800 million tons of raw coal is transported through this process system every year. The coal mining semicontinuous process system is matched and coordinated by a single-bucket excavator, truck, crushing station, and belt conveyor to complete open-pit coal mining operations. The system is essentially a serial process, and the cooperation between the pieces of equipment will seriously affect the performance of the system, so it is particularly important to study the optimization of coal mining truck flow in open-pit mines.

2. The Truck Flow Problem of Coal Mining Operations

2.1. Research Status of Truck Scheduling. After more than 30 years of development, China's truck optimization scheduling research has continuously improved the theory system of truck scheduling optimization. The developed and updated truck dispatching system has been put into use in large open-pit mines nationwide and has achieved basic scheduling functions (schematic diagram of dispatching process is shown in Figure 2). However, due to the characteristics of complexity, dynamic randomness, multiobjective, multi-constraint, multivariable, and real-time nature, open-pit mine truck scheduling is a typical NP problem. Therefore, all of the following need further research: selection and optimization of scheduling criteria, selection of calculation parameters and dynamic prediction, data collation and analysis, construction of scheduling decision algorithm, modeling optimization and simulation, improvement of dispatching optimization system, coal blending scheduling management, and process system link matching [5]. Although truck scheduling has a lot of theoretical output in terms of establishing mathematical models, algorithmic solutions, and scheduling criteria, there is still no comprehensive and systematic theoretical system applied and

popularized in mine production. The following truck scheduling theory research should focus on the coordination of theory and production practice and strive to overcome the randomness and complexity of the production process.

In terms of truck scheduling optimization in open-pit mines, there have been relevant studies focusing on the randomness of the scheduling process, using queuing theory and simulation methods to model and analyze the problem. The research of truck-electric shovel process is mainly focused on giving full play to equipment production efficiency. Kappas and Yegulalp assume that the open-pit mining transportation system is a stochastic system with Markov properties. Using the queuing network theory, the steady-state analysis of the open-pit mine “truck-electric shovel” system is realized through system simulation. Temeng et al. have developed an open-pit mine operation optimization model, which can meet the requirements of shovel and truck production matching. It can realize the scheduling arrangement of truck fleets with different loads and require the upper and lower limits of the material grades to be transported to the crushing station. Based on queuing theory, Najor and Hagan tried to analyze the queuing theory model to evaluate the loss of mining capacity caused by the queuing phenomenon of trucks in production, thereby improving the electric shovel-truck scheduling constraint model for large open-pit mines. Aruna et al. comprehensively summarized the application of queuing theory, target planning, system simulation, and operations research in open-pit mine electric shovel-truck process research. Based on the matching factor method, the truck scheduling problem was studied through computer simulation technology. Patterson et al. used the mixed integer linear programming (MILP) method to allocate the energy consumption of trucks and shovels in a way that minimizes the need to meet the target production. The objective function includes four kinds of energy consumption minimization: the energy consumption when the truck is driving, the energy consumption when the shovel is loading the truck, the energy consumption when

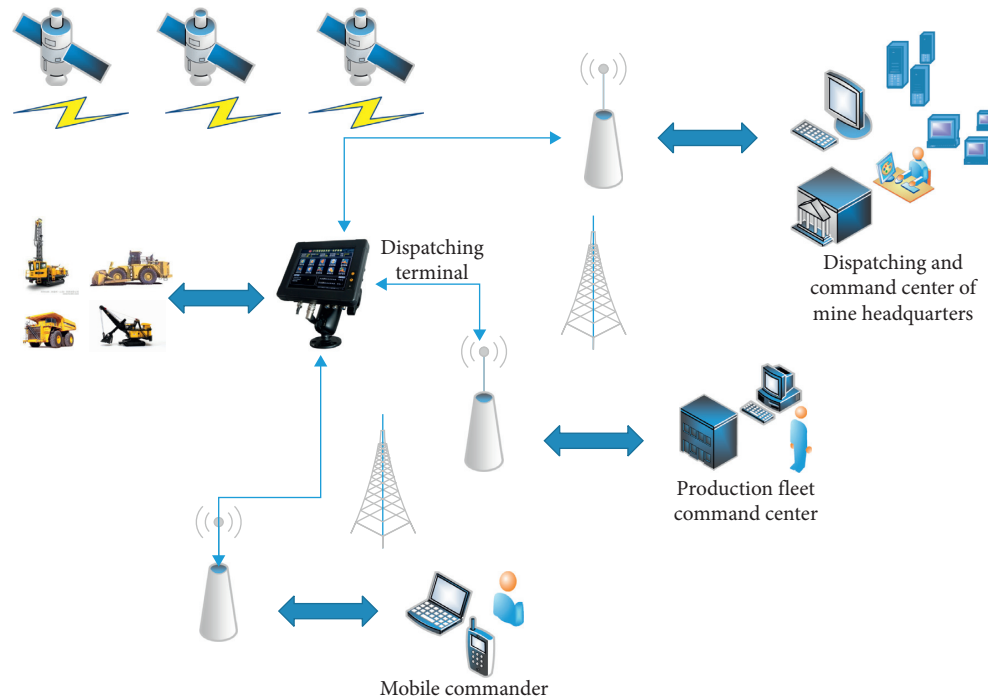


FIGURE 2: Schematic diagram of the dispatching process.

the truck is idle while waiting, and the energy consumption when the shovel is idle while waiting. The results of implementing the model in a case study show that it reduces the inefficient idle time of trucks [6–13].

