Traffic & Transportation

Comprehensive Optimisation Study of Train Formation Plans at Loading Stations Considering Multi-Shipment Direct Trains

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Original Scientific Paper
Submitted: 15 Jan 2025
Accepted: 6 May 2025
Published: 30 Mar 2026

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Publisher:
Faculty of Transport and Traffic Sciences, University of Zagreb

ABSTRACT

This paper analyses the situation where the car flows at loading stations are small and concentrated, and based on existing literature, proposes an optimisation model for multi-modal transportation in loading station train formation plans. This model transports small car flows by adding two types of multi-shipment direct trains. Based on this, an optimised train formation plan model for loading stations, considering multi-shipment direct trains, was designed. This model is a nonlinear 0-1 integer programming model that satisfies constraints such as the uniqueness of car flow organisation, reclassification capacity constraints at technical stations, conditions for operating direct trains from the loading station and small car flow organisation constraints. The objective is to minimise the costs associated with loading, unloading and reclassification during transportation. To enable the use of commercial solvers for solving the model, linearisation techniques were applied to convert the model into a linear form. Finally, the model is solved using Gurobi, with the example of the Northern Passage of Xinjiang Coal Transportation. According to the results, 6 multi-shipment direct trains are organised from the loading station to the unloading station, 3 multi-shipment direct trains are sent to the technical station en route, 2 groups of car flows are sent to the first technical station by local trains, and 10 other groups of car flows are organised into direct trains from the loading station to the technical station. The total cost is 28,922.6 train hours. Additionally, comparing the experimental results with the scheme that only uses local or detachable trains to transport small car flows demonstrates the effectiveness of the proposed model, As a result, the total train-hour consumption was reduced by 9.273% compared to the formation plan without considering multi-shipment direct trains. The utilisation rates of reclassification capacity at the two technical stations decreased by 100% and 25.57%, respectively. The case study fully demonstrates the effectiveness of the proposed model.

KEYWORDS

railway loading station; train formation plan; multi-shipment direct train; 0-1 programming model.

1. INTRODUCTION

Rail transport, with its competitive advantages of high capacity, low cost, low energy consumption and minimal pollution, has become a dominant mode for medium-to-long distance and bulk freight transport. It plays a vital role in the transportation of coal from Xinjiang. During the 2023 National People's Congress (NPC) and Chinese People's Political Consultative Conference (CPPCC), NPC deputies explicitly proposed accelerating the construction of the "Xinjiang coal outbound" transportation corridors and supporting infrastructure, as well as promoting the capacity expansion of the northern, central and southern corridors for Xinjiang coal transport. Among these, the northern corridor is responsible for coal transportation from Inner Mongolia and the Beijing-Tianjin-Hebei region. The primary freight directions in the Inner Mongolia and Beijing-Tianjin-Hebei regions are derived from the key loading stations along the northern corridor, such as Sangezhuang, Wangbu and Shanshan, located at the western end of the Lianha Railway. These loading stations are not only densely distributed but also characterised by relatively small freight flows and a concentration of flows in specific directions.

The Train Formation Plan (TFP) serves as a crucial foundation for the railway transportation organisation. It is not only a long-term and medium-term technical guideline for railway operations, but also the basis for formulating train schedules. The Train Formation Plan in Loading Stations (TFLS), as an important branch of the TFP, primarily organises multi-shipment direct trains based on the originating car flow from loading stations. TFLS can significantly reduce the pressure on technical stations and improve the direct rate of the originating car flow. Among them, multi-shipment direct trains can consolidate different destinations from the same or different loading stations into a single train. This approach not only improves the transportation efficiency of small car flows but also reduces the process of transporting small flows to the first technical station using small trains or through coupling and detaching operations. Given the characteristics of loading and unloading stations along the northern Xinjiang coal transportation corridor, the study of train formation plans for loading stations, considering multi-shipment direct trains, is of great significance.

Research on train formation planning has a long history both domestically and internationally, and can generally be divided into two main categories. The first category focuses on train formation planning at technical stations, often referred to as the traditional Train Formation Problem (TFP). The second category addresses the train formation planning at loading stations, known as the Train Formation at Loading Stations (TFLS) problem.

In the area of technical station train formation planning, Bodin et al. [1] viewed the train formation problem as a multi-commodity flow problem, where constraints such as balance and capacity laid the foundation for subsequent research. Haghani [2] developed a mixed-integer programming model with a nonlinear objective function and linear constraints, which not only involves car flow paths and train formation plans but also addresses the issue of empty car allocation. Lin et al. [3] proposed an efficient simulated annealing algorithm for large-scale train formation problems and validated it with a large-scale instance from the Chinese railway system, which includes 5,544 stations and over 520,000 batches of freight, producing an excellent formation plan. Keaton [4] developed a mixed-integer programming model to determine train departure frequencies, train paths and formation plans, and used Lagrangian relaxation to solve the model. However, the study lacked constraints on train sizes, resulting in optimal solutions that included overloaded trains. Building on previous work, Keaton [5] proposed a fully integer linear programming model with additional restrictions on the number of technical stations and maximum travel times from origin to destination. Another difference from his earlier work was the use of a dual adjustment procedure for relaxation to avoid overloaded trains, addressing the shortcomings of his earlier model. Badetskii [6] suggested that train formation plans, as long-term transportation plans, should consider the variability of car flow numbers during their development. To achieve this, he introduced the concept of fuzzy sets and proposed a method for determining the optimal flow threshold under uneven conditions. The use of variable standards in train formation planning can enhance its stability, reduce the number of adjustments and lower operational costs. Liang Dong [7], based on the introduction of step functions, proposed a 0-1 programming model for technical station grouping train formation plans. Through numerical examples, the model's effectiveness was validated, and its characteristics and applicable range were summarised. Xiao [8] proposed a comprehensive optimisation model for single and double group train formation plans in his research. A greedy algorithm was developed to solve the model, and the model and solution were tested in 19 actual freight yard railway subnetworks in China.

