

Optimization Model for Network Path Allocation Based on New Railway Channel for Transporting Coal from a Western Province and Target User's Demands

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Abstract: At present, the railways for coal transportation from a western province are confronted with tight capacity constraints. To fully exert the important guarantee role of this province's coal in China's economic and social development, this study proposes a new railway channel construction plan for coal transportation out of this province on the basis of the national overall plan for coal transportation, so as to further optimize the channel layout. Taking coal supply capacity, coal-fired power demand, railway transportation capacity, transportation costs, route allocation volume and other factors as decision variables, and taking the minimum overall procurement cost of target power plants in Ningxia, Sichuan and Chongqing as the goal, a mathematical model for optimizing the route allocation of the coal transportation network is constructed. Furthermore, starting from considering the overall benefits of the integration of coal mines, railways and power plants, a mathematical model for optimizing the route allocation of the coal transportation network based on the integrated benefits of coal-railway-power plants is established. The model solution shows that from the perspective of the railway industry alone, this province's coal needed by the target power plants is mainly transported outward through the Lanxin Railway, supplemented by the Linha Railway, and the competitiveness of the new channel is general; from the perspective of the national overall benefits, all this province's coal needed by the target power plants is transported outward through the new channel, which can reduce the overall operating cost by about 3.5 billion yuan and realize the maximization of national overall benefits.

Keywords: Coal Export; the New Railway; Overall Benefits; Path Allocation

1. Introduction

Due to its unique endowment and strategic position, a certain western province of China occupies an irreplaceable role in China's energy system for a long time. As one of the regions with abundant coal resources in China, the estimated coal reserve in this province stands at 2.19 trillion tons, occupying over 40 percent of the country's total geological reserves. Resource distribution follows a distinct pattern of "rich reserves in the north versus the south, and abundant deposits in the east versus the west", with 98% of regional coal resources concentrated in the northern part of the province. At present, four major coalfields have taken shape in this province, namely Tuha, Zhundong, Yili and Kubai [1-3]. Among them, the Tuha Coalfield enjoys unique geographical advantages in eastern part of the province. The Zhundong Coalfield has an outbound transportation distance approximately 600 kilometers longer than that of the Tuha mining area. It focuses on the development of demonstration projects for coal power and coal chemical engineering while participating in the outbound transportation of this province's coal and the external transmission of its electric power. The Yili Coalfield centers on coal chemical and coal-fired power sectors to implement local coal conversion. The Kubai Coalfield primarily meets the demand for coal for people's livelihood and industry in southern part of the province, with moderate development of coal power and coal coking.

This province's coal resources exhibit superior inherent quality, accompanied by typical geological advantages including concentrated spatial distribution, thick and multiple coal seams, as well as shallow burial depth[4]. It is dominated by long flame coal and non caking coal with low sulfur, low ash and high calorific value. The degree of variation of coal is relatively high, and more than 80% of coal belongs to high-quality steam coal and chemical coal [5-7]. Over the

period 2017–2024, the raw coal output in this province surged from 167 million tons to 541 million tons, registering an average annual growth rate of 18.28%. The proportion of coal production in the country increased from 4.5% to 11.3%; the consumption structure is mainly based on on-site transformation, with a coal export volume of about 140 million tons in 2024, and coal consumption within this province accounting for about 74%. As a strategic successor to the traditional production areas of Shanxi, Shaanxi, and Inner Mongolia [8], this province has effectively alleviated resource depletion and ecological pressure. This province's coal supply extends to over ten provincial-level regions across Southwest, Central and South China, continuously playing a key role as the cornerstone of the national energy security strategy. Looking ahead to the future, this province will gradually improve the entire industry chain cluster of "coal electrification" during the "15th Five-Year Plan" period, continuously increase the scale of coal and electricity transmission, and play a greater role in ensuring national energy security and promoting the formation of a new pattern of western development.

With the rapid development of the economy and society, the transportation capacity of this province's railways for external connectivity is constantly improving. Currently, the railway outbound transportation framework for this province's coal resources adopts a spatial pattern of "one primary corridor and two auxiliary wings", wherein the Lanxin Railway constitutes the major trunk corridor, which runs from Alataw Pass to Lanzhou, with a total length of 2351 kilometers. Its western segment primarily serves northern part of this province as well as key ports including Alataw Pass and Khorgos, while the eastern section covers extensive areas across inland China. This transportation corridor boasts the most robust economic efficiency and the broadest radiation coverage; the "North Wing" refers to the Linha Railway, which stretches from Hami to Linhe with a total length of 1328 kilometers. Serving as a pivotal corridor, it consolidates economic linkages between this province and Northeast China while facilitating the rational exploitation of coal and other mineral resources along its entire route. Correspondingly, the "South Wing" is the Geku Railway, which extends from Korla to Golmud with a total length of 1214 kilometers. Its western segment primarily serves southern part of this province and key ports

including Irkeshtam, whereas the eastern section connects to the Lanzhou railway hub via the Lanxin Railway and the Qingzang Railway.