The representative theoretical studies in China include the one by Ma and Li who have established a theoretical control model for truck dispatching systems. The model aims to minimize the remaining working time of the shovel, which can give full play to the efficiency of the shovel. Taking planned output control and ore quality control as examples, a multiobjective optimal control model of truck dispatching system was established [14]. Xing Jun and Sun Xiaoyu proposed the concepts of target output completion and current truck flow saturation and established real-time optimization scheduling criteria based on these two concepts. Based on the results of truck flow planning, the influence of random factors in the system is fully considered, and the transportation distance of trucks is also taken into account to achieve the overall optimal real-time scheduling. It is suitable for empty truck dispatching, heavy truck dispatching, and shovel-truck matching. The optimization effect is better. The production efficiency has been improved by 8.0%~17.8% after being proved to be used in open-pit mines [15, 16].

In terms of scientific method, several nonlinear machine learning based models, namely, feedforward neural network (FFNN), radial basis neural network (RBNN), general regression neural network (GRNN), support vector machine (SVM), and tree regression fitting model (TREE), are used to predict and solve engineering problem [17]. Moayedi et al. aimed to optimize adaptive neuro-fuzzy inference system (ANFIS) with two optimization algorithms, namely, genetic algorithm (GA) and particle swarm optimization (PSO), for

prediction of engineering problems, which is a new way to handle optimization of complex mathematical model [18].

Mine production is subject to many internal and external conditions. To ensure continuous production of mines, long-term, medium-term, and short-term production plans must be formulated. The short-term plan implementation method is truck dispatch [19]. As the continuous process of stripping outsourcing and wheel bucket is the mainstream trend of large open-pit mines in China, the optimization of truck scheduling in open-pit coal mining semicontinuous process systems will be the key research direction [20, 21].

2.2. Coal Mining Production Operations. In the production process of coal mining semicontinuous process system, mining, loading, transportation, and crushing are the main production operations. The equipment of each production operation must not only be reasonable in type selection, but also be optimized and matched. On the one hand, the equipment specifications must be adapted to the production capacity of the mine; on the other hand, it must be coordinated between each operation, and the parameter matching should be reasonable to ensure the efficiency and reliability of the entire system. Schematic diagram of spatial layout of coal mining semicontinuous process system is shown in Figure 3.

2.2.1. Mining and Loading. The capacity matching needs to be considered between the single-bucket excavator and the truck. Which single-bucket excavator the truck is dispatched to, the queue time of the truck, the loading time of the excavator, and the loaded coal quality information are the key issues in the coal mining process. Generally speaking, in



FIGURE 3: Schematic diagram of spatial layout of the coal mining semicontinuous process system.

order to give full play to the production capacity of the electric shovel, the production capacity of the truck should be slightly larger than the production capacity of the single-bucket excavator. However, in actual production, the number of trucks cannot be clearly specified. The truck flow planning scheme is to dispatch all available trucks for coal mining operations. As a result, there are too many trucks and long queues at the electric shovel, causing serious waste of production capacity.

2.2.2. Truck Transportation. Truck is the key equipment of transportation in open-pit mines. After receiving the dispatching, the truck goes to the designated single-bucket excavator to carry out the loading operation and then goes to the designated crushing station to unload the materials according to the scheduled route. Truck transportation needs to make corresponding arrangements according to the production needs of single-bucket excavators and crushing stations. The main problems at present are unreasonable truck scheduling and truck flow planning scheme.

2.2.3. Crushing. The crushing is a key operation in the coal mining semicontinuous process system which is different from the “single-bucket-truck” process. The truck transports the coal required by the production to the designated crushing station for unloading and crushing. The production capacity relationship between the front-end single-bucket truck and its subsequent crushing station-belt conveyor should be as follows: the actual production capacity of the single-bucket-truck part should be slightly larger than the actual production capacity of the crushing station part, which can reduce the continuous part of the crushing station equipment being in an empty state to ensure its full production capacity. However, in actual production, due to the large flow of trucks, the trucks will queue up at the crushing station for unloading. On the other hand, due to unreasonable truck flow planning, the crushing station will be left empty and operated at low load for a long time, wasting the crushing station ability.

2.2.4. Transport Operation of Belt Conveyor. The belt conveyor is the continuous part of the semicontinuous process

system. The crushing capacity of the crushing station in the production process should be slightly smaller than the transport capacity of the belt conveyor. The specific production capacity should be matched according to the overall production capacity of the semicontinuous system and the mine management level. In the transfer of each link of the belt conveyor, it is necessary to ensure that the transfer capacity of the previous link is slightly smaller than the transfer capacity of the latter link, in order to prevent the transport volume of the previous link from exceeding the capacity of the latter link, as one link jam can cause the entire semicontinuous series system to stop working.

The coal mining semicontinuous process system has many problems in mining, loading, truck transportation, crushing, and belt conveyor transportation. The coal mining semicontinuous system is a complete series system that integrates coal mining, coal transportation, and coal breaking. The matching degree of production capacity is the key factor to ensure the performance of the system [22, 23].

2.3. Key Issues of Coal Mining Truck Flow Optimization. The coal mining semicontinuous process is limited by the matching of production capacity between the process operations in the field production process. The truck transportation capacity must be larger than the crushing capacity of the crushing station to ensure the continuous crushing of materials. Unreasonable truck flow planning will cause a large amount of truck idle time at the loading and unloading points, that is, the time the truck waits for loading at the electric shovel and the time the truck waits for unloading at the crushing station. Truck flow planning and distribution strategy can reduce truck idle time.