In the field of loading station train formation planning, Lin et al. [9] constructed a nonlinear 0-1 programming model for loading station formation plans, based on the necessary conditions for organising direct trains and the selection of relevant parameters. Cao [10] developed a nonlinear 0-1 programming model for the scheduling of direct trains from loading stations, considering not only the transportation costs incurred during the train's journey but also incorporating inventory costs into the objective function. Li [11] introduced triple 0-1 decision variables from the perspective of logistics systems to build an optimisation model for train route organisation. Bo et al. [12] constructed a linear 0-1 programming model to validate the reasonableness of organising direct trains from loading stations with small volumes or loading stations that, despite having large volumes, cannot meet the conditions for full train departures. Wang et al. [13] developed a comprehensive optimisation model for loading station direct, technical direct and sectional train formation plans. By combining numerical examples, the model produced an optimised flow organisation plan with the least car-hour consumption, and through comparative analysis, the necessity and reasonableness of incorporating the conditions for sectional train operation into the comprehensive optimisation of train formation plans were verified. Jie [14] established an optimisation model for heavy-load technical direct train destination distribution, forming a relatively complete method for matching direct and heavy-load technical direct train formation plans. The method was validated with a numerical example of a non-linear network structure. Zhao [15] and others, considering the special requirements of loading stations, developed an optimisation model for the formation plan of step-by-step direct trains, with the objective of minimising train delays caused by passing multiple loading stations. They performed a real-case analysis based on data from the Chinese railway system.

In terms of solving the train formation plan, most scholars today employ heuristic algorithms to optimise train formation plans. Ahuja et al. [16] proposed a large-scale neighbourhood search algorithm to address train formation plan optimisation problems. Belosevic [17] introduced a multi-stage train formation optimisation model based on a variable neighbourhood search algorithm, which enhances local search capability by altering the neighbourhood structure during the search process. Ruf [18] proposed an adaptive large neighbourhood search algorithm to solve the integrated planning problem of railway formation yards. This algorithm combines multiple local search strategies and dynamically adjusts the neighbourhood structure to handle multi-level train formation, route allocation and resource scheduling problems. Zhang et al. [19] decomposed the train formation problem at classification yards into two subproblems and applied a two-stage decomposition algorithm to solve each subproblem independently, significantly improving solution efficiency. For medium-to-large-scale problems, the author used heuristic methods (such as greedy algorithms or local search) to initialise feasible solutions and further optimised them using linear relaxation or Lagrangian relaxation. Yaghini [20] designed a hybrid algorithm combining simulated annealing and the simplex method for solving train formation plan problems, where simulated annealing explores the solution space, and the simplex method evaluates and selects the neighbourhood of the current solution. Carey [21], by comprehensively considering factors such as departure lines, platforms and train route selection, proposed a train operation route optimisation model and solved it using multiple search strategies. Li [22] studied optimisation algorithms for single-group train formation plans and proposed a positive feedback search algorithm based on absolute conditions. This algorithm directly generates train flows by selecting eligible car flows, while for ineligible car flows, it optimises the process by probabilistically selecting the target station.

In summary, existing research on the optimisation of technical station train formation plans has developed relatively mature models and solution frameworks. However, studies focusing on loading station train formation plans are less abundant. Among the existing studies, Zhao [15] and others proposed a step-by-step direct train model for small car flows, but it was not integrated with other car flow organisation methods at the loading station. As a result, the optimisation of multi-modal train formation plans at loading stations remains underdeveloped.

2. PROBLEM DESCRIPTION AND ASSUMPTIONS

2.1 Problem description

In practice, the northern Xinjiang coal transportation corridor not only handles bulk freight such as coal, coke and containers, but also carries smaller freight flows, including speciality products, daily necessities, fertilisers and pesticides along the same route. For the small car flows generated at loading stations, the traditional transportation method involves using coupling/detaching trains or small shunting trains to transport these flows to the first technical station in the train's direction of travel, where they are reconfigured and integrated into the technical flow of the station. This method not only occupies the reconfiguration capacity of the technical station but also reduces its transportation efficiency. Therefore, adopting multi-shipment direct trains to consolidate small car flows into a single train not only saves the reconfiguration capacity of the technical stations but also improves the transportation efficiency of the small flows.

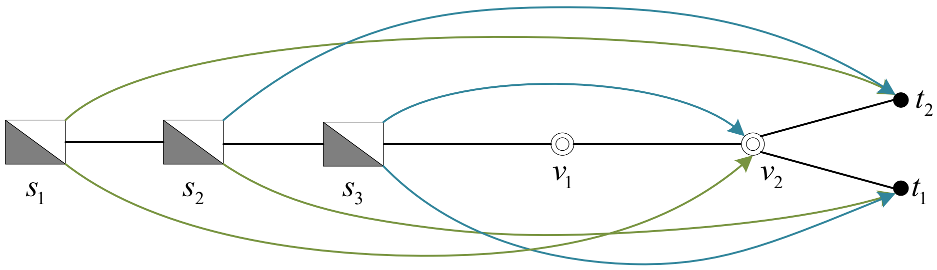

Figure 1 – The example of the train formation plan at loading stations considering multi-shipment trains

Figure 1 illustrates a simple diagram of the car flow at a loading station, which includes three loading stations (denoted as s_1, s_2 and s_3), two technical stations (denoted as v_1 and v_2), and two unloading stations (denoted as t_1 and t_2). This loading station has six car flows, where green lines represent smaller flows and blue lines represent larger flows. For this example, there are many ways to combine or directly transport these six groups of car flows. *Figure 2* shows several common transportation methods.

1) For the small car flows (denoted as $q_{s_1t_2}, q_{s_1v_2}$ and $q_{s_2t_1}$), local trains are used to transport them to the first reclassification yard v_1 ahead, where they are integrated into the technical flow of the reclassification yard for further transport. For the larger car flows $q_{s_2t_2}, q_{s_3t_1}$ and $q_{s_3v_2}$, direct trains from the loading station are used for transportation. This car flow organisation method presents certain issues. On one hand, it results in an excessive number of trains being operated, and on the other hand, it places too much pressure on the first reclassification yard v_2 at the loading station.
2) In this car flow organisation method, small car flows are merged with large car flows that have the same unloading stations at the corresponding loading stations ahead, resulting in the operation of multi-shipment direct trains from the loading stations to the unloading stations. Compared to the method shown in *Figure 2(a)*, this organisation significantly reduces the number of trains to be operated and does not utilise the reconfiguration capacity of the reclassification yard ahead, thereby freeing up its reconfiguration capacity. However, this method only exists under very ideal conditions, because in real-world transportation, not every small car flow can find a matching large car flow with the same unloading station at the loading station ahead for merging.
3) Unlike *Figure 2(b)*, in this case, both unloading stations are located in the section ahead of the reclassification yard v_2, and the originating car flow from the loading station to the reclassification yard consists of large car flows $q_{s_3v_2}$. Therefore, small car flows $q_{s_1t_2}, q_{s_1v_2}$ and $q_{s_2t_1}$ are merged with the large car flow $q_{s_3v_2}$ to form a multi-shipment direct train from the loading station to the reclassification yard. Once the multi-shipment direct train arrives at the reclassification yard, local trains are used to transport the small car flows to their respective unloading stations. This organisation method not only reduces the number of trains to be operated but also effectively addresses the situation where there is no large car flow that matches the unloading stations of the small car flows, thus preventing the issue of being unable to merge trains.