In recent years, with the increasing demand for this province's coal in inland areas, the railway transportation volume of coal has been increasing year by year, from 14.39 million tons in 2020 to 90.61 million tons in 2024. The proportion of railway transportation of this province's coal has remained above 50% throughout the year, as shown in Figure 1.

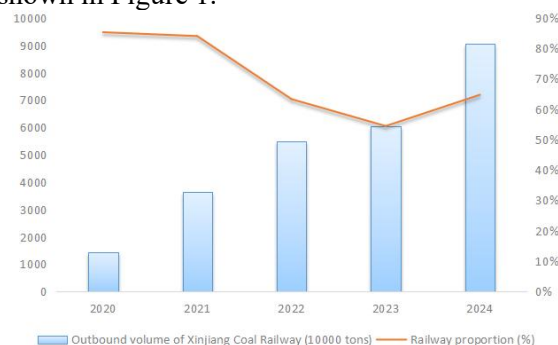


Figure 1. Schematic Diagram of This Province's Coal Railway Outward Transportation Volume Since 2020

Among these three outbound transportation corridors, the Lanxin Railway currently boasts the highest freight capacity and technical standards, serving as the core trunk route for this province's coal railway outbound transportation. By the end of 2024, the total coal transportation capacity of Linha Railway, Lanxin Railway, and Geku Railway is about 110 million tons per year. In 2024, the coal transportation volume of Lanxin Railway, Linha Railway, and Geku Railway accounted for 82.6%, 8.1%, and 9.3% of the railway transportation volume out of this province, respectively. The transportation capacity of Lanxin Railway has reached saturation. From the perspective of coal flow [9-13], Ningxia, Gansu, Sichuan, and Chongqing are the main supply provinces, accounting for 22.3%, 20.6%, 14%, and 7.6%, respectively.

In recent years, with the continuous increase in demand for coal transportation from this province, the contradiction between transportation demand and railway capacity has been constantly strengthened. Traditional railway design standards cannot meet the requirements of transportation capacity [14-15], and problems such as the lack of coordination between station and line capacity have affected this province's external coal supply guarantee. Therefore, based on the existing medium and long-term railway planning, relevant departments are conducting

research on new railway channel schemes for this province. The ultimate development goal is to increase the total freight capacity by about 120% by 2025, including an increase of about 127% in the coal transportation capacity of this province. By 2030, the total freight capacity will increase by about 50% compared to 2025, of which the capacity for transporting coal from this province will increase by about 52%.

Although the railway in this province has kept a good development trend in recent years — with both domestic freight volume and coal outbound transportation volume increasing year by year, and the railway construction plan improving steadily — there are still some obvious problems. Problem1: the current situation is that the capacity of coal transportation channels in this province is tight, and the strategic ability to serve and ensure national energy security needs to be improved. From the current operational situation of the "one main and two wings" railway channel for transporting coal from this province, the Lanxin Railway Channel is required to undertake a large number of "China-Europe Railway Express" tasks, occupying some of the coal freight capacity. In addition, the Lanxin high-speed railway is affected by various factors such as geological disasters, and its role in separating passenger trains on the Lanxin railway is relatively limited, resulting in a tense state of coal transportation on the Lanxin railway throughout the year. The Linha Railway currently operates as a single-track diesel railway; by 2024, its coal transportation volume has reached more than 80% of the designed capacity, and it also faces capacity bottlenecks. After the addition of passing stations, the coal transportation capacity of the Geku Railway has been enhanced. However, this channel is more closely linked to the southern part of this province, and the coal resource reserves within its radiation scope are much lower than those of the Lanxin Railway and the Linha Railway. During some periods, it serves as a detour channel for the Lanxin Railway, with low capacity utilization and limited contribution to the overall coal transportation of this province's railway network. Overall, the current railway channels for outward transportation from this province have the problem of "insufficient capacity and uneven utilization", and this has affected the security of energy transportation to a certain extent.