On the one hand, the problem of truck flow planning in semicontinuous process systems is closely related to the electric shovel. Among the truck scheduling criteria, there is the truck scheduling criterion of the maximum electric shovel method. During the production process, the electric shovel will generate a large amount of nonworking-hour time due to shovel adjustment, cutting, and running. Therefore, it is necessary to fully coordinate the transportation capacity of the truck, not only to prevent the shovel from being stopped due to the insufficient number of trucks but also to reduce the phenomenon of waiting in the

queue due to the excessive number of trucks. On the other hand, it is closely related to the crushing station. As a key node connecting the shovel-truck operation and the crushing station-belt conveyor operation in the semi-continuous process, the crushing station receives the materials unloaded by the truck. The crushing station crushes large pieces of hard materials into small rocks suitable for the belt conveyor that transports coal to the coal preparation plant. The crushing station is the important facility in the mining semicontinuous process system of the open-pit coal mine, and it is the key node to realize the efficient operation of the system. In the coal mining semicontinuous process system, the number of unloading points is much less than the loading points. Therefore, from the perspective of global dispatch, the crushing station at the unloading point is the key node of truck scheduling and control in the coal mining semicontinuous system. The flow of trucks greatly deviates from the capacity of the crushing station to process materials, which will cause a large number of trucks to queue or the crushing station to idle. If the actual truck flow rate of this path reaches the unloading point at a rate similar to the rate at which the crushing station processes the material, it is easy to control the stability of the truck flow at the unloading point.

Coal quality has become the most important factor that affects the benefits of mines. At present, production mines generally use a dispatch method that uses the ratio of the number of mining electric shovels equal to the ratio of coal quality requirements for rough coal distribution. The actual effect is not ideal, and the coal preparation plant is ultimately needed for further processing. In the coal mining semicontinuous process system, trucks transport coal of different qualities to the crushing station for coal blending. By restricting the flow of trucks carrying coal of different qualities, a reasonable ratio of coal at the crushing station can be achieved.

In summary, the optimization of truck flow in the coal mining semicontinuous process system should aim to complete the mine production tasks, while minimizing truck transportation cost, and meet the loading capacity of the electric shovel at the loading point, the production capacity of the crushing station at the unloading point, and constraint requirements such as coal blending. A combination of fixed shovel and random truck is adopted; that is, the electric shovel is fixed at the shovel point, but the assigned truck and the target crushing station are not fixed. When the truck completes the transportation task on a certain line, it can go to other routes matched with other shovels and crushing stations.

3. Key Parameters of Truck Flow Planning

3.1. Key Time Parameters. In the production cycle of the coal mining semicontinuous process system, a large number of time parameters are generated: the waiting time for loading, loading time, heavy truck running time, waiting time for unloading, unloading time, empty truck running time, running time, excavating time, rotating time, loading time of the shovel, stop time and running time of crushing station,

and full storage bin time of crushing station. The truck operation cycle of the coal mining semicontinuous process system is shown in Figure 4.

Truck flow planning should ensure that the accuracy of the prediction of the running time of each road segment can effectively improve the reliability of scheduling, and the randomness of the truck scheduling process should be eliminated as much as possible. The key time parameters are important basis for optimizing scheduling, and the accuracy of its prediction will directly affect the reliability of truck flow planning decisions.

The following time parameters are selected in the truck flow planning model of the coal mining semicontinuous process system:

- (i) Total shovel loading time: the time after the truck enters the loading area until the loading is completed and leaves the loading area, including the waiting time of the truck, the shovel running time, and the electric shovel loading time. Total shovel loading time is closely related to the loading environment, such as truck queuing, geological conditions, material block size, and the operation level of the electric shovel driver. All of them affect the total shovel loading time.
- (ii) Total truck unloading time: the time after the truck enters the unloading area until the unloading is completed and leaves the unloading area, including the queuing time of the truck, the idle time of truck because the material is full in the crushing station's bin, and the unloading time of the truck. Similarly, the total unloading time of the truck is closely related to the unloading environment. For example, the queuing situation of the truck, the height of the receiving bin of the crushing station, and the operating conditions of the crushing station will affect the total unloading time of the truck.
- (iii) Truck empty running time: the empty running time on the path from unloading point i to loading point j .
- (iv) Truck heavy running time: heavy running time on the path from loading point j to unloading point i .

3.2. Triangular Fuzzy Number. Due to the high randomness of the production process of coal mining semicontinuous process, it is impossible to accurately obtain the parameter data of truck real running time. In the past process of truck scheduling and truck flow regulation research, the truck running process was defined as Poisson distribution. Poisson distribution is a discrete probability distribution commonly seen in statistics and probability. The principle is to count the number of events per unit time interval in a discrete random process. When an event occurs randomly and independently at a fixed average instantaneous rate λ (or density), then the frequency or number of occurrences of this event in unit time approximately follows Poisson distribution $P(\lambda)$. Random variables that follow the Poisson distribution are often counted in time. Therefore, it is natural



FIGURE 4: Truck running cycle of coal mining semicontinuous process system.

in previous studies to consider the truck running process as a Poisson distribution and define the truck running time parameters with the Poisson distribution.

Let X_1, X_2, L, X_n be the sample with the parameter λ Poisson distribution, and the observed value x_1, x_2, L, x_n, n_i be the number of samples with the observed value x_i .