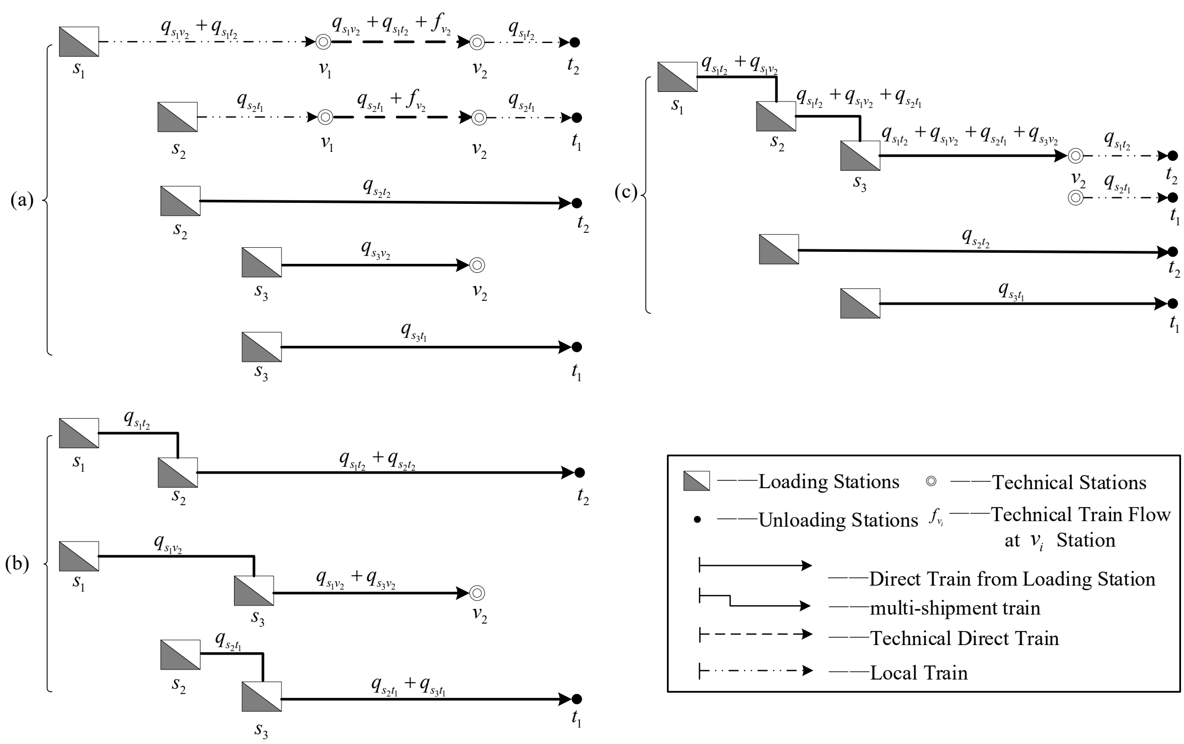

Figure 2 – The possible combinatorial strategies of car flows

In practice, due to the combinatory nature of the cargo, it is challenging to reasonably determine which car flows should be merged. For example, if there are n batch of small car flows at the loading station that need to be transported, and at least two car flows must be combined to form a multi-shipment direct train, the number of possible cargo combinations will increase exponentially, i.e. $O(2^n)$. Therefore, the key focus of this paper is to develop a reasonable train formation plan for the loading station, aiming to minimise the total cost.

2.2 Problem assumptions

Before introducing the mathematical model, there are some preconditions that should be noted. Since this paper studies the train formation plan problem in a unidirectional network and does not consider the selection of car flow routes, some appropriate assumptions need to be made to make the proposed model more targeted [23].

1) It is that the railway network can provide comprehensive transportation services and meet the basic assumed conditions necessary to satisfy the specific transportation requirements of certain goods.
2) It is assumed that the operating routes of all car flows are known and follow the reasonable transportation routes defined in the "National Railway Specific Car Flow Routes".
3) During the journey from the departure station to the destination station, freight trains can undergo reconfiguration operations at any reclassification yard, and can follow the technical flows of different yards to operate multiple direct trains.

3. MATHEMATICAL MODEL

The sets, parameters and variables are listed in *Table 1.*

Table 1 – The descriptions of notations

Sets	Meanings
L	Set of loading stations
$V(s)$	Set of the first reclassification yards ahead of the loading stations s (in the direction of train travel)
$\phi(s')$	The set of loading stations ahead of the loading station s'
$\delta(s')$	Set of loading stations behind the loading station s'
$V(s,t)$	Set of all reclassification yards passed by trains travelling $s \rightarrow t$ (excluding the first reclassification yard)

Parameters	Meanings
q_{st}	Originating car flow from s to t
m_{st}	Number of direct trains from the loading station from s to t
w_{st}^0	Train hour consumption per train at the loading and unloading stations for direct trains from the loading station, organised by the originating car flow from s to t
w_{st}^1	Train hour consumption per train at the loading and unloading stations for direct trains from the loading station, organised by the originating car flow from s to t and reconfigured at the reclassification yard.
w_{st}^2	Train hour consumption per train at the loading and unloading stations for multi-shipment direct trains from the loading station to the unloading station, organised by the originating car flow from s to t
w_{st}^3	Train hour consumption per train at the loading and unloading stations for multi-shipment direct trains from the loading station to the reclassification yard, organised by the originating car flow from s to t
w_{st}^4	Train hour consumption per train at the loading and unloading stations for technical direct trains, organised after the originating car flow from s to t is transported to the first reclassification yard by local trains
τ_k	Time consumption per train for reconfiguration at the reclassification yard k
$L_{s's}$	Distance between the loading station s' and the loading station s.
R_k	Reconfiguration capacity of the reclassification yard k
n_k	Reconfiguration car flow at the reclassification yard k
α	The coefficient for converting distance cost to time cost (determined by the average speed of freight trains)
Decision variables	**Meanings**
x_{st}	Does the car flow q_{st} operate a direct train from the loading station to the unloading station?
$x_{st}^{s't'}$	Does the car flow q_{st} merge with the car flow $q_{s't'}$ to organise and operate a multi-shipment direct train from the loading station to the reclassification yard?
$y_{st}^{s't'}$	Does the car flow q_{st} merge with the car flow $q_{s't'}$ to organise and operate a multi-shipment direct train from the loading station to the unloading station?
x_{st}^k	Does the car flow q_{st} organise the operation of a direct train from the loading station to an intermediate reclassification yard?
z_{st}^k	Does the car flow q_{st} get transported to the adjacent reclassification yard by a local train and then organised into a technical direct train?

