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Developing a joint supply chain plan for the coal industry considering conflict resolution strategies

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Abstract. An integrated coordination planning problem pertaining to the energy enterprise aims to balance the plans submitted by the production and distribution branches to mitigate the conflict between them. The conception of this research comes from the challenges encountered in practice in the energy industry. Practical experience indicates that conflicts occur commonly among the respective plans made by the production and distribution branches. A plan coordinating approach is proposed that considers two aspects: maximizing company profit and minimizing the gap between the proposed plans and the coordinating ones that implement a conflict resolution approach. We apply genetic algorithm to handle this nonlinear optimization problem. A case study of the world's largest coal supplier in China shows that if conflicts occur in the original plans, the most effective method is to adjust the original plans from a global perspective, which has a strong relationship with the overall interests. The proposed model can effectively neutralize the secondary influences of the conflict.

1. Introduction

Preparation of a preoperational plan is good for supply chain systems to coordinate multiple producers, carriers, and distributors and advance the efficiency of the mentioned systems. The conception of this research derives from the challenges encountered in practice from the viewpoint of the world's largest coal supplier in China. Its main business covers coal production, rail transportation, and power generation, as shown in Figure 1. The operation of numerous subsidiaries depends on the planning management from the group headquarters. At the beginning of the planning stage, the production and distribution branches are required to submit their plans to the command center at the group's headquarters. Due to the separation and independence of the business among the sub-branches, the occurrence of conflicts is extremely common and it is not easy for the branches to overcome these conflicts on their own. One should take the operation report in February 2012 as an example, which indicates a 40% gap between the production plan and the distribution plan. According to the business report, in February 2016, the group company ran fifty coal mines and twenty-two types of coals were involved.

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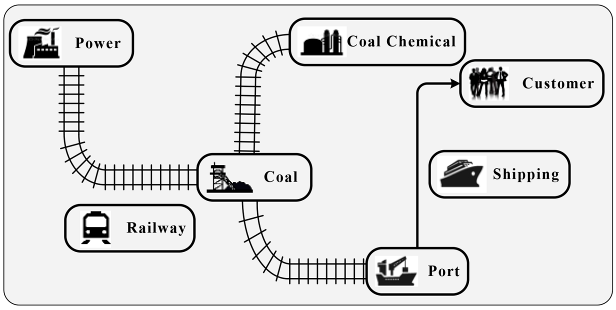

Figure 1. Operation structure of the vertical integration company.

Distribution areas cover thirteen provinces, cities, and regions and three customer categories are involved. A number of national, local, and owned railway lines have participated in the operation. The number of corresponding constraints and variables in the model is huge. Bhatnagar et al. [1] addressed the coordination of multiple plants in terms of production planning in a vertically integrated firm and they identified the critical problems that managers and researchers must address to ensure that production and inventory decisions can be determined in a manner optimal for the organization as a whole.

Several examples of such scenarios exist at home and abroad. In particular, in the industry, the mode of mass production, transportation, and distribution imposes a higher demand for plan management. An example is Broken Hill Proprietary Billiton Ltd. (BHP), whose corporate headquarters set the planning objectives and determine a balanced operation plan, while the secondary units are responsible for the decomposition and implementation [2]. Another example is Companhia Vale do Rio Doce. Vale is a Brazilian multinational corporation engaged in metals and mining and it is one of the largest logistics operators in Brazil. Vale is the largest producer of iron ore and nickel in the world. The company also currently operates nine hydroelectricity plants and a large network of railroads, ships, and ports used to transport its products [3]. Its headquarters are responsible for not only setting the objectives and principles, determining a balanced operation plan, performing comprehensive optimization, and providing the optimization plan, but also controlling the operation plan. The secondary units act only as business workshops, having lower autonomy.

Complex supply chain information generated from multiple branches is no longer suitable to be processed only by experience. Time and manpower consumption are the main constraints. In this paper, a mathematical optimization method involving an embedded conflict resolution strategy is proposed to solve this problem, as shown in Figure 2. In the mathematical model, conflicts information is reflected as illogical constraints, implying that we cannot find

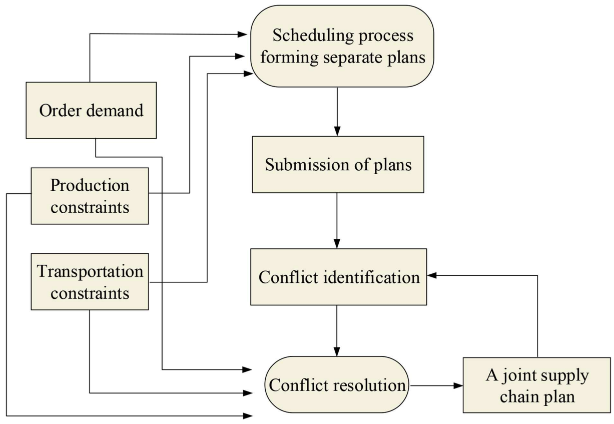

Figure 2. Process flow of planning operation.

feasible solutions using the original model. Therefore, some human interventions must be imposed on the model to deal with conflicts. The main measure embedded in our planning procedure is the application of the conflict resolution approach to achieve coordination between the multiple plans of different branches. In this process, we pay particular attention to the effect of implementation. It should be noted that the degree of dissatisfaction of each branch is directly proportional to the significant differences existing between their respective plans and the plans formulated after conflict resolution. This factor must be taken into account in the model through a quantified method.

The remaining research is organized as follows. The proposed coordinating model is described in Section 3. A heuristic method employed for solving the problem is presented in Section 4. In Sections 5 and 6, a test network and a case study are presented to validate the model and algorithm.

2. Literature review

Given the conclusion drawn by Goyal and Gupta, the coordination between the buyer and supplier is good for both sides [4]. In studies pertaining to the supply chain, an increasing number of researchers have focused on the coordination of production and distribution from strategic, tactical, or operational perspectives [5]. In contrast, the research on the integrated production-distribution scheduling problem is relatively recent, and it is termed as the integrated production-distribution planning or scheduling; this domain includes studies such as those of Pundoor and Chen [6], Pornsing et al. [7], Zhong and Jiang [8], Russel et al. [9], Kishimoto et al. [10], Ma et al. [11], and Scholz-Reiter et al. [12]. In the models presented in some studies, for example, in Cheng et al. [13], Devapriya et al. [14], and Noroozi et al. [15], one or a combination of cost-based, time-based, and revenue-based performance measures is often seen as the goal of system optimization [16–23], and the relevant truck routes, fleet size, job processing or batching are seen as constraints. The literature pertaining to the methods employed to balance the respective plans of the different branches in the integrated supply chain, aimed at minimizing the total global cost from the global perspective, is quite limited in scope. A tradeoff approach [11] is directed at determining the plants and warehouses that should operate to serve customers with the total cost lying between the total global cost and the costs in the respective branches. Sawik [24] merged production and distribution operations by formulating a mathematical approach. The major decision-making involved determining whether the customer orders could be completed as planned under different disruption scenarios or not; however, the specific quantity was not considered.