Assuming that X follows the Poisson distribution, then there is $X \sim P(\lambda)$ and the probability distribution is listed as follows:

$$P(X = K) = \frac{\lambda^k e^{-\lambda}}{k!}, \quad k = 0, 1, 2, L, \lambda > 0. \quad (1)$$

The maximum likelihood estimation of the easily obtained Poisson distribution parameter λ is

$$\lambda = \bar{x}. \quad (2)$$

The maximum likelihood estimation is that a random sample is known to satisfy a certain probability distribution, and the approximate value of the parameter is derived using the results of multiple trials. Maximum likelihood estimation is based on the idea that a certain parameter is known to maximize the probability of this sample, so this parameter is simply used as the estimated true value. However, the average value or the maximum probability of the truck's running time parameter is taken as the key time parameter into the mathematical model for solution, and the result is quite different from the actual one. Previous studies believed that the operations of heavy running time, loading time, and unloading time meet the Poisson process. In fact, these

processes are highly nonuniform. In the coal mining semicontinuous process system, the amount of time generated by the interaction between the various processes in the series process system should be fully considered. Therefore, triangular fuzzy numbers are used to count various time parameters in this paper.

For the time parameters of the total shovel loading time and the total unloading time of the truck, we count the fuzzy information, and the membership function takes a trigonometric function. Therefore, the total shovel loading time and the total unloading time of the truck can be regarded as fuzzy variables, and the membership or credibility distribution can be obtained by the method of fuzzy statistics. Definition 1 The fuzzy number A belongs to the real number field R , and the membership function can be defined. If $u_A(x)$ can be expressed as

$$u_A(x) = \begin{cases} 0, & x \leq a, \\ \left(\frac{x-a}{2(b-a)} \right), & a < x \leq b, \\ \left(\frac{1-(x-c)}{2(b-c)} \right), & b \leq x < c, \\ 0, & x \geq c, \end{cases} \quad (3)$$

it is called a triangular fuzzy number and is written as $A = (a, b, c)$, ($a \leq b \leq c$), where a and c are, respectively, the

lower and upper limits of the fuzzy number, and b is the most likely value. The data is allowed to be asymmetrically distributed; that is, $b - a \neq c - b$. This can better describe the actual situation of trucks queuing and other uncertain phenomena [24]. Triangular fuzzy number distribution is shown in Figure 5.

Truck running time is related to road conditions, truck conditions, drivers, and other factors. Open-pit mine truck operation time is divided into heavy running time and empty running time. The running time of empty truck is relatively stable, taking the constant. Statistical parameters of fuzzy trigonometric numbers are used for the running time of heavy trucks.

4. Fuzzy Expected Traffic Flow Planning Model

4.1. Application Case Studies. Shenhua Baorixile Energy Co., Ltd. (abbreviated as Shenbao Energy Company) was developed and constructed in 1980 by Baorixile open-pit coal mine, which is now part of a joint-stock coal enterprise controlled by the National Energy Investment Group. Shenbao Energy Company has obtained a total resource of 2.3 billion tons, and it is No. 1 open-pit coal mine currently producing coal. The state has an approved production capacity of 35 million tons per year. All raw coal of the mine comes from the coal mining semicontinuous process system. The main equipment for coal mining operations are 6 WK series electric shovels, 50 TR100 trucks, and 4 sets of crushing stations. In practice, if electric shovels and trucks are in no fault state, all of them will be put into use. No. 3 and No. 4 crushing stations are used as spares for each other according to the production task requirements.

Baorixile open-pit coal mine uses a semicontinuous process system with electric shovels, trucks, semifixed crushing stations, and belt conveyors for raw coal transportation. The system equipment information is shown in Table 1.

In the actual production of the mine, 6 electric shovels are placed at 6 loading points. In this case, No. 1, 2, and 3 crushing stations were used as unloading points. Therefore, the mine has 6 loading points and 3 unloading points. The capacity of the coal transport truck is 100 t/h; the production capacity of electric shovels 1, 2, and 3 is 2800 t/h; and that of 4, 5, and 6 is 1250 t/h. The crushing production capacity of the three crushing stations is 2000 t/h on No. 1, 2500 t/h on No. 2, and 2500 t/h on No. 3. The coal quality ratio requirements are as follows: No. 9 coal and No. 11 coal are roughly mixed at 2 : 1; No. 9 coal loading points are No. 1, 3, 4, and 6; No. 11 coal loading points are No. 2 and 5; and production task requirements of the output of one shift are not less than 50,000 tons. Baorixile No. 1 open-pit coal mine adopts manual dispatching method: production dispatchers subjectively judge the ratio of electric shovel to truck according to the production needs of electric shovel, truck, and crushing station; which electric shovel is needed; and which crushing station the unloading truck is going to. However, the overall awareness of manual scheduling is poor, and there is often no truck loading or unloading or

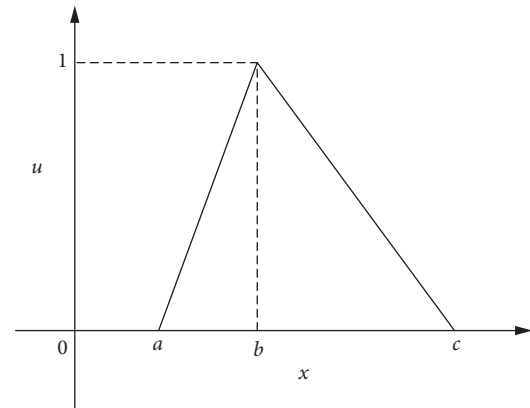


FIGURE 5: Triangular fuzzy number distribution.

truck queuing at electric shovels and crushing stations due to unreasonable truck flow. The dispatchers and drivers are subjective and random. The blind pursuit of production leads to chaotic scheduling, resulting in truck queuing caused by dispatching and insufficient supply in the crushing station. The crushing station is often in the “overload” and “low load” state, which seriously restricts the ability of the semicontinuous production system. At the same time, the mine adopts a dispatch method that uses the ratio of the number of mining electric shovels equal to the ratio of coal quality requirements for rough coal distribution. The actual effect is not ideal, and the coal preparation plant is ultimately needed for further processing. The Shenbao open-pit mine is shown in Figure 6, and the scene of the crushing station and the receiving bin is shown in Figure 7.