3.1 Objective function

The freight train formation plan is developed based on predefined train routes, through technical analysis and economic benefit calculations, to generate high-quality car flow organisation schemes. Generally, the formulation of a freight train formation plan needs to follow several optimisation objectives. (1) Maximise the organisation of direct trains to transport goods, especially for long-distance cargo, while minimising unnecessary stops at reclassification yards along the route to reduce time consumption and accelerate vehicle turnover. (2) Minimise the shunting workload at reclassification yards, and, without affecting cargo transportation, reduce unnecessary reconfigurations of trains along the route as much as possible to achieve greater savings in reconfiguration train hours. (3) Maximise the revenue of the railway transportation system to the greatest extent, which means minimising the costs of various transportation stages while ensuring the timely and full completion of transportation tasks.

Loading and unloading costs

The loading and unloading costs incurred during the organisation of the originating car flow can be categorised into the following five types, depending on the different ways the car flows are organised:

$$L_1 = \sum_{s\in L} \sum_{t\in U(s)} q_{st} w_{st}^0 x_{st} \tag{1}$$

$$L_2 = \sum_{s \in L} \sum_{t \in U(s)} \sum_{k \in V(s,t)} q_{st} w_{st}^1 x_{st}^k \tag{2}$$

$$L_3 = \sum_{s \in L} \sum_{t \in U(s)} \sum_{s' \in \phi(s)} \sum_{t \in U(s')} (q_{st} w_{st}^2 \, y_{st}^{s't'} + \alpha L_{ss'} y_{st}^{s't'}) \tag{3}$$

$$L_4 = \sum_{s \in L} \sum_{t \in U(s)} \sum_{s' \in \phi(s)} \sum_{t' \in U(s')} (q_{st} w_{st}^3 \, x_{st}^{s't'} + \alpha L_{ss'} x_{st}^{s't'}) \tag{4}$$

$$L_5 = \sum_{s \in L} \sum_{t \in U(s)} \sum_{k \in V(s)} q_{st} w_{st}^4 z_{st}^k \tag{5}$$

Here, *Equation 1* represents the loading and unloading costs incurred by direct point-to-point trains organised from the originating car flow. *Equation 2* represents the loading and unloading costs incurred by direct trains, organised at the reclassification yard k, from the originating car flow. *Equation 3* and *Equation 4* represent the loading and unloading costs for organising multi-shipment direct trains from the loading station to the unloading station, and from the loading station to the reclassification yard, respectively. *Equation 5* represents the loading and unloading costs for organising technical direct trains after the originating car flow is transported to an adjacent reclassification yard by local trains.

It should be noted that when organising multi-shipment direct trains from the originating car flow, not only are loading and unloading costs incurred, but also delays caused by the waiting time for the car flow to perform coupling/detaching operations when transporting vehicles to the forward loading station. This delay is represented by the distance between the two loading stations $L_{s's}$.

Thus, for different car flow organisation methods of the originating car flow at the loading station, the total loading and unloading costs Z_1 can be expressed as the following *Equation 6*:

$$Z_1 = L_1 + L_2 + L_3 + L_4 + L_5 \tag{6}$$

Reconfiguration costs

Train reconfiguration is the largest and most consuming technical operation required at reclassification yards. For different organisation methods of the originating car flow, the reconfiguration costs can be divided into two cases:

(1): The reclassification yard where the originating car flow is reconfigured is an adjacent reclassification yard. The reconfiguration cost k of the originating car flow can be expressed as:

$$K_1 = \sum_{s \in L} \sum_{t \in U(s)} \sum_{k \in V(s)} \tau_k z_{st}^k q_{st} \tag{7}$$

(2): The originating car flow is reconfigured at intermediate reclassification yards. When reclassification yard k is an intermediate reclassification yard, the reconfigured originating car flow generally consists of two parts: the first part is the direct train from the loading station reconfigured at yard k, and the second part is the multi-shipment direct train from the unloading station to the reclassification yard.

For example, in *Figure 3*, small car flows $q_{s_1 v_2}$ and $q_{s_2 t_1}$ are combined with large car flow $q_{s_3 v_2}$ to form a multi-shipment direct train from the loading station to the reclassification yard. Additionally, small car flow $q_{s_1 t_2}$ and large car flow $q_{s_2 t_2}$ also form a multi-shipment direct train from the loading station to the reclassification yard. At this point, the number of car flows reconfigured at reclassification yard v_2 is $q_{s_1 t_2} + q_{s_2 t_1} + q_{s_2 t_2}$. It can be observed that when $x_{s_1 t_2}^{s_2 t_2}$ and $x_{s_2 t_2}^{v_2}$ are both set to 1, car flows $q_{s_1 t_2}$ and $q_{s_2 t_2}$ are both reconfigured at reclassification yard v_2. However, when $x_{s_2 t_1}^{s_3 v_2}$ and $x_{s_3 v_2}$ are both set to 1, only car flow $q_{s_2 t_1}$ is reconfigured at yard v_2. This is because the unloading station of car flow $q_{s_3 v_2}$ is v_2, so car flow $q_{s_3 v_2}$ is not reconfigured at the reclassification yard.

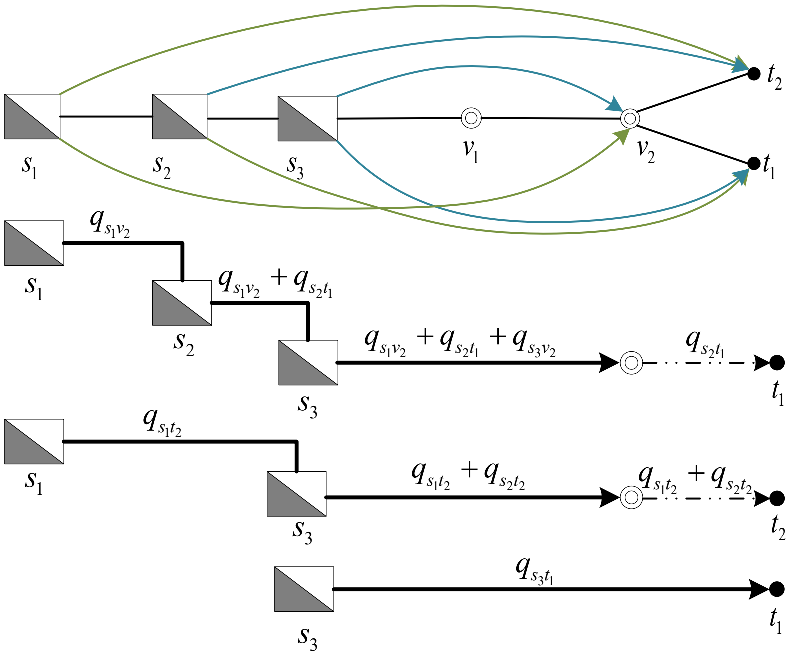

Figure 3 – The example of n_k

Therefore, the car flow n_k reconfigured at reclassification yard k and the reconfiguration cost K_2 can be expressed as *Equation 9*:

$$n_k=\sum_{s\in L}\sum_{t\in U(s)}(q_{st}x_{st}^k+\sum_{s'\in\delta(s)}\sum_{t'\in U(s')}q_{s't'}x_{s't'}^{st}x_{st}^k+\sum_{s'\in\delta(s)}\sum_{t'\in U(s')}q_{s't'}x_{s't'}^{st}x_{sk}) \tag{8}$$

$$K_2=\sum_{k\in V(s,t)}\tau_k(n_k)\text{, } s\in L\text{, } t\in U(s) \tag{9}$$

Thus, the total reconfiguration cost required for the originating car flow is *Equation 10*:

$$Z_2=K_1+K_2 \tag{10}$$

The goal of the integrated optimisation of the train formation plan at the loading station in this paper is to select the optimal car flow organisation method for transporting the originating car flow from the loading station, such that the sum of the loading and unloading costs during transportation and the reconfiguration costs at the reclassification yards is minimised.

The objective function of this model is *Equation 11*:

$$min\ Z=Z_1+Z_2 \tag{11}$$

3.2 Constraints

Flow exclusive condition

In the process of car flow organisation, there are multiple organisation methods for car flow q_{st} that allow goods to be transported from the loading station to the unloading station. However, for a given car flow q_{st}, only one of these methods can be selected to transport the goods. Therefore, the car flow organisation must satisfy the requirement of uniqueness.

$$x_{st}+\sum_{k\in V(s,t)}x_{st}^k+\sum_{s'\in\phi(s)}\sum_{t'\in U(s')}x_{st}^{s't'}+\sum_{s'\in\phi(s)}\sum_{t'\in U(s')}y_{st}^{s't'}+\sum_{k\in V(s)}z_{st}^k=1\text{,}\quad \forall s\in L\text{, } t\in U(s) \tag{12}$$

Conditions for operating the direct train from the loading station

The direct train from the loading station is the most effective and efficient method for organising the originating car flow. Whether it can be successfully operated depends on certain conditions. In this paper, the allowed maximum number of loading and unloading vehicles, also known as the station's maximum capacity, is generally approximately equal to the daily average originating car flow to that destination. A multi-shipment direct train can only be operated when this capacity is greater than or equal to the number of direct trains to that destination. That is:

$$(q_{st} + \sum_{s' \in \delta(s)} \sum_{t \in U(s')} (q_{s't'} x_{s't'}^{st} + q_{s't'} y_{s't'}^{st}) - m_{st}) x_{st} \geq 0 \text{，} s \in L\text{，} t \in U(s) \tag{13}$$

Reconfiguration capacity constraint

When the originating car flow is transported to the first reclassification yard by a local train for technical operations, the reconfiguration capacity R_k of the first reclassification yard should satisfy *Equation 14*:

$$R_k \geq \sum_{s \in L} \sum_{t \in U(s)} q_{st} z_{st}^{k} \text{，} \forall k \in V(s) \tag{14}$$

When the originating car flow is organised as a direct train or a multi-shipment direct train from the loading station to an intermediate reclassification yard, the reconfiguration capacity of the reclassification yard should be no less than the originating car flow undergoing technical operations at that yard:

$$R_k \geq \sum_{s \in L} \sum_{t \in U(s)} (n_k) \text{，} \forall k \in V(s,t) \tag{15}$$

Relationship constraint between multi-shipment direct trains and direct trains from the loading station

When organising a multi-shipment direct train for originating car flow q_{st} from the loading station to the unloading station t, it should be ensured that the preceding loading station s' has a direct train to the unloading station t. That is, when $y_{st}^{s't'} = 1$, $x_{s't'} = 1$ must hold. Therefore, this constraint can be expressed as:

$$y_{st}^{s't'} \leq x_{s't'}\text{，} \forall s \in L\text{，} t \in U(s)\text{，} s' \in \phi(s)\text{，} t' \in U(s') \tag{16}$$

It is important to note that when organising a multi-shipment direct train for originating car flow q_{st} from the loading station to reclassification yard k, the car flow q_{st} will not only merge with the direct train from its preceding loading station s' heading to reclassification yard k, but may also merge with the direct train from the loading station to the unloading station, provided that the unloading station of the car flow $q_{s't'}$ served by the direct train is reclassification yard k, and $k \in V(s,t)$. Therefore, this constraint can be expressed as:

$$x_{st}^{s't'} \leq x_{s't'}^{k}\text{，} \forall s \in L\text{，} t \in U(s)\text{，} s' \in \phi(s)\text{，} t' \in U(s')\text{，} k \in V(s',t') \tag{17}$$

$$x_{st}^{s't'} \leq x_{s't'}\text{，} \forall s \in L\text{，} t \in U(s)\text{，} s' \in \phi(s)\text{，} t' \in U(s') \cup V(s,t) \tag{18}$$

Constraint on the organisation of small car flows

In the process of organising car flows at the loading station, for smaller originating car flows, the assembly time for organising a full direct train is quite long, often taking more than a week. Therefore, when organising smaller originating car flows, it is often considered to transport these flows to the preceding reclassification yard by local trains or to organise a multi-shipment direct train for their transport. Thus, when the flow volume for a particular destination at a loading station s is smaller than the number of direct trains required for that destination, it should be decided to either organise a multi-shipment direct train or transport these flows to the preceding reclassification yard.