Problem2: the functional division and positioning of the outbound railway channel need to be

further optimized. From the development plan of the this province's railway channel, the Lanxin Railway Channel is positioned to guarantee coal supply and operate China-Europe freight trains in the Hexi and Southwest regions of Gansu Province. Capacity expansion measures mainly include tapping into existing facilities to improve efficiency, adjusting passenger train operation routes, optimizing locomotive operation organization, etc. However, it cannot significantly improve the freight capacity of the existing Lanxin railway. The Linha Railway Channel is positioned to serve coal transportation in regions such as Ningxia and Southwest China, provide emergency supply guarantee for Central China, East China and other regions, support the development of border areas through port interconnection, and significantly improve freight capacity through electrification transformation, second-line expansion and operation of 10000-ton trains, making it the main source of incremental capacity for the railway channels exiting this province; the Geku Railway Channel is positioned to serve coal transportation in the southwest region, which will improve traction quality and timely initiate research on the expansion of a second line. Although the Linha Railway is the focus of the next phase of capacity expansion and renovation, it is affected by the line alignment scheme. The demand for coal services along the line is relatively weak, and the distance from the Zhundong area to the Ningdong area in Ningxia is about 160 kilometers, resulting in relatively poor transportation timeliness, making it difficult to exert the auxiliary supporting effect on the Lanxin Corridor. The existing Lanxin Railway has limited potential for capacity improvement, and its capacity to guarantee coal transportation in the Hexi Corridor and the southwest region is insufficient. While the New Railway Channel, which is also part of the "one-axis" corridor, can effectively fill the coal gap in areas such as Jiujia and effectively release the medium and long-distance transportation capacity of the Lanxin Railway, its current planning and positioning fail to give full play to its alignment advantages. Overall, there is a problem of "sufficient total quantity and poor structure". From the perspective of the national overall transportation pattern, there is still scope for further optimization in the functional division of labor.

Problem3: the research depth on railway channel allocation that breaks the limitations of a single

industry and stands from the perspective of the country's overall interests is insufficient. Currently, the relevant research on the railway for transporting coal from this province to other regions within the industry mainly focuses on the perspective of railway development planning and operation, often focusing on railway capacity, layout optimization, channel division of labor [16-18], transportation costs, etc. As the main demanders for transporting coal from this province to other regions, the coal production enterprises in this province and the coal-fired power enterprises outside this province need to adapt to the channel arrangements within the railway planning framework. Their insufficient participation in the early stage of the demonstration of railway construction planning and channel division of labor has led to problems such as low railway plan fulfillment rate, insufficient guarantee of vehicle equipment, and high transportation costs after the railway is put into actual operation, which affects the operational efficiency of customers and is not conducive to the adjustment of the national "truck-to-rail" transportation structure and the promotion of the market-oriented reform of railway freight transport.

From the perspective of the main regional demand for coal transportation from this province to other regions, during the "15th Five-Year Plan" period, the proposed thermal power and coal chemical projects in Ningxia will be put into construction and operation one after another, leading to a continuous growth in coal consumption and a further increase in the demand for coal imported from this province. The Sichuan-Chongqing region has poor coal resource endowment [19] and has long been one of the main regions with structural coal shortage in China, while this province has become the second largest coal supply province. With the continuous improvement of railway channels for transporting coal from this province to other regions, how to give full play to the unique advantages of each channel, rationally allocate the transportation volume of each channel, so as to improve the overall national economic benefits, reduce the coal procurement costs of downstream users, and contribute to reducing the social logistics costs, needs further in-depth research.

According to the relevant development planning of the railway channel out of this province, the possible new railway channel out of this province starts from Wutongshui Station of Linha Railway

in the west, ends at Wuweinan Station of Lanxin Railway in the east, and then connects to Lanxin Railway. The line scheme passes through Hongshaliang, Dazhuangzi, etc., with a total length of about 900 kilometers. If completed, it can achieve the remarkable effect of parallel diversion with the Lanxin Railway channel.

In response to the problem of how to allocate transportation routes and volumes rationally to achieve the lowest procurement cost for end-users under the future railway layout, this study constructs Optimization Model of Coal Transport Network Path Assignment (CTNPA) and conducts typical case analysis; From the perspective of national socio-economic development, with the goal of minimizing overall operating costs and maximizing economic benefits, Optimization Model of Coal Transportation Network Path Assignment Based on Coal-Power Plant Integration Revenue (CTNPA-CPPIR) was further constructed. Through case analysis and verification, this model provides a reference for the selection of coal transportation channels and path allocation in this province in the future.

2. Materials and Methods

2.1 Model Construction Conditions and Variable Parameters

According to the proposed new railway channel plan in this study, a new railway pattern can be formed, mainly consisting of Lanxin Railway, New Railway Channel, and Linha Railway, with Jiangnao Railway, Naowu Railway, and Hongnao Railway as the rear assembling channels.

To present the allocation results guided by the optimal overall cost of the country, the model is constructed based on the following assumptions:

- 1) During the decision-making period, the coal transportation plan is known, and the paths and supply-demand quantity relationships of the main transportation plans are assumed to be predetermined, assuming that the attributes of the coal freight products such as the origin station, destination station, and stopping plan are predetermined.
- 2) During the decision-making period, the demand for coal freight transportation is relatively stable without significant fluctuations, and the same OD can be split.
- 3) The layout of stations and route conditions on the transportation mainline remain relatively stable, and the transportation

capacity of the route and stations does not undergo significant changes.