4.2. Parameter Data. The fuzzy expected truck flow planning model includes parameters such as total shovel loading time, total truck unloading time, truck heavy running time, and truck empty running time. The statistical processing of the field data by fuzzy trigonometric numbers can be obtained: total shovel loading time can be expressed as a fuzzy variable (5.5, 7.5, 10.6); total truck unloading time can be expressed as a fuzzy variable (3.5, 5, 7.8). The fuzzy variable time for truck heavy running time is shown in Table 2, and the constant time for truck empty running time is shown in Table 3.

4.3. Fuzzy Expected Truck Flow Planning Model. The mathematical programming with fuzzy variables in the objective function or constraints is called fuzzy programming. At present, the solution to fuzzy programming problems is to first transform its objective function or constraint condition into an equivalent or approximate deterministic optimization model and then solve it. Fuzzy planning is a type of uncertain planning. The key time parameters in open-pit coal truck scheduling are analyzed using triangular fuzzy number statistics. Fuzzy statistics are used to describe the uncertain information to obtain the total shovel loading time, the total truck unloading time, and

TABLE 1: Equipment information of mining semicontinuous system in Baorixile open-pit mine.

Equipment	Model	Number	Production capacity	Manufacturer
Shovel	WK-10B	3	10 m ³	Taiyuan Heavy Industry
	WK-20	3	20 m ³	Taiyuan Heavy Industry
Truck	TR100	50	100 t	Terex
	2#, 3#	2	2500 t/h	Luoyang Mine
Crushing station	1#	1	2000 t/h	Sandvik
	4#	1	3500 t/h	MMD

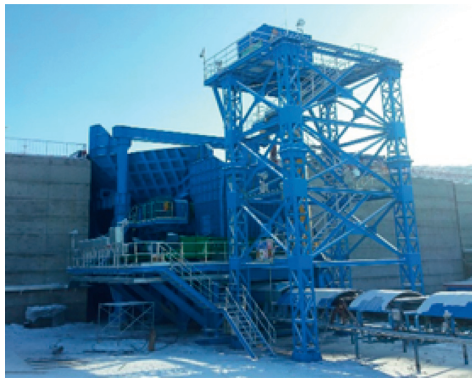


(a)



(b)

FIGURE 6: Shenbao open-pit mine.



(a)



(b)

FIGURE 7: Scene of crushing station and receiving bin.

TABLE 2: Heavy truck operation data.

Loading point	Unloading point		
	Crushing station 1	Crushing station 2	Crushing station 3
1	(8.5, 10.0, 12.8)	(9.5, 11.0, 13.1)	(8.8, 9.5, 12.2)
2	(6.5, 8.0, 9.7)	(7.5, 9.2, 11.5)	(8.2, 9.0, 11.2)
3	(7.1, 8.2, 11.2)	(8.0, 9.0, 10.7)	(6.4, 7.6, 9.6)
4	(5.8, 7.0, 9.2)	(6.3, 7.2, 8.9)	(5.8, 7.0, 9.2)
5	(6.2, 8.0, 12.3)	(5.0, 7.0, 9.5)	(6.3, 8.0, 10.8)
6	(7.5, 8.5, 9.9)	(6.5, 8.5, 11.0)	(6.5, 7.5, 10.9)

truck heavy running time, which can establish the fuzzy expectation model of truck flow planning.

Given a clear fuzzy programming model in order to obtain the maximum expected return the following fuzzy expected value model was established for decision-making:

$$\begin{cases} \max & \{E[f_1(x, \varepsilon)]\} \\ \text{subject to} & E[g_j(x, \varepsilon)] \leq 0 (j = 1, 2, \dots, p). \end{cases} \quad (4)$$

The truck flow planning model is composed of objective function and constraint conditions. The objective function

TABLE 3: Empty truck running time data.

Loading point	Unloading point		
	Crushing station 1	Crushing station 2	Crushing station 3
1	7.2	7.5	6.8
2	5.8	6.6	6.5
3	5.6	6.1	4.9
4	5.1	5.0	4.8
5	6.9	5.1	5.5
6	6.0	6.2	5.2

The data were obtained from the Shenbao open-pit mine truck dispatching system.

of the truck flow planning model adopts the model with the minimum expected value of number of trucks dispatched. Because there are fuzzy parameters in the objective function in this model, the fuzzy expected value model is adopted here.

The objective function is

$$N_t = \min E \left[\sum_{i=1}^m \sum_{j=1}^n (T_{ij} + L_{ij}) X_{ij} + \sum_{i=1}^m \sum_{j=1}^n (T_{ji} + D_{ji}) Y_{ji} \right]. \quad (5)$$

In the formula, N_t is the actual number of trucks dispatched; T_{ij} is the empty time on the path from unloading point i to loading point j , min; L_{ij} is the total shovel loading time on the path from unloading point i to loading point j (including waiting time for loading, shunting time of truck), min; X_{ij} is the shunting time of truck on the path from unloading point i to loading point j , trucks/min; T_{ji} is the truck heavy running time on the path from loading point j to unloading point i , min; D_{ji} is the total truck unloading time on the path from loading point j to unloading point i (including waiting time for unloading, shunting time of truck), min; Y_{ji} is the heavy truck flow on the path from loading point j to unloading point i , trucks/min; m , n are the numbers of loading points and unloading points.