Define a piecewise function $\varepsilon(x)$ for this purpose:

$$\varepsilon(x)=\begin{cases}0 & x<0\\ 1 & x\geq 0\end{cases} \tag{19}$$

This constraint is expressed as *Equation 20*:

$$\sum_{k\in V(s)} z_{st}^{k}+\sum_{s'\in H(s)}\sum_{t'\in U(s')} x_{s't'}^{st}+\sum_{s'\in H(s)}\sum_{t'\in U(s')} y_{s't'}^{st}+\varepsilon(q_{st}+\sum_{s'\in H(s)}\sum_{t'\in U(s')} q_{s't'}x_{s't'}^{st}+\sum_{s'\in H(s)}\sum_{t'\in U(s')} q_{s't'}y_{s't'}^{st}-m_{st})=1 \tag{20}$$

3.3 Model linearisation

A piecewise function exists in *Equation 20*. To linearise this constraint, an auxiliary variable w_{st} is introduced. The variable w_{st} satisfies the following constraints:

$$M(1-w_{st})+(q_{st}+\sum_{s'\in H(s)}\sum_{t'\in U(s')} q_{s't'}x_{s't'}^{st}+\sum_{s'\in H(s)}\sum_{t'\in U(s')} q_{s't'}y_{s't'}^{st}-m_{st})\geq 0,\ \forall s\in L,\ t\in U(s) \tag{21}$$

$$Mw_{st}-(q_{st}+\sum_{s'\in H(s)}\sum_{t'\in U(s')} q_{s't'}x_{s't'}^{st}+\sum_{s'\in H(s)}\sum_{t'\in U(s')} q_{s't'}y_{s't'}^{st}-m_{st})\geq 0,\ \forall s\in L,\ t\in U(s) \tag{22}$$

The two constraints above ensure that when the flow of the $s\rightarrow t$ direction at the loading station s is less than the required number of direct trains for that direction, the auxiliary variable w_{st} must be 0; conversely, when the assembled flow exceeds the required number of direct trains, w_{st} must be 1. Here, M is a very large positive number.

Equation 20 can be expressed as *Equation 23*:

$$\sum_{k\in V(s)} z_{st}^{k}+\sum_{s'\in H(s)}\sum_{t'\in U(s')} x_{s't'}^{st}+\sum_{s'\in H(s)}\sum_{t'\in U(s')} y_{s't'}^{st}+w_{st}=1,\ \forall s\in L,\ t\in U(s) \tag{23}$$

3.4 Analysis of model complexity

The integrated optimisation model for the train formation plan at the loading station, considering multi-shipment direct trains, is constructed as follows:

$$min\ Z=Z_1+Z_2 \tag{24}$$

$$s.t.\begin{cases}(12),(13),(14),(15),(16),(17),(18)\\ M(1-w_{st})+(q_{st}+\sum_{s'\in H(s)}\sum_{t'\in U(s')} q_{s't'}x_{s't'}^{st}+\sum_{s'\in H(s)}\sum_{t'\in U(s')} q_{s't'}y_{s't'}^{st}-m_{st})\geq 0,\ \forall s\in L,\ t\in U(s)\\ Mw_{st}-(q_{st}+\sum_{s'\in H(s)}\sum_{t'\in U(s')} q_{s't'}x_{s't'}^{st}+\sum_{s'\in H(s)}\sum_{t'\in U(s')} q_{s't'}y_{s't'}^{st}-m_{st})\geq 0,\ \forall s\in L,\ t\in U(s)\\ \sum_{k\in V(s)} z_{st}^{k}+\sum_{s'\in H(s)}\sum_{t'\in U(s')} x_{s't'}^{st}+\sum_{s'\in H(s)}\sum_{t'\in U(s')} y_{s't'}^{st}+w_{st}=1,\ \forall s\in L,\ t\in U(s)\\ x_{st},\ x_{st}^{s't'},\ y_{st}^{s't'},\ x_{st}^{k},\ z_{st}^{k},\ w_{st}\in\{0,1\}\end{cases} \tag{25}$$

After linearising *Equation 20*, which includes the 0-1 variables for determining the organisation method of each car flow and the auxiliary 0-1 variables introduced during the linearisation process, the model becomes a typical linear 0-1 integer programming problem. *Table 2* lists the decision variables and the number of constraints included in the model. Based on the analysis of *Table 2*, the computational complexity of solving the integrated optimisation problem for the train formation plan at the loading station, considering multi-shipment direct trains, primarily depends on the number of loading stations, unloading stations and reclassification yards in the studied region. In addition, due to the unique organisation method of multi-shipment direct trains, the complexity of solving this problem is also influenced by the geographical distribution of the loading stations within the study area.

Undoubtedly, leveraging more popular decomposition algorithms and heuristic algorithms in the field of optimisation would be a promising approach to solving this model, as these methods feature more sophisticated solving processes and frameworks. However, the key technical challenge of this study lies in addressing the imbalance in car flow among stations within the loading area, as well as the fact that certain stations lack the capacity to independently organise direct trains from the loading station. Building upon the traditional train formation plan model for loading stations, this study incorporates the organisation of multi-shipment direct trains and employs mathematical language to meticulously describe their organisation process and interrelations with other operational structures. Given the characteristics of the research problem and the complexity of the model, this study adopts the GUROBI solver to efficiently solve the proposed model.

Table 2 – Analysis of the number of variables and constraints in the model

Type	Variables or constraints	Quantity
Variables	$x_{st}, z_{st}^{k}, w_{st}$	$\lvert L\rvert \times \lvert U(s)\rvert$
	$x_{st}^{s't'}, y_{st}^{s't'}$	$\lvert L\rvert \times \lvert U(s)\rvert \times \lvert\phi(s)\rvert \times \lvert U(s')\rvert$
	x_{st}^{k}	$\lvert L\rvert \times \lvert U(s)\rvert \times \lvert V(s,t)\rvert$
Constraints	*Equations 12, 13, 21, 22, 23*	$\lvert L\rvert \times \lvert U(s)\rvert$
	Equation 14	$\lvert V(s)\rvert$
	Equation 15	$\lvert V(s,t)\rvert$
	Equation 16	$\lvert L\rvert \times \lvert U(s)\rvert \times \lvert\phi(s)\rvert \times \lvert U(s')\rvert$
	Equation 17	$\lvert L\rvert \times \lvert U(s)\rvert \times \lvert\phi(s)\rvert \times \lvert U(s')\rvert \times \lvert V(s',t')\rvert$
	Equation 18	$\lvert L\rvert \times \lvert U(s)\rvert \times \lvert\phi(s)\rvert \times \lvert U(s') \cup V(s,t)\rvert$

4. CASE ANALYSIS

4.1 Case background introduction

To validate the effectiveness of the optimisation model and algorithm, this paper constructs a simulation case based on the current direct cargo transportation demand and status of the Northern Xinjiang Coal Transportation Corridor. In this case, the Linhe-Harbin Railway (Lin-Ha Line) and Tangbao Railway serve as key channels for transporting bulk goods such as coal and containers from Xinjiang to the Beijing-Tianjin-Hebei region, collectively forming the Northern Xinjiang Coal Transportation Corridor. Among them, the loading stations such as Sangezhuang, Wangbu and Qiquanhu are all under the jurisdiction of the Urumqi Railway Bureau and handle a significant portion of the freight transportation tasks for the Northern Xinjiang Coal Transportation Corridor. Their service scope mainly covers the unloading stations in the Beijing-Tianjin-Hebei region and several reclassification yards along the northern corridor. Based on the Linhe-Harbin Railway and Tangbao Railway, this paper determines the flow of trains departing from stations such as Sangezhuang and arriving at their respective destinations, in accordance with the specified flow routes. A single-direction network model is constructed, with major freight stations in the Xinjiang region serving as loading stations. The network includes 7 loading stations, 12 reclassification yards and 6 unloading stations, with the specific network structure shown in *Figure 4*.