In production-distribution problems, collaborative cooperation as the core of supply chain management will help the member units to achieve the win-win purposes in a hierarchical system [25–27]. Two contrasting objectives are included in the existing studies that are specified by different branches such as reducing cost and improving service level. Considering that conflict of interest is a frequent and recurrent phenomenon in different stakeholder groups, its role in decision-making in the supply chain must be given due attention [11]. These conflicts, however, can result in mutual influences, and these mutual influences may significantly impact the production-distribution planning. Many existing studies have focused on solving the integrated production-distribution problems using multi-objective programming and formulated different goals and conflicting objectives as multi-objective programming problem [28,29]. Similarly, the bi-level programming approach is used to formulate those participants that belong to different stakeholder groups as two optimization problems, and the leader decisions at the top are constrained by the results of the follower [30–32]. This approach can eliminate conflicts and enhance coordination between the different decision entities, which is vital for ensuring supply chain efficiency. However, different decision entities are dissatisfied when large differences exist between their respective plans and the ones formulated after conflict resolutions. Bilevel programming cannot measure such differences. Thus, we need to take the expression of dissatisfaction into account in our model as a quantitative measure. In our research, a novel conflict resolution approach is developed to control the conflict resolution between the participants in an integrated production-distribution planning problem.

A few studies such as in Chen and Vairaktarakis [33], Chen and Lee [34], Xuan [35], and Zhong et al. [36] focused on production scheduling considering the delivery process, in which the distribution operations were mainly carried out by third-party carriers, with emphasis on road transportation with homogeneous vehicles or the Vehicle Routing Problem (VRP). The collaboration of job processing and rail timetable from time dimension is one of the aspects that has received insignificant attention [37]. Several similar researches of production and transportation problem were investigated by Moons et al. [38], Li and Li [39], Liotta et al. [40], and Azadian et al. [41].

3. Integrated scheduling model

Herein, a production and distribution network is considered that consists of several production branches combined in set I, self-owned railway and state-owned railway lines denoted by the set L, distribution branches denoted by set J of demand nodes, set of coal types M, and classes of customers defined by the set N. Production branches I and distribution branches J are located in different geographical areas, and the coal is delivered though railway lines. The model is proposed to maximize the economic objective and minimize the penalty cost due to conflict resolution considering constrains of real production, transportation, and demand.

3.1. Symbol notations

From the viewpoint of our model, the manager of the integrated group company makes the following decisions:

(i) Determining the optimal coal types and output;

(ii) Selecting the best transport route;

(iii) Providing optimal matching relationships with the customer requirements.

The variables in this paper are listed as follows:

Network

$i = 1, \dots, I$	Production branches
$\lvert I\rvert$	The total number of production branches
$j = 1, ..., J$	Distribution branches
$\lvert J\rvert$	The total number of distribution branches
$l = 1, ..., L$	Alternative transport routes
$\lvert L\rvert$	The total number of routes
$m = 1, ..., M$	Coal types
$\lvert M\rvert$	The number of coal types
$n = 1, ..., N$	Categories of customer
$\lvert N\rvert$	Is the number of customer categories
$k = 1, ..., K$	Transportation segments in dispatching network
$\lvert K\rvert$	The total number of segments

$k(l)$ The set of segments included in the route l

$l(k)$ The set of routes via the segment k

Production branch

$[\underline{a}_{im}, \bar{a}_{im}]$ Production plan in the range of $\underline{a}_{im}$ to $\bar{a}_{im}$ of production branch i for type m

$[0, T_{im}]$ Capacity of production branch i for type m

$[\underline{A}_i, \bar{A}_i]$ Upper and lower bounds of productivity of production branch i

$[0, T_i]$ Productivity of production branch i

c_{im} Variable cost per unit of type m from production branch i

c_i Fixed production cost of production branch i

Transportation network

d_k Capacity of segment k

s_k Length of segment k

p_k Transportation cost per ton-km of segment k

Distribution branch

$[\underline{B}_{jmn}, \bar{B}_{jmn}]$ Demand plan in the range of $\underline{B}_{jmn}$ to $\bar{B}_{jmn}$ from customer class n in the area j for type m

$[0, T_{jmn}]$ Largest demand size for customer class n for type m in the area j

$[\underline{B}_{jn}, \bar{B}_{jn}]$ Demand plan from customer class n in the area j in the range of $\underline{B}_{jn}$ to $\bar{B}_{jn}$

$[0, T_{jn}]$ Demand size in the area j for customer class n

p_{jmn} Selling price in the area j for customer class n, type m

c_{jm} Selling cost in the area j for type m

Decision variables

x_{ijmln} Optimal amount from production branch i to demand branch j using route l for customer class n and coal type m

Y_i If the production branch i operates, $Y_i = 1$; otherwise, $Y_i = 0$

3.2. Basic assumptions

To facilitate the model formulation, we considered that the following assumptions would hold throughout this study.

Assumption 1. A large fluctuation will accrue if the scheduled cycle is short. In practice, the railway vehicle turnover cycle is the key influencing factor in the scheduled cycle. Therefore, we define the scheduled cycle to be longer than one day.

Assumption 2. Our research has been advancing from a strategic viewpoint, and the train dispatching problem, which is investigated in operational terms, is not considered in the proposed model.

3.3. Model constraints

The proposed model considers two types of constraints: hard and soft constraints. Hard constraints ensure the feasibility of the coordination scheduling model, and soft constraints control the quality of the results.

3.3.1. Hard constraints

According to Constraint (1), the freight volume cannot exceed the capacity of segment.

$$\sum_i \sum_j \sum_m \sum_{l(k)} \sum_n x_{ijmln} \leq d_k \quad \forall k. \tag{1}$$

Constraint (2) ensures the output for any production branch i, and coal type m must have adequate production such that the output can be larger than the lower bound and must not have excessive production such that the output can be less than the upper bound. Thus, the following formula is utilized to determine and describe the capacity restriction for any production branch $i \in I$, coal type $m \in M$:

$$0 \leq x_{im} \leq Y_i \cdot T_{im} \quad \forall i, m, \tag{2}$$

where:

$$x_{im} = \sum_j \sum_l \sum_n x_{ijmln} \quad \forall i, m. \tag{3}$$

The total output of production branch i can be calculated through Eq. (5). For any production branch i, the total output should satisfy the following expression:

$$0 \leq x_i \leq Y_i \cdot T_i \quad \forall i, \tag{4}$$

where:

$$x_i = \sum_j \sum_l \sum_m \sum_n x_{ijmln} \quad \forall i. \tag{5}$$

Different demand areas are subject to a limit and should satisfy Inequal. (6) for any demand area j, customer class n, and coal type m:

$$0 \leq x_{jmn} \leq T_{jmn} \quad \forall j, m, n, \tag{6}$$

where:

$$x_{jmn} = \sum_i \sum_l x_{ijmn} \quad \forall j, m, n. \tag{7}$$

The total demand in area j for the customer class n should satisfy Inequal. (8), and it can be calculated using Eq. (9):

$$0 \leq x_{jn} \leq T_{jn} \quad \forall j, n, \tag{8}$$

where:

$$x_{jn} = \sum_i \sum_m \sum_l x_{ijmln} \quad \forall j, n. \tag{9}$$

3.3.2. Soft constraints on production

For any production branch i and coal type m, Inequals. (10) and (11) ensure that the respective production plan will satisfy the requirements of each production branch. In practice, $\underline{a}_{im}$ and $\bar{a}_{im}$ can be equal.