In the objective function, E is the expected operator; X_{ij} and Y_{ji} are decision variables; T_{ij} is deterministic parameter variable; and L_{ij} , D_{ji} , and T_{ji} are fuzzy time parameter variables. Because there are uncertain variables in the objective function, the objective function is taken as the minimum expected value of number of trucks dispatched [25–27].

The constraints are as follows:

(1) Constraints of truck flow continuity:

Loading point:

$$\sum_{i=1}^3 Y_{ji} - \sum_{i=1}^3 X_{ij} = 0 \quad (j = 1, 2, 3). \quad (6)$$

$$\sum_{j=1}^6 X_{ij} - \sum_{j=1}^6 Y_{ji} = 0 \quad (i = 1, 2, 3). \quad (7)$$

(2) Constraints of electric shovel's mining and loading capacity:

$$\begin{aligned} Y_{j1} + Y_{j2} + Y_{j3} &\leq 0.467, \quad (j = 1, 2, 3), \\ Y_{j1} + Y_{j2} + Y_{j3} &\leq 0.208, \quad (j = 4, 5, 6). \end{aligned} \quad (8)$$

(3) Constraints of production capacity of crushing station:

$$\begin{aligned} \sum_{j=1}^6 Y_{j1} &\leq 0.333, \\ \sum_{j=1}^6 Y_{j2} &\leq 0.417 \sum_{j=1}^6 Y_{j3} \leq 0.417. \end{aligned} \quad (9)$$

(4) Constraints on coal quality:

$$\begin{aligned} Y_{1i} + Y_{3i} &= 2Y_{2i}, \quad (i = 1, 2, 3), \\ Y_{4i} + Y_{6i} &= 2Y_{5i}, \quad (i = 1, 2, 3). \end{aligned} \quad (10)$$

(5) Production task constraints:

$$\sum_{j=1}^6 \sum_{i=1}^3 Y_{ji} \geq 1.042. \quad (11)$$

(6) Nonnegative constraints:

$$X_{11}, L, X_{36}, Y_{1,1}, L, Y_{63} \geq 0. \quad (12)$$

Unloading point:

5. Solving Truck Flow Planning Model Using Particle Swarm Optimization Algorithm

5.1. Introduction to Particle Swarm Optimization. Particle swarm optimization (PSO) was proposed by Dr. Eberhart and Dr. Kennedy together. It is a random search algorithm based on group collaboration developed by simulating the foraging behavior of birds. It is generally considered to be a type of swarm intelligence (SI). The basic core of the particle swarm optimization algorithm is to use the information sharing of the individuals in the group so that the entire group has to move from disorder to order in problem solving process, so as to obtain the optimal solution of the problem.

Particle swarm optimization is a kind of intelligent optimization algorithms. This algorithm starts from a

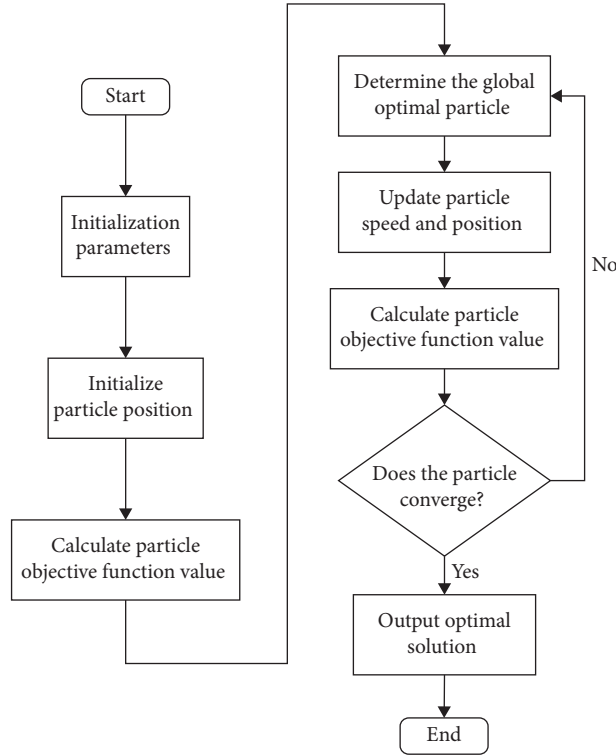


FIGURE 8: Flowchart of particle swarm optimization algorithm.

random solution, iteratively finds the optimal solution, evaluates the quality of the solution through fitness, and follows the currently searched optimal value to find the global optimal. The particle swarm optimization algorithm has an efficient search capability and strong versatility and is suitable for handling various types of objective functions and constraints.

Initially, the PSO algorithm defined each particle as a possible solution to the D -dimensional space problem, with particle i being represented by $X_i = (X_{i1}, X_{i2}, \dots, X_{iD})$. Each particle also remembers its previous best position $P_i = (P_{i1}, P_{i2}, \dots, P_{iD})$, and its speed in multidimensional space is represented by $V_i = (V_{i1}, V_{i2}, \dots, V_{iD})$. In each iteration, the P vector of the particle with the greatest fitness in the vicinity of the local particle and the specified g are combined with the P vector of the current particle to adjust the velocity of the multidimensional space, and then this velocity is used to calculate the new position of the particle. The speed adjustment affected by the individual's previous best position P is called individual learning ability, while the speed adjustment affected by the neighboring best position is called group learning ability [28]. The particle swarm optimization process is shown in Figure 8.