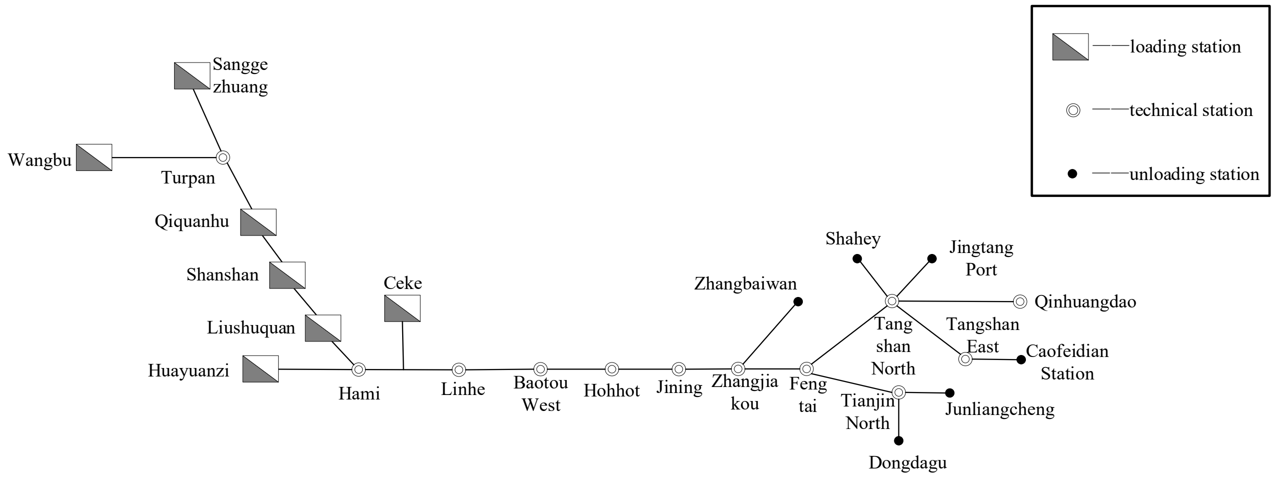

Figure 4 – Network structure diagram

To facilitate the description and solution of the model, the stations in the case study are specially numbered. *Figure 5* shows the network structure diagram after the numbering.

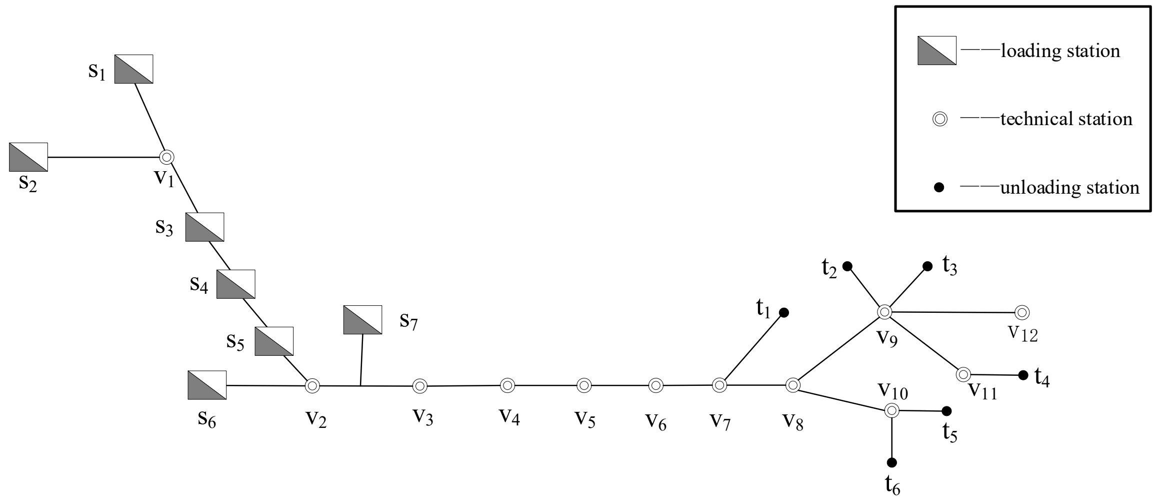

Figure 5 – Numbered diagram

4.2 Parameter settings

The relevant parameters involved in the model will be explained in the following text or table format.

The planned car flow, as the most important component of the train formation plan, not only represents the railway freight demand but also determines the type of trains to be operated between OD pairs and how the flows of trains should be grouped into different train formations. As a medium- and long-term transport plan for the railway transport sector, the loading station freight train formation plan usually requires reasonable forecasting of freight demand over a certain period to obtain the daily average planned car flow. The daily average car flow between various OD pairs in the case network is shown in *Table 3* below.

Table 3 – Planned traffic flow between OD pairs (trains)

Origin station / Destination station	s_1	s_2	s_3	s_4	s_5	s_6	s_7
t_1	30	23	0	15	34	0	56
t_2	45	60	37	62	0	0	0
t_3	0	43	0	73	83	53	94
t_4	0	165	63	24	105	64	108

Origin station / Destination station	s_1	s_2	s_3	s_4	s_5	s_6	s_7
t_5	45	37	0	107	0	0	0
t_6	100	0	42	0	0	0	56
v_1	0	0	0	0	0	0	0
v_2	0	0	0	0	0	0	0
v_3	0	0	0	0	0	0	0
v_4	0	0	52	0	0	0	0
v_5	20	0	0	51	53	53	0
v_6	0	0	0	0	0	0	0
v_7	45	0	30	0	0	58	0
v_8	0	40	0	0	0	0	0
v_9	100	0	0	42	0	0	0
v_{10}	0	0	0	0	60	0	0
v_{11}	40	0	0	0	0	0	0
v_{12}	0	20	0	41	0	0	0

In addition to the daily average planned car flow, the equipment, capacity and technical standards of the loading/unloading stations and technical stations are also essential components of the train formation plan.