2.2 Objective Function

Existing studies often use a variety of models for railway route assignment, such as ant colony algorithm [20-25]. This study proposes a mathematical model for optimizing the path allocation of coal transportation networks (Optimization Model of Coal Transport Network Path Assignment, CTNPA), the objective function is shown in equation (1). The optimization objective of this model is to minimize the procurement cost of power plants based on the service path allocation of the entire coal transportation network, which is F (ten thousand yuan) in the formula.

$$\text{Min } F = \sum_{i,j \in N} \sum_{p \in P} x_{ij}^p \eta_{ij}^p \quad (1)$$

In the formula, I represents the coal mine site collection, indexed with i , that is $i \in I$; J represents the collection of power plant sites, indexed with j , that is $j \in J$; N represents the collection of railway transportation sections, indexed with n , that is $n \in N$; P represents the collection of service paths, indexed with p , $P = P_r \cup P_v$ ($p \in P$, including trunk railway service routes $pr \in Pr$, transfer service path of branch roads $pv \in Pv$); x_{ij}^p represents the coal freight volume from coal mine i to power plant j through service path p ; η_{ij}^p represents the converted transportation costs through service path p , for the freight demand from coal mine i to power plant j .

This objective function (1) only starts from the perspective of coal-fired power enterprises at the downstream of the coal consumption chain. Considering that the integrated industrial system from coal mines, railways to power plants is owned by the state, according to the principle of maximizing the overall benefits of the country, the sales revenue of coal mines and railway transportation revenue can offset some of the purchasing costs of power plants, this study further proposes a mathematical model for optimizing the path allocation of coal transportation network based on the integrated benefits of coal-railway-power plant (Optimization Model of Coal Transportation Network Path Assignment Based on Coal-Power Plant Integration Revenue, CTNPA-CPPIR), the

objective function is shown in equation (2).

$$\text{Min } F_{\text{integration}} = \sum_{i,j \in N} \sum_{p \in P} x_{ij}^p \pi_{ij}^p \quad (2)$$

In the formula, π_{ij}^p represents the converted transportation costs through service path p considering integrated benefits, for the freight demand from coal mine i to power plant j ; $F_{\text{integration}}$ represents the procurement cost of the power plant considering the benefits of integration, with a unit of 10000 yuan.

2.3 Constrained Conditions

During the optimization process, this model is constrained by factors such as coal production, railway capacity, demand of coal mine and power plant, the specific constraints are as follows.

Balancing the constraints of coal demand, production and sales, and ensuring that the allocated transportation volume can meet both the demand of power plants and the output of coal mines, and that all coal mines have export sales volume, can be expressed as equations (3-5).

$$\sum_{i \in I} q_{ij} \geq Q_j \quad \forall j \in J \quad (3)$$

$$\sum_{j \in J} q_{ij} \leq Q_i^{\max} \quad \forall i \in I \quad (4)$$

$$\sum_{j \in J} q_{ij} \geq Q_i^{\min} \quad \forall i \in I \quad (5)$$

In these formulas, Q represents the coal freight demand aggregation, $q \in Q$; Q_j represents the demand for power plant j ; q_{ij} represents the freight demand from coal mine i to power plant j ; $Q_i^{\max}$ represents the upper limit of the external supply of coal mine i ; $Q_i^{\min}$ represents the lower limit of external transportation supply for coal mine i .

Constraint on freight demand between coal mines and power plants, ensuring that the coal demand of each power plant can be met under different path sets, can be expressed as:

$$q_{ij} = \sum_{p \in P} x_{ij}^p \quad \forall i \in I, j \in J \quad (6)$$

Service arc traffic allocation constraint, the total transportation volume of the service arc is formed by summarizing the coal transportation volume of each path, can be expressed as equations (7-8).

$$y_{ij}^a = \sum_{p \in P} x_{ij}^p \delta_p^a \quad \forall a \in A, i \in I, j \in J \quad (7)$$

$$z_{ij}^n = \sum_{p \in P} x_{ij}^p \delta_p^n \quad \forall n \in N, i \in I, j \in J \quad (8)$$

In these formulas, y_{ij}^a represents the coal freight

volume from coal mine i to power plant j through service arc a ; z_{ij}^n represents the coal freight volume from coal mine i to power plant j through railway transportation section n ; δ_p^n is used to judge whether service path p is served by railway transportation section n , $\delta_p^n \in \{0, 1\}$; δ_p^a is used to judge whether service path p is being served by service arc segment a , $\delta_p^a \in \{0, 1\}$.