5.2. Particle Swarm Optimization Solution Steps. The steps to solve the model are as follows:

- (i) Step 1: solve the fuzzy expected value of the triangular fuzzy variable to obtain the corresponding time parameter:

TABLE 4: Simulation results of empty truck flow.

j	i					
	1	2	3	4	5	6
1	0.0001	0.1386	0.0695	0.0005	0.0000	0.0000
2	0.0000	0.0007	0.0000	0.2073	0.2075	0.0002
3	0.0000	0.0000	0.2089	0.0000	0.0000	0.2065

TABLE 5: Simulation results of heavy truck flow.

j	i		
	1	2	3
1	0.0003	0.0003	0.0000
2	0.0698	0.0000	0.0700
3	0.1388	0.0000	0.1394
4	0.0002	0.2077	0.0000
5	0.0000	0.1390	0.0689
6	0.0001	0.0697	0.1379

$$\begin{aligned}
 E[\xi] &= \int_{-\infty}^{+\infty} x d u_A(x) = \int_a^b x d \left(\frac{x-a}{2(b-a)} \right) \\
 &\quad + \int_b^c x d \left(1 - \frac{x-c}{2(b-c)} \right) \\
 &= \frac{1}{2(b-a)} \int_a^b x dx - \frac{1}{2(b-c)} \int_b^c x dx \\
 &= \frac{1}{2(b-a)} * \frac{1}{2} (b^2 - a^2) - \frac{1}{2(b-c)} * \frac{1}{2} (c^2 - b^2) \\
 &= \frac{a + 2b + c}{4}.
 \end{aligned} \tag{13}$$

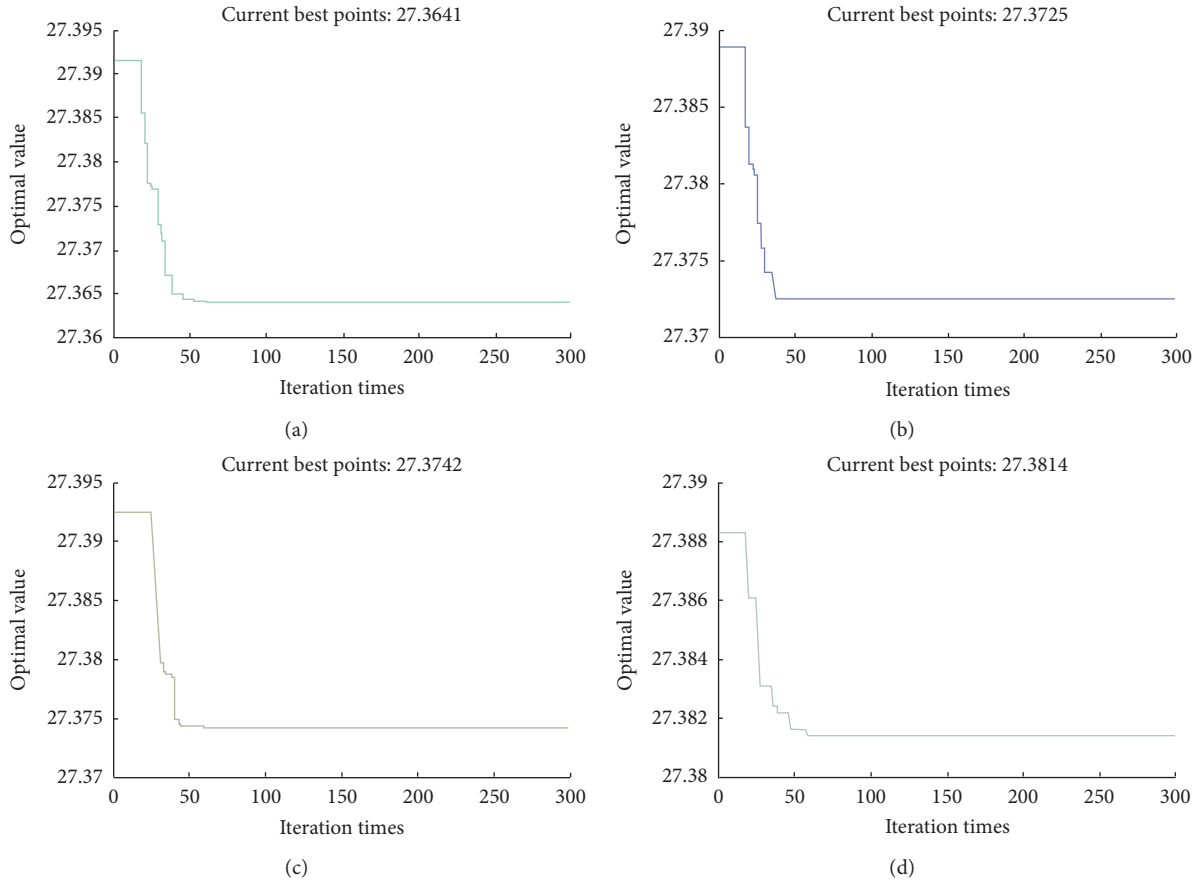


FIGURE 9: Fitness evolution curve.

- (ii) Step 2: select appropriate control parameters: particle population size $N=100$; inertia coefficient $w=0.8$; acceleration coefficient $c_1=c_2=0.5$; maximum number of iterations $T=300$.
- (iii) Step 3: initialize the particle position x and velocity v of the swarm, the particle optimal position p and the optimal value p_{best} , and the particle swarm global optimal position g and the optimal value g_{best} .
- (iv) Step 4: update the position x and velocity v , and process the boundary conditions to determine whether to replace the individual optimal position p and the optimal value p_{best} of the particle, and the global optimal position g and the optimal value g_{best} of the particle swarm.