$$Y_i \cdot \underline{a}_{im} \leq x_{im} \leq Y_i \cdot \bar{a}_{im} \quad \forall i, m, \tag{10}$$

$$Y_i \cdot \underline{A}_i \leq x_i \leq Y_i \cdot \bar{A}_i \quad \forall i. \tag{11}$$

The logic conflicts among the respective production plans can be eliminated by introducing several slack variables into Inequals. (10) and (11). Therefore, Inequals. (10) and (11) are reformulated into Inequals. (12)–(17) and Eqs. (18) and (19). A slack variable ensures that a feasible solution can be found even if the conflicting constraints exist. Eqs. (18) and (19) ensure that the coordination of the plan can only go in one direction.

$$0 \leq Y_i \cdot (\underline{a}_{im} + \underline{d}_{im}) \leq x_{im} \leq Y_i \cdot (\bar{a}_{im} + \bar{d}_{im}) \leq T_{im} \quad \forall i, m, \tag{12}$$

$$0 \leq Y_i \cdot (\underline{A}_i + \underline{d}_i) \leq x_i \leq Y_i \cdot (\bar{A}_i + \bar{d}_i) \leq T_i \quad \forall i, \tag{13}$$

$$-Y_i \cdot \underline{a}_{im} \leq \underline{d}_{im} \leq 0, \tag{14}$$

$$-Y_i \cdot \underline{A}_i \leq \underline{d}_i \leq 0, \tag{15}$$

$$0 \leq \bar{d}_{im} \leq Y_i \cdot (T_{im} - \bar{a}_{im}), \tag{16}$$

$$0 \leq \bar{d}_i \leq Y_i \cdot (T_i - \bar{A}_i), \tag{17}$$

$$\bar{d}_{im} \times \underline{d}_{im} = 0, \tag{18}$$

$$\bar{d}_i \times \underline{d}_i = 0. \tag{19}$$

3.3.3. Soft constraints on distribution

For any demand area j, coal type m, and customer class n, Inequals. (20) and (21) ensure that the respective distribution plans will satisfy the requirements of each distribution branch:

$$\underline{B}_{jmn} \leq x_{jmn} \leq \bar{B}_{jmn} \quad \forall j, m, n, \tag{20}$$

$$\underline{B}_{jn} \leq x_{jn} \leq \bar{B}_{jn} \quad \forall j, n. \tag{21}$$

Similarly, several slack variables are introduced into Inquals. (20) and (21) and we reformulate these equations into Inequals. (22)–(25) and Eqs. (26) and (27):

$$0 \leq \underline{B}_{jmn} + \underline{d}_{jmn} \leq x_{jmn} \leq \bar{B}_{jmn} + \bar{d}_{jmn} \leq T_{jmn} \quad \forall j, m, n, \tag{22}$$

$$0 \leq \underline{B}_{jn} + \underline{d}_{jn} \leq x_{jn} \leq \bar{B}_{jn} + \bar{d}_{jn} \leq T_{jn} \quad \forall j, n, \tag{23}$$

$$\underline{d}_{jmn}, \underline{d}_{jn} \leq 0, \tag{24}$$

$$\bar{d}_{jmn}, \bar{d}_{jn} \geq 0, \tag{25}$$

$$\bar{d}_{jmn} \times \underline{d}_{jmn} = 0, \tag{26}$$

$$\bar{d}_{jn} \times \underline{d}_{jn} = 0. \tag{27}$$

3.4. Economic and coordinating objectives

A coordination scheduling model is proposed based on the hard and soft constraints. Soft parameters α and β, which are the coefficients used to balance the magnitude of the subobjective function, are introduced into the two objectives.

$$\begin{aligned}\text{Objective function} &= \text{Max (income} - \text{selling cost} \\ &\quad -\text{cost of coordinated adjustment)} \\ &= \max \alpha(Z_1 - Z_2) - \beta * DBS.\end{aligned} \tag{28}$$

The income and selling costs can be formulated using Inequals. (23) and (24), respectively.

$$Z_1 = \sum_j \sum_m \sum_n \left(p_{jmn} \cdot \sum_i \sum_l x_{ijmln} \right), \tag{29}$$

$$\begin{aligned} Z_2 = &\sum_i \sum_m \left(c_{im} \cdot \sum_j \sum_l \sum_n x_{ijmln} \right) \\ &+ \sum_j \sum_m \left(c_{jm} \cdot \sum_i \sum_l \sum_n x_{ijmln} \right) \\ &+ \sum_i \sum_j \sum_n \sum_m \sum_{l(k)} p_k \cdot x_{ijmln} \\ &+ \sum_i Y_i c_i. \end{aligned} \tag{30}$$

In practice, the coordination quality is measured by the difference between the original plans and the final coordinated ones. That is, the final coordinated plans are better if they involve less changes than the original plans. Since the adjustments in the plans are measured by the changes in the formulated plans compared to the original plans, we obtain the coordinating objective as follows:

$$\begin{aligned} DBS = &Z_3 + Z_4 + Z_5 + Z_6 = \sum_i \sum_m (|\bar{d}_{im}| + |\underline{d}_{im}|) \\ &+ \sum_i (|\bar{d}_i| + |\underline{d}_i|) + \sum_j \sum_m \sum_n (|\bar{d}_{jmn}| \\ &+ |\underline{d}_{jmn}|) + \sum_j \sum_n (|\bar{d}_{jn}| + |\underline{d}_{jn}|). \end{aligned} \tag{31}$$

4. Solution algorithm

The scale of the real problem is always relatively large. In order to ensure that the operation managers can obtain a solution within a reasonable amount of time, we apply Genetic Algorithm (GA) to the proposed model. It has been successfully applied to multiple related issues, e.g., integrated scheduling and rescheduling of railway transportation [37,42], VRP solution [43], supply chain design problems [44], and transportation scheduling problems [45]; besides, the effectiveness of the algorithm has been demonstrated. The procedure for the GA employed in this study is similar to the general procedure, as defined in the following steps:

1. The GA uses real-number encoding, and the encoding structure of the chromosome is shown in Figure 3. The column indicates different decision variables and each row indicates one solution. To improve the calculation efficiency, infeasible information concerning the initial samples must be excluded. For example, the production branch a cannot produce the coal type b according to its natural condition. Therefore, the element at the column $(i^*j^*m^*n^*l+(a-1)^*m+b)$ must be set to "0", that is, $\bar{d}_{im}=0$.
2. The quality of chromosomes is evaluated. In this step, the hard and soft constraints are absorbed into the objective function, that is, the model is transformed to correspond to an unconstrained optimization. The fitness function can be expressed as follows.

$$\begin{aligned}&\text{Fitness function} = \text{Income} - \text{selling cost}\\&-\text{hard constraints penalty} - \text{soft constraints}\\&\text{penalty} - \text{cost of coordinated adjustment}\\&= \alpha\ (Z_1 - Z_2) - \text{Hard constraints} - \text{Soft}\\&\text{constraints} - \beta^*\ \text{DBS}.\end{aligned} \tag{32}$$

The hard constraints (Z_7) can be defined as a penalty for a value that is not within the range of maximum and minimum values. Therefore, we can resolve the following equation, where M is a sufficiently large positive number.