The constraint of line transportation capacity, ensuring that the traffic volume of each service arc does not exceed the capacity limit, can be expressed as equations (9-10).

$$\sum_{i \in I} \sum_{j \in J} y_{ij}^a \leq Cap_a \quad \forall a \in A \quad (9)$$

$$\sum_{i \in I} \sum_{j \in J} z_{ij}^n \leq Cap_n \quad \forall n \in N \quad (10)$$

In these formulas, Cap_a represents the transportation capacity of service arc a ; Cap_n represents the carrying capacity of railway transportation section n .

Decision variable constraints, can be expressed as equations (11-14). In the formula, $|^+$ represents a positive integer.

$$q_{ij} \in |^+ \quad \forall i \in I, j \in J \quad (11)$$

$$x_{ij}^p \in |^+ \quad \forall p \in P, i \in I, j \in J \quad (12)$$

$$y_{ij}^a \in |^+ \quad \forall a \in A, i \in I, j \in J \quad (13)$$

$$z_{ij}^n \in |^+ \quad \forall n \in N, i \in I, j \in J \quad (14)$$

2.4 Model Validation

This study selected five coal mines located in this province as the starting points for coal supply, and 24 power plants (referred to as PP) located in Ningxia, Sichuan, and Chongqing as coal demand points. The above-mentioned coal mines will be transported through the Lanxin Railway, the New Railway Channel, and the Linha Railway, forming a multi-path distribution network for multiple coal mines to supply multiple power plants. The geographical relationship between coal mines, power plants, and railways is shown in Figure 2.



Figure 2. Schematic Diagram of Coal Mines, Power Plants, and Railway Locations

According to the site survey, the quantity and transportation routes of coal supplied by the five coal mines to 24 power plants in 2023 are shown in Table 1. It can be seen that in 2023, the five coal mines supplied a total of 7.6049 million tons to 24 power plants, with the Lanxin Railway as the main transportation channel.

The total procurement cost of power plants under the above existing schemes is 4908.45 million yuan, and the total procurement cost of power plants after considering the integrated benefits is 4900.65 million yuan. To verify the cost-saving effect of the research model on procurement costs, the coal supply volume of coal mines and the demand volume of power plants in 2023 were respectively input into the models CTNPA and CTNPA-CPPIR. The optimized coal route allocation scheme is shown in Table 2.

According to model calculations, the total procurement cost of power plants under the CTNPA model is 4467.69 million yuan, and under the CTNPA-CPPIR model, the total procurement cost of power plants considering integrated benefits is 4390.61 million yuan, which is significantly reduced by 440.76 million yuan and 510.04 million yuan respectively compared to the actual transportation plan, resulting in significant cost savings. It is worth noting that the New Railway and Wuhu Railway have not yet been built in 2023, and the actual procurement plan of the power plant is affected by various factors such as customer loyalty and coal price fluctuations. The optimized calculation results of the model have some differences from the actual situation, and are only for comparative verification purposes.

Table 1. Actual Situation of Coal Mine Transportation Allocation in 2023

Coal	Power plant	Transportation route	Transportation Volume (10000 tons)
Coal-A	PP1	Wujiang-Lanxin-Baolan	20.0
Coal-A	PP2	Wujiang-Lanxin-Baolan	50.0
Coal-A	PP3	Wujiang-Lanxin-Baolan	25.0
Coal-A	PP6	Wujiang-Lanxin-Baolan	10.0
Coal-A	PP7	Wujiang-Lanxin-Baolan	40.0
Coal-A	PP8	Wujiang-Lanxin-Baolan	30.0
Coal-A	PP9	Lanxin-Baolan	30.0
Coal-A	PP13	Wujiang-Lanxin-Baolan-Taizhong	11.5
Coal-A	PP14	Wujiang-Lanxin-Baolan-Taizhong	10.0
Coal-A	PP15	Wujiang-Lanxin-Baolan-Taizhong	20.0
Coal-A	PP17	Wujiang-Lanxin	27.8
Coal-A	PP20	Lanxin	17.0

Coal-B	PP4	Wujiang-Lanxin-Baolan	50.0
Coal-B	PP22	Wujiang-Lanxin	5.0
Coal-B	PP24	Wujiang-Lanxin	26.9
Coal-C	PP5	Wujiang-Lanxin-Baolan	20.0
Coal-C	PP12	Wujiang-Lanxin-Baolan-Taizhong	20.0
Coal-C	PP19	Wujiang-Lanxin	30.0
Coal-D	PP10	Lanxin-Baolan	70.0
Coal-D	PP23	Lanxin	87.9
Coal-E	PP11	Lanxin-Baolan	70.0
Coal-E	PP16	Lanxin	24.0
Coal-E	PP18	Lanxin	22.4
Coal-E	PP21	Lanxin	43.0
Total			760.49