The speed update is

$$v_{id} = w \times v_{id} + c_1 \times \text{rand}() \times (p_{id} - x_{id}) + c_2 \times \text{rand}() \times (p_{gd} - x_{id}). \quad (14)$$

The location update formula is

$$x_{id} = x_{id} + v_{id}. \quad (15)$$

- (v) Step 5: determine whether the termination condition is satisfied: if it is satisfied, the search process is ended

and the optimized value is output; if it is not satisfied, iterative optimization is continued [29, 30].

5.3. Simulation Solution. Bring the data of the truck transportation parameters of the Shenbao open-pit mine: the total shovel loading time, total truck unloading time, truck heavy running time, and truck empty running time into the solving step of the particle swarm algorithm to achieve the minimum number of trucks and meet constraints such as truck flow continuity, electric shovel mining and loading capacity, crushing station production capacity, coal quality, production tasks, and nonnegative constraints. Get the following truck flow planning results.

Through 4 simulations, the optimal solution is 27.3641; this means that the minimum number of trucks dispatched is 27.3641 under the target output and various constraints. The corresponding unloading point i and loading point j are as shown in Table 4. Heavy truck flow is shown in Table 5.

The intelligent algorithm represented by particle swarm is an approximate algorithm constructed based on the principle of bionics. When optimizing the model, the determination of the internal parameter inertia coefficient w and the acceleration coefficient $c_1=c_2$ requires multiple tests. Finally, optimizing the result is generally volatile, and multiple simulations are still needed to avoid falling into the local optimal solution.

TABLE 6: Number of empty trucks.

j	i					
	1	2	3	4	5	6
1	0	67	34	0	0	0
2	0	0	0	100	100	0
3	0	0	101	0	0	101

TABLE 7: Number of heavy trucks.

j	i		
	1	2	3
1	0	0	0
2	34	0	34
3	67	0	67
4	0	100	0
5	0	66	34
6	0	34	67

Using particle swarm optimization to solve the fuzzy expectation model, the fitness evolution curve obtained after 4 independent simulations is shown in Figure 9.

In order to enable producers to view the truck flow dispatching plan, the shift truck flow dispatching plan is determined according to the empty and heavy truck flows obtained from the simulation results. In principle, the decimal part is automatically rounded up, and the continuity of the loading point and the unloading point is considered. It is the number of heavy trucks leaving the loading point being equal to the number of empty trucks leaving the unloading point. Table 6 shows the number of empty trucks for one shift, and Table 7 shows the number of heavy trucks.

From the simulation results, it can be seen that the truck flow planning scheme can be realized only by satisfying the corresponding empty truck flow and heavy truck flow. In fact, the number of trucks dispatched in production is the actual number of coal mining trucks in the mine. For example, in the actual production mine in this case, there are 50 coal mining trucks, and all the trucks that have no faults in production are usually put into production. As a result, the production scheduling is complicated, and the production capacity of the truck is wasted. The labor intensity, the wear of the truck and tires, and the fuel cost of the truck are increased. The truck will have a lot of idle time waiting in queue. Through the model, the minimum number of trucks dispatched is 27.3654 which can meet the production conditions. Considering the scheduling error in production, 30 trucks can meet the production requirements under reasonable scheduling. On the other hand, through the solution of the model, it can be seen that No. 1 electric shovel in this case can complete all production tasks without any loading work. It saves the production capacity of the electric shovel while reducing the production and operation costs, such as reducing the maintenance of coal steps, watering, leveling, and other operating procedures.

The results of truck flow planning can be used as the basis for decision making for the actual number of trucks dispatched in the mine production. The intelligent algorithm can obtain a variety of local optimal solutions by adjusting

control parameters to provide decision makers with a variety of truck flow planning solutions.

6. Conclusion

Based on the characteristics of the coal mining semi-continuous process system, this paper analyzes the interaction between production operations such as mining, loading, transportation, and crushing, taking Shenbao open-pit mine as an example to establish the truck flow planning model of mining semicontinuous process system. The following conclusions are obtained:

- (1) Based on the coal mining semicontinuous process system, the problem of process capacity matching between electric shovel, truck, and crushing station is analyzed. The key parameters of the truck flow planning problem of the process system are proposed, such as the total shovel loading time, the total truck unloading time, the truck empty running time, and truck heavy running time. The statistical analysis using the triangular fuzzy number and its membership function can intuitively show the randomness and uncertainty of the truck scheduling process.
- (2) Taking the minimum expected value of each truck as the objective function and establishing the coal mining semicontinuous process system with the continuity of the loading and unloading point, the shovel mining and loading capacity, the crushing station production capacity, the coal quality constraints, and the production tasks as the constraints, we solved the fuzzy expected truck flow planning model using particle swarm intelligence algorithm. The simulation results show that the results of truck flow planning can effectively reduce the number of truck dispatches, transportation costs, and truck queuing.

The cooperation between the various operations of the semicontinuous process affects the truck scheduling performance. For example, the real-time bin height and the actual crushing efficiency of the crushing station will affect the queuing time of the truck. The arrival rate of the truck will also seriously affect the actual crushing efficiency of the crushing station. The arrival process of the truck at the corresponding semicontinuous unloading point in production is no longer a Poisson process. Therefore, the use of data mining and prediction methods to optimize and model trucks in real time in coal mining semicontinuous process systems needs further study.

Data Availability

The data used to support the findings of this study were obtained from the Shenbao open-pit mine truck dispatching system.

Conflicts of Interest

The authors declare no conflicts of interest.

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