Hard constraints:

$$\begin{aligned}Z_7 =& M^*\max[0,\bar{a}_{im}+\bar{d}_{im}-T_{im}]+M^*\max\\&[0,-\underline{a}_{im}-\underline{d}_{im}]+M^*\max[0,\bar{A}_i+\bar{d}_i-T_i]\\&+M^*\max[0,-\underline{A}_i-\underline{d}_i]+M^*\max[0,\bar{B}_{jmn}\\&+\bar{d}_{jmn}-T_{jmn}]+M^*\max[0,-\underline{B}_{jmn}-\underline{d}_{jmn}]\\&+M^*\max[0,\bar{B}_{jn}+\bar{d}_{jn}-T_{jn}]\\&+M^*\max[0,-\underline{B}_{jn}-\underline{d}_{jn}]\\&+M^*\max[0,\sum_i\sum_j\sum_m\sum_{l(k)}\sum_n x_{ijmln}-d_k].\end{aligned} \tag{33}$$

Similarly, the soft constraints (Z_8) can be formulated as follows:

Soft constraints:

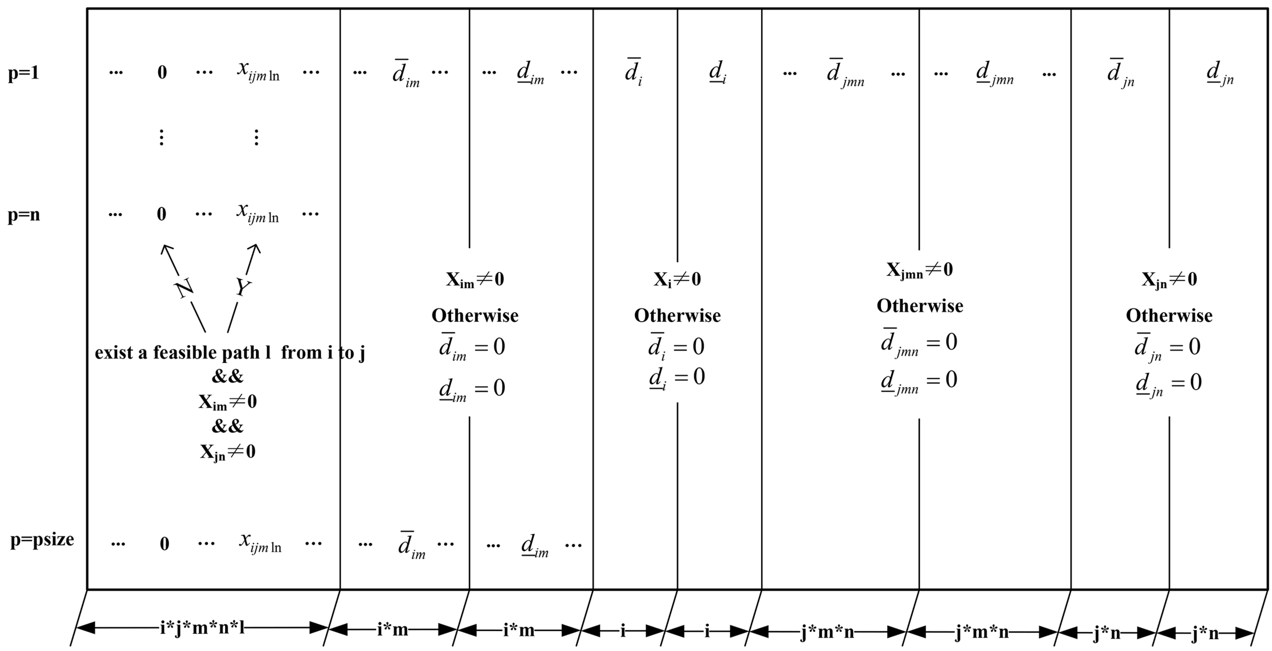

Figure 3. Encoding style and solution expression of Genetic Algorithm (GA) chromosomes.

$$Z_8 = M^* \max[0, x_{im} - \bar{a}_{im} - \bar{d}_{im}]$$
$$+ M^* \max[0, \underline{a}_{im} + \underline{d}_{im} - x_{im}]$$
$$+ M^* \max[0, x_i - \bar{A}_i - \bar{d}_i]$$
$$+ M^* \max[0, \underline{A}_i + \underline{d}_i - x_i]$$
$$+ M^* \max[0, x_{jmn} - \bar{B}_{jmn} - \bar{d}_{jmn}]$$
$$+ M^* \max[0, \underline{B}_{jmn} + \underline{d}_{jmn} - x_{jmn}]$$
$$+ M^* \max[0, x_{jn} - \bar{B}_{jn} - \bar{d}_{jn}]$$
$$+ M^* \max[0, \underline{B}_{jn} + \underline{d}_{jn} - x_{jn}]. \quad (34)$$

3. The crossover and mutation operations are two major operations, which are shown in Figure 4, and these operations can further improve the quality of solutions and enrich the diversity of solutions. An arithmetic crossover process is applied to two chromosomes at a time and two new solutions can be obtained using Eqs. (35) and (36):

$$\mathrm{X}_{p,j} = \mathrm{X}_{p+1,j} * \mathrm{rand} + \mathrm{X}_{p,j} * (1 - \mathrm{rand}), \quad (35)$$

$$\mathrm{X}_{p+1,j} = \mathrm{X}_{p,j} * \mathrm{rand} + \mathrm{X}_{p+1,j} * (1 - \mathrm{rand}). \quad (36)$$

We apply a nonuniform mutation process to one chromosome and a new solution can be obtained using Eqs. (37) and (38):

$$X_{p,j} = X_{p,j} - X_{p,j} * \mathrm{rand} * (1 - \mathrm{gen}/\mathrm{maxgen})^2, (37)$$

$$X_{p,j} = X_{p,j} + X_{p,j} * \mathrm{rand} * (1 - \mathrm{gen}/\mathrm{maxgen})^2. (38)$$

5. Discussion in a test network

We designed a test network including 7 points, 9 segments, and 1 OD demand, as shown in Figure 5. The parameters of each segment are labeled on the segment, representing, in order, the sequence number, length, capacity, and transportation cost per ton-km in the sequence. We set $i = 1$, $j = 1$=, $m = 2$, $n = 2$, and $l = 4$. The related costs and prices are given in Table 1. Table 2 lists the upper and lower bounds for the production and distribution branches. For simplicity, we assume that:

$$a_{11} = a_{12}, \quad T_{11} = T_{12}, \quad B_{111} = B_{112} = B_{121} = B_{122},$$

$$T_{111} = T_{112} = T_{121} = T_{122}, \quad B_{11} = B_{12}, \text{ and } T_{11} = T_{12}.$$

Table 1. Related costs and prices ($i = 1$, $j = 1$).

	$n = 1$		$n = 2$	
	$m = 1$	$m = 2$	$m = 1$	$m = 2$
C_{jm}	124	141	124	141
P_{jmn}	511	658	475	607
C_{jm}	5	5	5	5
C_i	5000			

Table 2. Original plans for production and distribution branches.