Table 2. Optimized Coal Mine Transportation Allocation in 2023

Coal	Power plant	Transportation route	Transportation Volume (10000 tons)
Coal-A	PP1	Jiangnao-Wuhu-Linha-Baolan	20
Coal-A	PP2	Jiangnao-Wuhu-Linha-Baolan	50
Coal-A	PP3	Jiangnao-Wuhu-Linha-Baolan	25
Coal-A	PP5	Wujiang-Lanxin-Baolan-Taizhong	20
Coal-A	PP6	Wujiang-Lanxin-Baolan	10
Coal-A	PP7	Wujiang-Lanxin-Baolan	40
Coal-A	PP8	Wujiang-Lanxin-Baolan	30
Coal-A	PP9	Wujiang-Lanxin-Baolan	8.5
Coal-A	PP10	Jiangnao-Wuhu-Linha-Baolan	70
Coal-A	PP11	Wujiang-Lanxin-Baolan	70
Coal-A	PP12	Wujiang-Lanxin-Baolan-Taizhong	20
Coal-A	PP14	Wujiang-Lanxin-Baolan-Taizhong	10
Coal-A	PP15	Jiangnao-Wuhu-Linha-Baolan	20
Coal-A	PP17	Wujiang-Lanxin	27.84
Coal-A	PP18	Wujiang-Lanxin	22.39
Coal-A	PP19	Wujiang-Lanxin	2
Coal-A	PP20	Wujiang-Lanxin	17
Coal-A	PP23	Wujiang-Lanxin	25.86
Coal-A	PP24	Wujiang-Lanxin	26.9
Coal-B	PP4	Wujiang-Lanxin-Baolan-Taizhong	50
Coal-B	PP13	Jiangnao-Wuhu-New Railway	11.5
Coal-B	PP16	Wujiang-Lanxin	24
Coal-B	PP23	Jiangnao-Wuhu-New Railway	46
Coal-C	PP19	Wujiang-Lanxin	33
Coal-D	PP9	Lanxin-Baolan	21.5
Coal-E	PP21	Wujiang-Lanxin	42.96
Coal-E	PP23	Wujiang-Lanxin	16.04
Total			760.49

3. Results and Discussion

3.1 Case Description and Selection of Relevant Parameters

This study focuses on the aforementioned five coal mines and 24 power plants, conducting model analysis based on projected future annual supply and demand data. By 2030, the production and available external transport volumes for each coal mine are shown in Table 3, with a total production of 176 million tons and a total available external transport volume of 56.95 million tons.

Table 3. Coal Mine Production and Outward Transportation Volume

Coal	Production capacity by 2030 (10000 tons)	Forecast production for 2030 (10000 tons)	Forecast outbound volume for 2030 (10000 tons)
Coal-A	6000	6000	2555
Coal-B	4500	4500	208
Coal-C	600	600	339
Coal-D	3500	3500	1711
Coal-E	3000	3000	883
Total	17600	17600	5695

By 2030, the coal demand of power plants is expected to be as shown in Table 4, with a total demand of 42.15 million tons, including 24.91 million tons in the Ningxia region, 13.46 million tons in the Sichuan region, and 3.78 million tons in the Chongqing region.

Table 4. Coal Demand for Power Plants in Target Regions by 2030

Target power plant	Location	The demand for coal in this province (10000 tons)
PP1	Ningxia	68
PP2	Ningxia	140
PP3	Ningxia	91
PP4	Ningxia	140
PP5	Ningxia	210
PP6	Ningxia	128
PP7	Ningxia	148
PP8	Ningxia	146
PP9	Ningxia	427
PP10	Ningxia	136
PP11	Ningxia	377
PP12	Ningxia	216
PP13	Ningxia	85
PP14	Ningxia	128
PP15	Ningxia	51
PP16	Sichuan	475
PP17	Sichuan	574
PP18	Sichuan	93
PP19	Sichuan	71
PP20	Sichuan	64
PP21	Sichuan	69
PP22	Chongqing	46

PP23	Chongqing	85
PP24	Chongqing	247
Total		4215

Based on the expansion and renovation of the Linha Railway, the station and hub renovation of the Lanxin Railway, the New Railway, and the planned railway design of Naowu, the available transportation capacity of each railway is shown in Table 5.

Table 5. Coal Demand for Power Plants in Target Regions by 2030

Serial number	Railway	Transportation capacity(10000 tons/year)
1	Jiangnao	10000
2	Linha	10000
3	the New Railway	5100
4	Lanxin	2000
5	Ganwu	10000
6	Baolan	8500
7	Wujiang	10000
8	Taizhong	1200

3.2 Model Solving and Analysis

Substitute the initial data into the model for solving, calculating under two scenarios: whether to consider integrated benefits (benchmark data) and considering integrated benefits, the transportation route plan for the target power plants supplied by each coal mine in 2030 is obtained, as well as the carrying capacity of each railway transportation section. Among them, the plan that does not consider the integrated benefit scenario is shown in Table 6, and its traffic distribution is shown in Figure 3.