Parameter	Lower bounds	Upper bounds	Maximum capacity
a_{im}	40	40	#
T_{im}	#	#	50
A_i	70	90	#
T_i	#	#	100
B_{jmn}	15	20	#
T_{jmn}	#	#	25
B_{jn}	40	40	#
T_{jn}	#	#	50

5.1. Optimal results

The experiment was applied to a personal computer featuring Intel Core i5, 2.60 GHz CPU, and 4 GB RAM. The population size is 100 and the iteration terminates 500 times. The crossover and mutation rates are 0.95 and 0.10, respectively. The parameter α in the objective is set to 1 and $\beta = 200$. Table 3 presents the results of the experiment. The quality of the scheduling coordination was controlled by the objective. To attain a higher quality for coordinated plans, slight changes were made.

A comparison between calculation results and those of the other algorithms, such as Genetic Algorithm-Simulated Annealing (GASA) and PSO, is made, as shown in Table 4. Several conclusions can be derived as follows:

1. The lower bound is the condition in which the original plans from all partners are used as the final plans instead of making adjustments. The optimal results show that A_i is 80 and $a_{11} = a_{12} = 40$. The demand for any n is 40, that is, $B_{11} = B_{12} = 40$ and $T_{111} = T_{112} = T_{121} = T_{122} = 20$. All products can be digestive and all demands can be satisfied. The results show that the value of the hard constraints is $5.0^*M = 5.0e + 10$. We must refer to the network bottleneck section to provide further explanation. The outflow capacity of the network is the summation of the capacities of segments 1 and 2, which is equal to 100. The inflow capacity of the network is the summation of the capacities of segments 5, 6, and 7, being equal to 75. Thus, the capacity of the network is determined by the bottleneck section. The total supply and demand are both 80; thus, there is a capacity gap

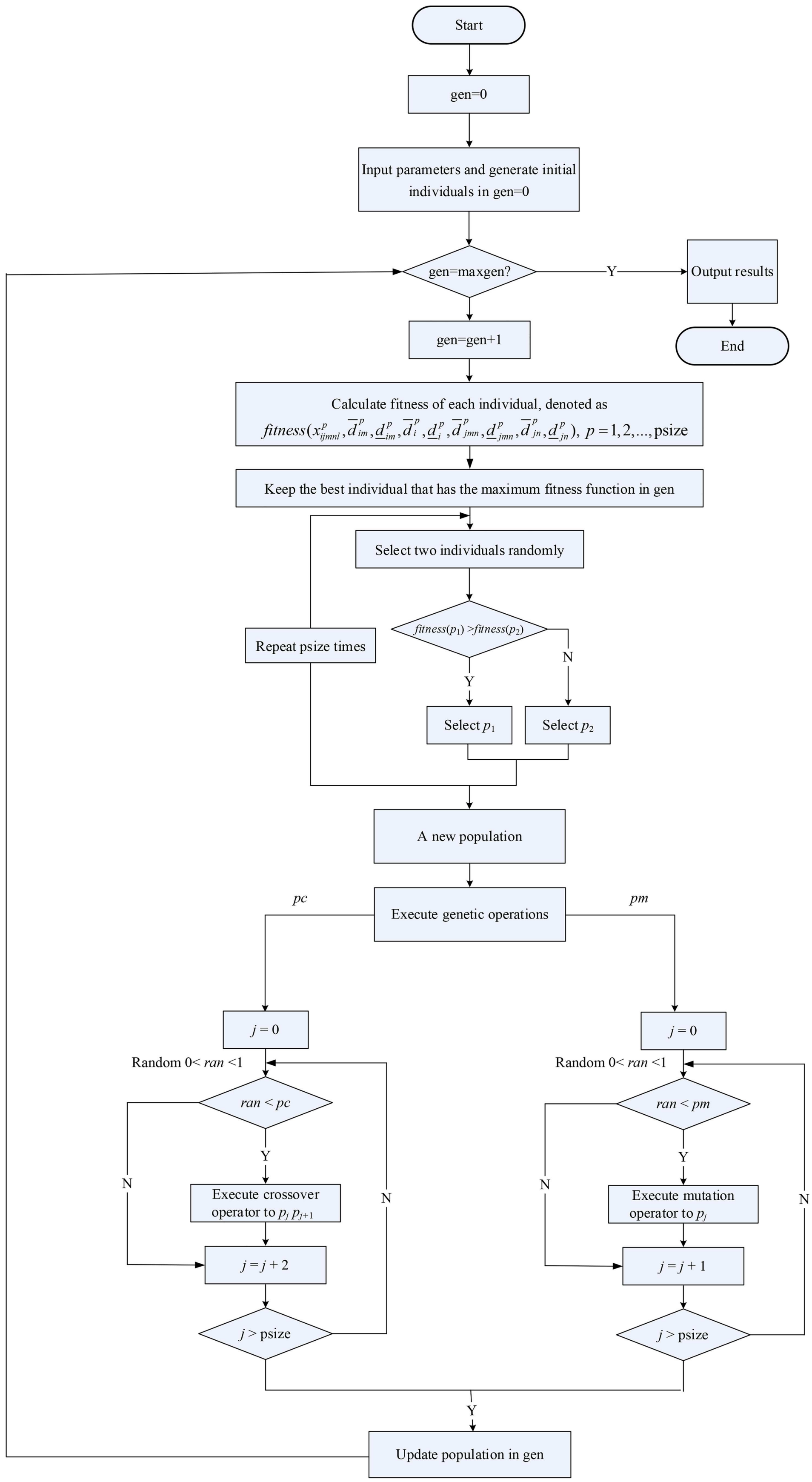

Figure 4. Process flow of the Genetic Algorithm (GA).

Table 3. Coordination results for the test network.

$\underline{a}_{im}$	$\bar{a}_{im}$	$\underline{A}_i$	$\bar{A}_i$	$\underline{B}_{jmn}$	$\bar{B}_{jmn}$	$\underline{B}_{jn}$	$\bar{B}_{jn}$
$\underline{d}_{11}$: -1.73	$\bar{d}_{11}$: 0	$\underline{d}_1$: 0	$\bar{d}_1$: 0	$\underline{d}_{111}$: 0	$\bar{d}_{111}$: 0	$\underline{d}_{11}$: -4.97	$\bar{d}_{11}$: 0
				$\underline{d}_{112}$: 0	$\bar{d}_{112}$: +0.27		
$\underline{d}_{12}$: -3.28	$\bar{d}_{12}$: 0			$\underline{d}_{121}$: 0	$\bar{d}_{121}$: 0	$\underline{d}_{12}$: -0.03	$\bar{d}_{12}$: 0
				$\underline{d}_{122}$: 0	$\bar{d}_{122}$: 0		

Table 4. Results of adjustment scheduling obtained by different methods.

Method	Hard and soft constraints	DBS				Objective	CPU (s)
		Z_3	Z_4	Z_5	Z_6		
GA	0	$1.00e+3$	0	54.13	$1.00e+3$	$1.49e+4$	32
GASA	0	$1.00e+3$	0	4.50	$1.00e+3$	$1.51e+4$	161
PSO	0	$1.00e+3$	0	0.05	$1.00e+3$	$1.50e+4$	35

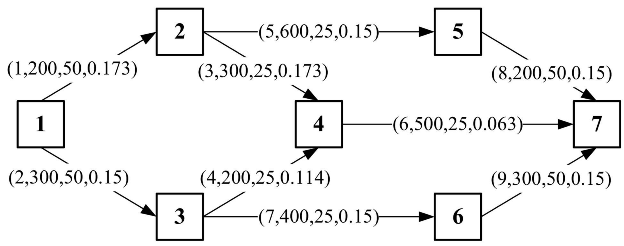

Figure 5. Simple test network.

of 5 units between the transportation capacity and demand;

2. The upper bound is the condition in which β approaches zero. This condition means that we can adjust the respective plans as long as the largest objective function can be achieved;

3. The largest differences between the algorithms correspond to the CPU time. GA can search for an optimal solution in 32 s, but similar results cost GASA and PSO approximately 161 s and 35 s, respectively. Figures 6 and 7 depict the plots of the objective value versus the iterations and the required time of each algorithm, respectively, to obtain the best solution; the y-axis represents the objective function and x-axis denotes, respectively, the corresponding generations and computational time. Clearly, GA is a good choice.

5.2. Effect of hard and soft constraints

In this section, the impact of a sensitive segment capacity and β variations on the coordination results

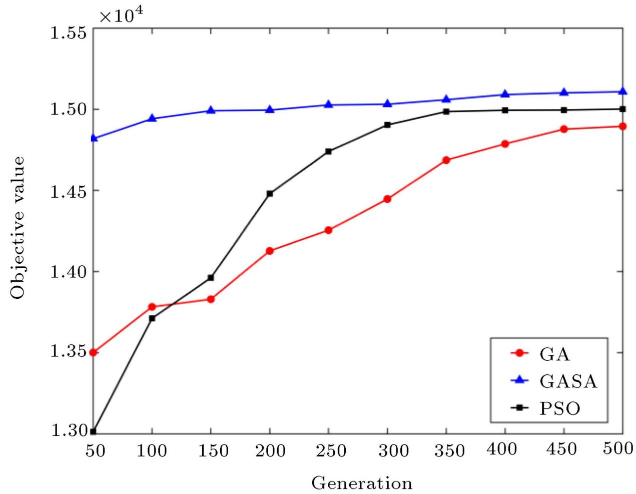

Figure 6. Genetic Algorithm (GA) convergence curve for the sample network.

for the model is explored. From Figure 8, we can see that when the sensitive segment capacity variability (such as for segment #6) and β value are at a high level, the results become similar. Due to the capacity limit effect, all the conditions in which the capacity of Segment #6 is lower than 30 will have a lower level of objective value irrespective of the value of β. The network bottleneck section can again be considered for further explanation. It is indicated that hard constraints imply a penalty of M times on exceeding capacity, which has a significant negative impact on the objective value. Thus, the model tends to avoid constraint penalties.

Next, an attempt is made to fix the capacity of

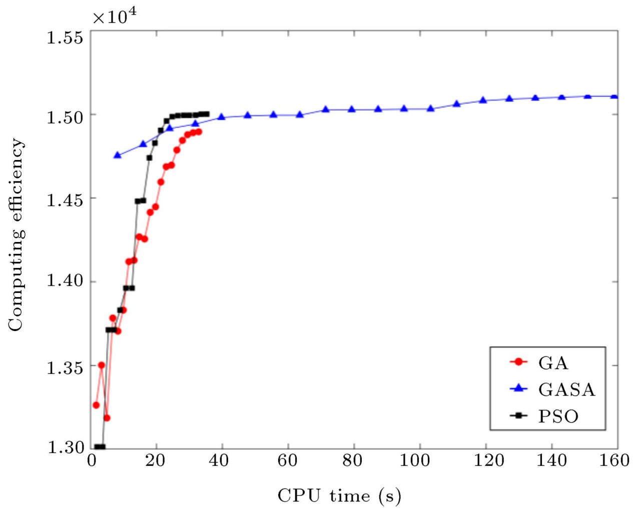

Figure 7. Time required by each algorithm to obtain its best solution.

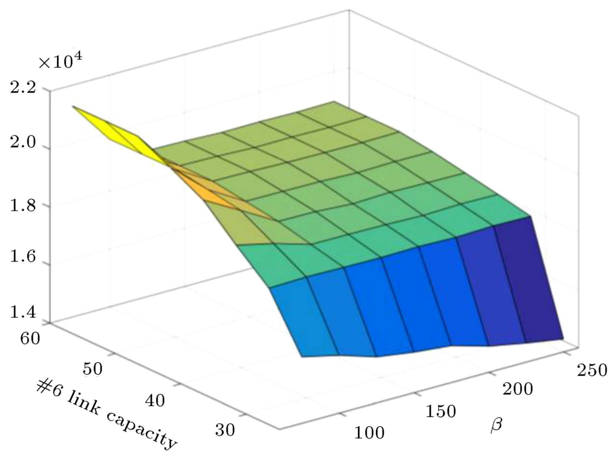

Figure 8. Illustration of the impact of sensitive segment and parameter β.

the sensitive segment #6 to be 25 and examine the impact of the key parameter β. Based on the discussion in the previous section, the model tends to avoid the significantly negative effect resulting from constraint penalties. From Table 5, we can see that the DBS reasonably exhibits an increasing tendency along with the increase in β. It can be expected that the DBS exhibits growth regularity in a reasonable range of β.

Table 6 shows the impact of the key parameters on the DBS in case of insufficient segment capacity. Here, we fix the capacity of key segment #6 to 50 and examine another notable effect of β. When the capacity of segment #6 is sufficient, the hard and soft constraints do not exert any influence. The results show that at lower β (equal to 75–125), the final coordinated plan can be used to obtain extra profit by adjusting the original plans. Inversely, at a higher $\beta (\beta \geq 150)$, extra profit cannot cover the DBS. Therefore, the DBS is 0 and the objective is stable

Table 5. Impact of β on solutions (capacity of segment 6 is set to 25).

Beta	Objective	Hard and soft constraints	DBS				CPU time (s)
			Z_3	Z_4	Z_5	Z_6	
75	1.63e+04	0	375.2	0	0	375.2	63.2
100	1.60e+04	0	500.2	0	0	500.2	63.5
125	1.56e+04	0	625.4	0	0	625.4	64.1
150	1.54e+04	0	750.2	0	0	750.2	63.9
175	1.53e+04	0	875.7	0	0	875.7	62.8
200	1.49e+04	0	1001.3	0	0	1001.3	32.7
225	1.47e+04	0	1125.7	0	0	1125.7	33.2
250	1.44e+04	0	1252.0	0	0	1252.0	39.0
275	1.42e+04	0	1376.1	0	0	1376.1	48.1
300	1.38e+04	0	1501.0	0	0	1501.0	48.9
325	1.37e+04	0	1626.1	0	0	1626.1	43.4
350	1.35e+04	0	1751.3	0	0	1751.3	57.4
400	1.28e+04	0	2001.5	0	0	2001.5	52.6
500	1.20e+04	0	2501.4	0	0	2501.4	55.0
600	1.10e+04	0	3001.1	0	0	3001.1	51.4
700	9.60e+03	0	3502.0	0	0	3502.0	51.8

Table 6. Impact of β on solutions (capacity of segment 6 is set to 50).