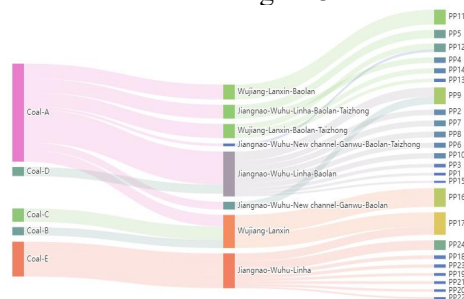


Figure 3. Schematic Diagram of Transportation Allocation Scheme without Considering the Integration

Table 6. Transportation Allocation Plan without Considering the Integration

Coal	Power plant	Transportation route	Transportation Volume (10000 tons)
Coal-A	PP1	Jiangnao-Linha-Baolan	68
Coal-A	PP2	Jiangnao-Linha-Baolan	140
Coal-A	PP3	Jiangnao-Linha-Baolan	91
Coal-A	PP4	Jiangnao-Linha-Baolan-Taizhong	140

Coal-A	PP5	Jiangnao-Linha-Baolan-Taizhong	210
Coal-A	PP6	Jiangnao-Linha-Baolan	128
Coal-A	PP7	Jiangnao-Linha-Baolan	148
Coal-A	PP8	Jiangnao-Linha-Baolan	146
Coal-A	PP9	Jiangnao-New Railway-Ganwu-Baolan	197
Coal-A	PP10	Jiangnao-Linha-Baolan	136
Coal-A	PP11	Wujiang-Lanxin-Baolan	377
Coal-A	PP12	Jiangnao-New Railway-Ganwu-Baolan-Taizhong	69
Coal-A	PP12	Wujiang-Lanxin-Baolan-Taizhong	147
Coal-A	PP13	Wujiang-Lanxin-Baolan-Taizhong	85
Coal-A	PP14	Wujiang-Lanxin-Baolan-Taizhong	128
Coal-A	PP15	Jiangnao-Linha-Baolan	51
Coal-A	PP16	Wujiang-Lanxin	267
Coal-A	PP17	Wujiang-Lanxin	27
Coal-B	PP16	Wujiang-Lanxin	208
Coal-D	PP9	Jiangnao-Linha-Baolan	230
Coal-C	PP17	Wujiang-Lanxin	339
Coal-E	PP17	Jiangnao-Linha	208
Coal-E	PP18	Jiangnao-Linha	93
Coal-E	PP19	Jiangnao-Linha	71
Coal-E	PP20	Jiangnao-Linha	64
Coal-E	PP21	Jiangnao-Linha	69
Coal-E	PP22	Jiangnao-Linha	46
Coal-E	PP23	Jiangnao-Linha	85
Coal-E	PP24	Jiangnao-Linha	247

The plan considering the integrated benefit scenario is shown in Table 7, and its traffic distribution is shown in Figure 4.

Table 7. Transportation Allocation Plan Considering the Integration

Coal	Power plant	Transportation route	Transportation Volume (10000 tons)
Coal-A	PP1	Jiangnao-New Railway-Ganwu-Baolan	68
Coal-A	PP2	Jiangnao-New Railway-Ganwu-Baolan	140
Coal-A	PP3	Jiangnao-New Railway-Ganwu-Baolan	91
Coal-A	PP4	Jiangnao-New Railway-Ganwu-Baolan-Taizhong	140
Coal-A	PP5	Jiangnao-New Railway-Ganwu-Baolan-Taizhong	210
Coal-A	PP7	Jiangnao-New Railway-Ganwu-Baolan	46
Coal-A	PP8	Jiangnao-New Railway-Ganwu-Baolan	146
Coal-A	PP9	Jiangnao-New Railway-Ganwu-Baolan	427
Coal-A	PP10	Jiangnao-New Railway-Ganwu-Baolan	136