Beta	Objective	Hard and soft constraints	DBS				CPU time (s)
			Z_3	Z_4	Z_5	Z_6	
75	$2.13e+04$	0	1496.7	746.7	1503.7	1495.7	34.5
100	$1.98e+04$	0	1003.3	0	1003.3	1003.3	36.5
125	$1.90e+04$	0	785.9	0	786.0	785.9	37.9
150	$1.90e+04$	0	0	0	0	0	38.4
175	$1.90e+04$	0	0	0	0	0	39.4
200	$1.90e+04$	0	0	0	0	0	37.0
225	$1.90e+04$	0	0	0	0	0	36.4
250	$1.90e+04$	0	0	0	0	0	37.1

Table 7. Results for the impact of supply and demand relation.

Beta	Objective	Hard and soft constraints	DBS				CPU time (s)
			Z_3	Z_4	Z_5	Z_6	
Overdemand	$1.90e+04$	0	$2.50e+03$	$1.25e+03$	0	$2.50e+03$	32.5
Oversupply	$1.63e+04$	0	$2.51e+03$	0	$2.49e+03$	$2.49e+03$	32.4

at 1.90E+04. The coordinating results represent the tradeoff results between the extra income and DBS.

5.3. Relationship between production and demand

Finally, we examine the effect of various combinations of supply and demand scales (Table 7). In case of overdemand, the demand amount is 1.5 times that of the original scenario in the test network. Inversely, the supply amount is 1.5 times. It is reasonable to increase the number of products to coordinate plans in case of overdemand. Figure 9 shows the adjustment range. The circles in the graph express the decision variables, and the length of the vertical lines represents the adjustments of the decision variables. For example, the graph describing $\bar{d}_{im}$ and $\underline{d}_{im}$ has two points and two vertical lines. The two points represent a_{11} and a_{12}. In case of oversupply, $a_{11} = a_{12} = 1.5^{*}40 = 60$. The two vertical lines describe the adjustment direction and size. The direction of the lines is downward, indicating that $\underline{d}_{11} = \underline{d}_{12} = 10$.

6. Case study

The Shenhua Group is the world's largest coal supplier in China, and its integrated operation mode is very representative in the integrated supply chain. Multiple cooperative units participate in the integrated operation such as coal production branches, railway companies, ports companies, and power plants. However, the coordination problem becomes increasingly complicated since more conflicts occur with rapid expansion of business scale. In order to provide a more scientific and effective solution for practical work, Shenhua Group is adopted here as a case study.

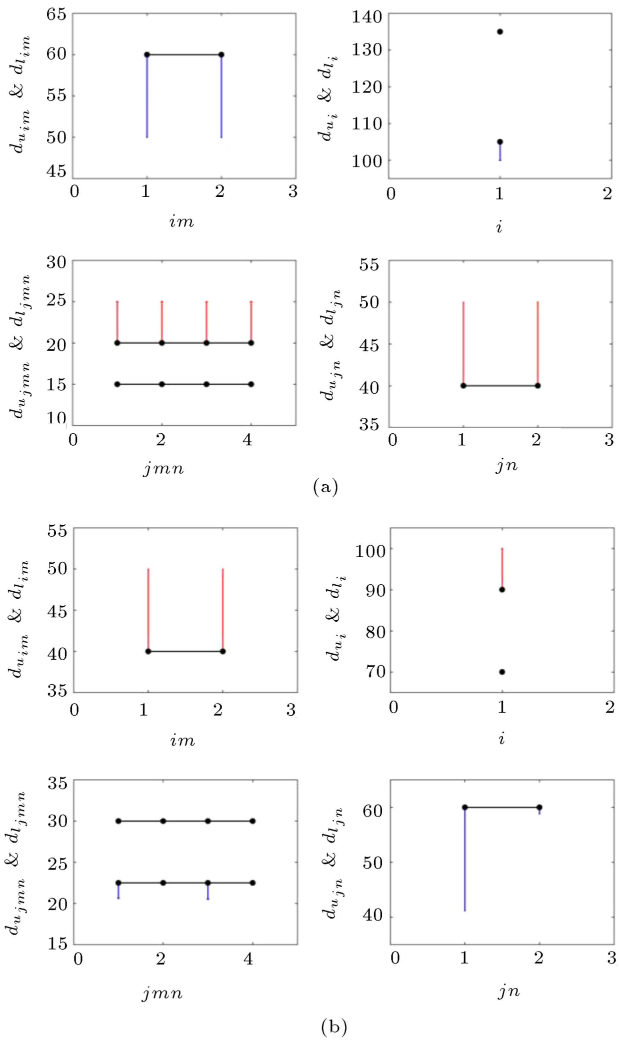

Figure 9. Optimal coordination results for the test network: (a) Oversupply and (b) overdemand.

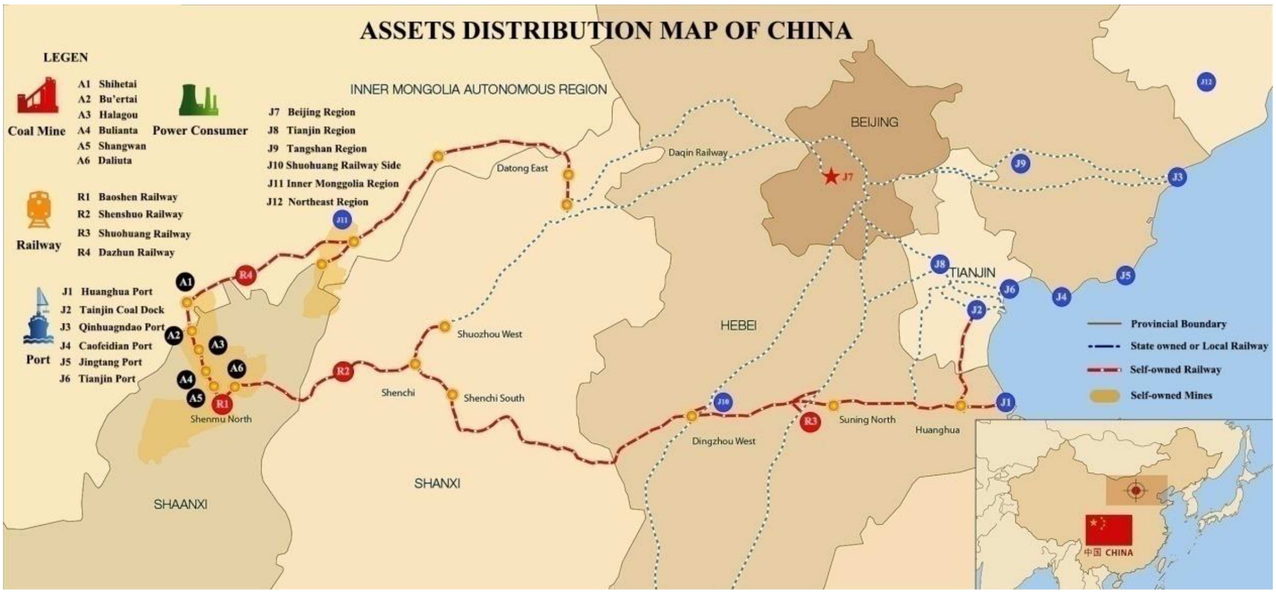

Figure 10. Asset distribution map of Shenhua Group in China.

From Figure 10, we can see that six coal production branches located in Shanxi Province and two own port companies are involved in the case study. Multiple self-owned railway lines connect production places and distribution regions. Coal is also consumed in its own power plants and other social ports and power facilities. The relevant parameters are presented in Tables 8–10. It should be noted that the upper and lower bounds listed in Table 9 are considered equal in our study, which is also entirely realistic.

Table 8. Information for production branch i.

i	C_i (10^4yuan)	$\underline{A}_i$ (10^4ton)	$\bar{A}_i$ (10^4ton)	T_i (10^4ton)
1	2515	40	200	300
2	7522	40	200	300
3	3342	40	200	300
4	4320	40	200	300
5	3077	40	200	300
6	1270	40	200	300

Table 9. Production plans from coal mine i for type m.

	m		
i	1	2	3
1	45	0	45
2	0	50	40
3	69	0	50
4	50	54	0
5	40	55	0
6	0	55	45

Table 10. Variable production cost per unit of coal for coal mine i and type m.

	m		
i	1	2	3
1	169	0	129
2	0	180	109
3	106	0	145
4	126	108	0
5	109	138	0
6	0	117	95

Without loss of generality, the demand size is the average value of the historical sale data in practice. We set:

$$[\underline{B}_{jn},\ \bar{B}_{jn}] = [30, 30], [0, Y_{jn}] = [0, 40],\ [\underline{B}_{jmn}, \bar{B}_{jmn}]$$

$$= [20, 20],\ [0, T_{jmn}] = [0, 30].$$

The other parameters are defined according to operational experience:

$$T_{im} = 100, \quad c_{jm} = 4.67, \quad \beta = 125.$$

The results for a practical setting are given in Figure 11. The network in Figure 11 presents a simple diagram of the chart presented in Figure 10.

The population size is 100 and the iteration terminates 500 times. The crossover and mutation rates are 0.90 and 0.10. From Figure 12, we can see that the trajectory of the hybrid of constraints and DBS terminates after 500 generations in 12.2 min. However,

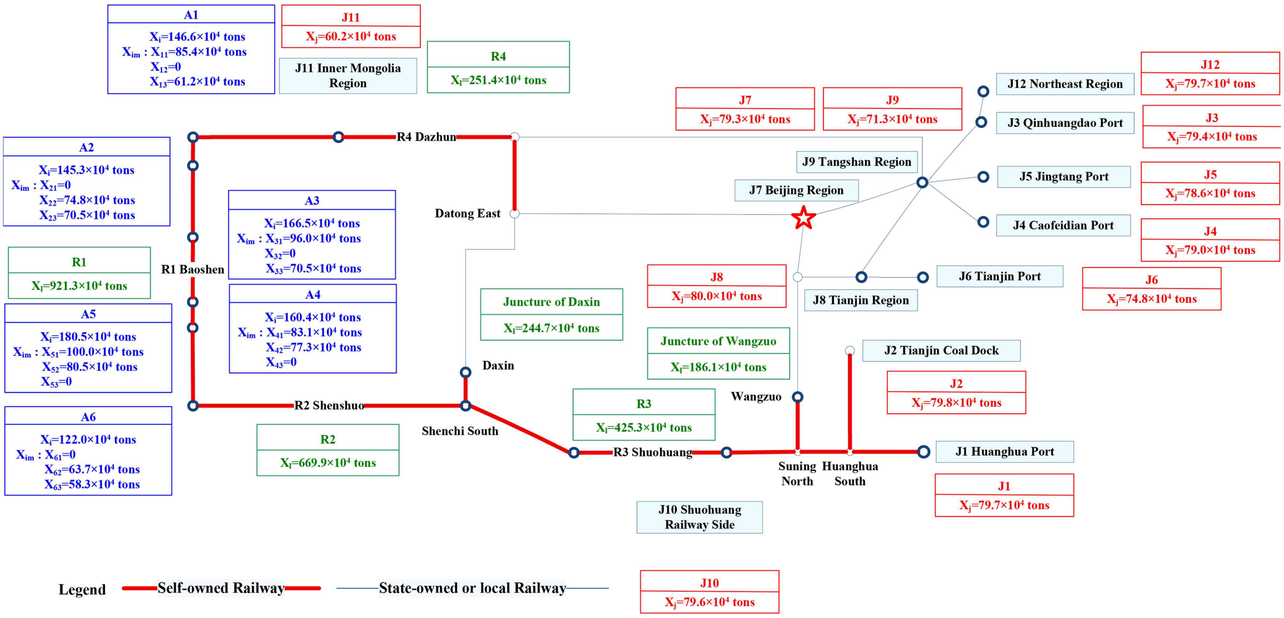

Figure 11. Practical presentation for operational plan in daily management.

Table 11. Coordination result for the network illustrated in Figure 10.

Method	Hard and soft constraints	DBS				Objective	CPU (min)
		Z_3	Z_4	Z_5	Z_6		
GA	0	$4.04e+004$	0	$6.50e+004$	$2.52e+004$	$1.0050e+005$	12.2

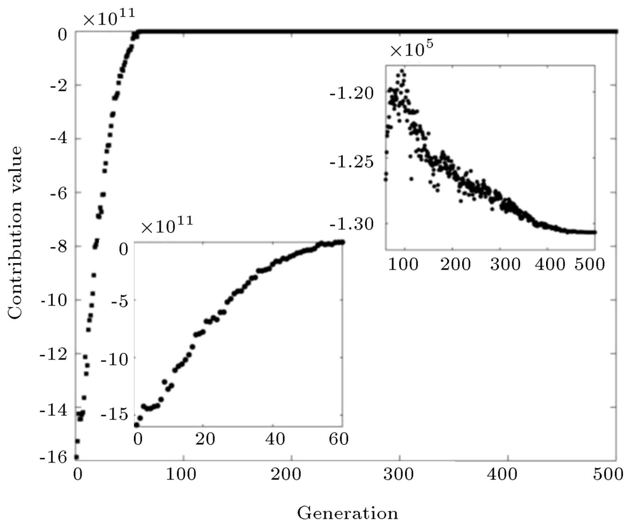

Figure 12. Trajectory of the hybrid of hard and soft constraints.

we can get an approximate optimal solution after 50 generations when making quick decisions is essential. The improvement of the objective is not notable with the increasing number of iterations. The subgraph on the left shows the iterative process of the hard and soft constraints before 60 steps, and it is noted to approach 0 rapidly. The DBS curve for 60–500 steps is zoomed in in the right subgraph, and the objective contributions are listed in Table 11.

7. Conclusions

The integrated coordination supply chain planning problem has become increasingly crucial since conflicts commonly exist among the respective plans from all branches. The contribution of this paper is the proposal of a scheduling model based on hard and soft constraints. On the one hand, we attempted to maximize the company profit and minimize the gap between the proposed plans and the coordinating plans. Due to the effect of the DBS, the problem can be seen as a tradeoff strategy between the increased profits and cost of coordinated adjustment.

The results for the Shenhua Group case suggest the following practical observations. The conflict resolution strategy that should be employed is the one that (1) functions by replacing high-intensity labor and experience-dependent leadership decision-making mechanisms and (2) promptly identifies the marginal contribution of each branch in the supply chain without tedious and repetitive statistical analysis. We compared several algorithms and all of them can obtain an optimal and similar solution. However, rapid decision response in a short time is still a challenging topic. In particular, the rescheduling method with the conditions of flexible information such as fluctuation of market demand, the weather condition, and policy change should be considered in further studies.

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