Coal-A	PP11	Jiangnao-New Railway-Ganwu-Baolan	293
Coal-A	PP12	Jiangnao-New Railway-Ganwu-Baolan-Taizhong	216
Coal-A	PP13	Jiangnao-New Railway-Ganwu-Baolan-Taizhong	85
Coal-A	PP14	Jiangnao-New Railway-Ganwu-Baolan-Taizhong	128
Coal-A	PP15	Jiangnao-New Railway-Ganwu-Baolan	51
Coal-A	PP22	Jiangnao-New Railway	46
Coal-A	PP23	Jiangnao-New Railway	85
Coal-A	PP24	Jiangnao-New Railway	247
Coal-B	PP17	Jiangnao-New Railway	139
Coal-B	PP21	Jiangnao-New Railway	69
Coal-D	PP6	Linha-New Railway-Ganwu-Baolan	128
Coal-D	PP7	Linha-New Railway-Ganwu-Baolan	102
Coal-C	PP11	Jiangnao-New Railway-Ganwu-Baolan	84
Coal-C	PP17	Jiangnao-New Railway	255
Coal-E	PP16	Jiangnao-New Railway	475
Coal-E	PP17	Jiangnao-New Railway	180
Coal-E	PP18	Jiangnao-New Railway	93
Coal-E	PP19	Jiangnao-New Railway	71
Coal-E	PP20	Jiangnao-New Railway	64

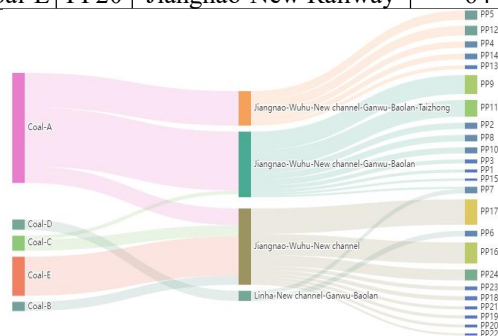


Figure 4. Schematic Diagram of Integrated Transportation Allocation Scheme

Without considering the integrated scenario, the total objective function value of the model is 24710.7 million yuan, while when considering the integrated scenario, the total objective function value of the model is 21177.8 million yuan. Under the scenario of integrated benefits, the comprehensive cost is lower, which can further reduce procurement costs by about 3.5 billion yuan, reflecting significant advantages in the overall benefits of integration; from the perspective of coal procurement sources for power plants, according to the integrated scenario, 15 out of 24 power plants have experienced changes in coal sources. For example, the 690000 tons of coal originally supplied by coal mine E through the Linha railway channel for power plant 21 has been changed to be supplied by coal

mine B and transferred to the New Railway.

Without considering the integrated scenario, the transportation capacity of the Lanxin Railway reaches 100%, while the New Railway only has a transportation volume of 2.66 million tons. When considering the integrated benefits, the transportation volume of the Lanxin Railway is transferred to the New Railway, and the transportation volumes of the Jiangnao Railway and the Ganwu Railway are also increased, as shown in Table 8.

Table 8. Changes in Railway Transportation Volume (10000 tons).

Railway	Without considering the integration	Considering the integration
Jiangnao	2215	3985
Linha	1949	230
Lanxin	2000	0
Baolan	2491	2491
Wujiang	2000	0
Taizhong	350	350
New Railway	266	4215
Ganwu	266	2491

4. Conclusions

To further implement and refine the national planning scheme for the layout of coal transportation channels from this province, effectively alleviate the current tight capacity of railways departing this province, clarify the functional positioning of each channel, optimize the allocation of traffic volume and flow direction among different channels, effectively improve the service guarantee capacity of coal transportation from this province, the model for optimizing coal transportation network path allocation (CTNPA) and the model for optimizing coal transportation network path allocation based on the integrated benefits of coal-power plants-railway (CTNPA-CPPIR) have been constructed, taking the coal sales plans of 5 coal mines within this province and 24 power plants outside this province as examples, the following conclusions were drawn through analysis.

(1) According to the CTNPA model calculation, the transportation cost of the above-mentioned coal mines from this province to power plants in Ningxia, Sichuan, and Chongqing is the lowest through the Lanxin Railway, followed by the Linha Railway, and the highest through the New Railway. By 2030, the 42.15 million tons of coal required by the power plants will be prioritized through the Lanxin Railway, fully utilizing the abundant capacity of the Lanxin Railway and

mainly transported to Sichuan, Chongqing, and southern Ningxia. The rest of the coal will be transported through the Linha Railway and mainly transported to the northern and central parts of Ningxia, serving as a backup channel for Sichuan and Chongqing. Only from the perspective of transportation cost, this plan has the lowest procurement cost for the power plant.

(2) Considering that the New Railway, coal mines within this province, and power plants outside this province are all national economic entities, starting from the overall national benefits, the CTNPA-CPPIR model is used to calculate that all power plants purchase this province' coal through the New Railway, reducing the overall procurement cost by about 3.5 billion yuan, achieving the maximization of national overall benefits, and fully mobilizing the transportation enthusiasm of enterprises.

(3) The New Railway out of this province can fully utilize the gathering capacity of the newly-built Jiangnao Railway and Naowu Railway, effectively alleviate the capacity shortage of the Lanxin Railway, and fill the regional channel gap. Its functional positioning should be further scientifically demonstrated, and its advantages in line location should be fully utilized.

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