In actual transportation operations, the equipment capacity and operational consumption of stations are determined based on the scale of the national railway network and freight volume. However, the case in this paper only selects a local transport network. Therefore, to ensure the rationality of the results, it is necessary to refer to relevant data from actual stations during the calculation process and adjust the technical parameters of each station using the same proportional scale.

By reviewing the regulations in the "Station Details" and reasonably processing relevant data, the technical parameters of the reclassification yards were finally determined. The content shown in *Table 4* presents the technical parameter values for each reclassification yard in the network.

Table 4 – Technical parameters of technical stations

Station	Number	Time per train reformation τ_k (h)	No change through time savings t_k^j (h)	Reclassification capacity R_k (train)
Turpan	v_1	3.9	2.9	200
Hami	v_2	3.5	2.1	180
Linhe	v_3	4.0	2.5	160
Baotou West	v_4	3.2	2.2	240
Hohhot	v_5	3.6	2.1	220
Jining	v_6	3.7	2.2	240
Zhangjiakou	v_7	4.0	2.6	200
Fengtai	v_8	4.3	2.8	300
Tangshan North	v_9	4.0	3.0	190
Tianjin North	v_{10}	3.6	2.6	200
Tangshan East	v_{11}	3.8	2.8	180
Qinhuangdao	v_{12}	4.0	3.0	220

Under the same organisation method, the time required for loading and unloading a single cargo at the loading and unloading stations is generally the same. Therefore, the average consumption time for loading and unloading operations under each organisation method is selected as the value for the station's loading and unloading operation time parameter. The values of w_{st}^0, w_{st}^1, w_{st}^2, w_{st}^3 and w_{st}^4 are set to 17, 13, 13, 14 and 16, respectively. In addition, the number of direct trains from the loading station, denoted as m_{st}, is set to 55.

4.3 Optimisation results

Based on the above data, the model was solved using Python 3.7 programming and GUROBI on a personal computer (Intel® Core™ CPU @ 2.40GHz). The optimal solution was obtained with an objective value of 28,922.6 vehicle hours. The results include: 6 multi-shipment direct trains from the loading stations to the unloading stations, 3 multi-shipment direct trains from the loading stations to the intermediate reclassification yards, 2 groups of trains sent to the first reclassification yard using local trains, and the remaining 10 groups of trains organised as direct trains from the loading stations to the intermediate reclassification yards. The solution is as follows:

$x_{s_3t_2}, x_{s_3v_7}, x_{s_4t_5}, x_{s_4v_{12}}, x_{s_5t_1}, x_{s_5v_5}, x_{s_5v_{10}}=1$

$x_{s_1t_6}^{v_{10}}, x_{s_1v_9}^{v_8}, x_{s_2t_4}^{v_{11}}, x_{s_3t_4}^{v_9}, x_{s_3v_4}^{v_3}, x_{s_4t_2}^{v_9}, x_{s_4t_3}^{v_8}, x_{s_5t_3}^{v_8}, x_{s_5t_4}^{v_7}, x_{s_6t_4}^{v_9}, x_{s_6v_7}^{v_4}=1$

$x_{s_1v_{11}}^{s_3v_7}, x_{s_2t_3}^{s_3v_7}, x_{s_2v_8}^{s_3v_4}, x_{s_3t_6}^{s_5v_{10}}=1$

$y_{s_1t_1}^{s_5t_1}, y_{s_1t_2}^{s_3t_2}, y_{s_1t_5}^{s_4t_5}, y_{s_1v_5}^{s_5v_5}, y_{s_1v_7}^{s_3v_7}, y_{s_2t_1}^{s_5t_1}, y_{s_2t_2}^{s_3t_2}, y_{s_2t_5}^{s_4t_5}, y_{s_2v_{12}}^{s_4v_{12}}, y_{s_4t_1}^{s_5t_1}, y_{s_4v_5}^{s_5v_5}=1$

$z_{s_6t_3}^{v_2}, z_{s_6v_5}^{v_2}=1.$

The above optimisation results are converted into the train formation plan from the loading stations, as shown in *Table 5*.

Table 5 – Case loading station train formation plan table

Train type	Origin station	Destination station	Attracted car flow	Reclassification station
Multi-shipment direct train from the loading station to the unloading station	s_3	t_2	$q_{s_1t_2}, q_{s_2t_2}, q_{s_3t_2}$	---
	s_4	t_5	$q_{s_1t_5}, q_{s_2t_5}, q_{s_4t_5}$	---
	s_4	v_{12}	$q_{s_2v_{12}}, q_{s_4v_{12}}$	---
	s_5	t_1	$q_{s_1t_1}, q_{s_4t_1}, q_{s_5t_1}$	---
	s_5	t_4	$q_{s_4t_4}, q_{s_5t_4}$	---
	s_5	v_5	$q_{s_1v_5}, q_{s_4v_5}, q_{s_5v_5}$	---
Multi-shipment direct train from the loading station to the technical station	s_5	v_{10}	$q_{s_3t_6}, q_{s_5v_{10}}$	v_{10}
	s_3	v_7	$q_{s_1v_{11}}, q_{s_1v_7}, q_{s_2t_3}, q_{s_3v_7}$	v_7
	s_3	v_4	$q_{s_2v_8}, q_{s_3v_4}$	v_3
Direct train from the loading station to the technical station	s_1	t_6	$q_{s_1t_6}$	v_{10}
	s_1	v_9	$q_{s_1v_9}$	v_8
	s_2	t_4	$q_{s_2t_4}$	v_{11}
	s_3	t_4	$q_{s_3t_4}$	v_9
	s_4	t_2	$q_{s_4t_2}$	v_9
	s_4	t_3	$q_{s_4t_3}$	v_8
	s_5	t_3	$q_{s_5t_3}$	v_8
	s_5	t_4	$q_{s_5t_4}$	v_7
	s_6	t_4	$q_{s_6t_4}$	v_9
	s_6	v_7	$q_{s_6v_7}$	v_4
Local train	s_6	t_3, v_6	$q_{s_6t_3}, q_{s_6v_6}$	v_2
	s_4	t_4	$q_{s_4t_4}$	v_2

To visually present the optimisation results, the optimal solution is illustrated in *Figures 6* and *7*, showcasing the train formation planning optimisation model based on this study and the corresponding traffic flow organisation scheme for the case.

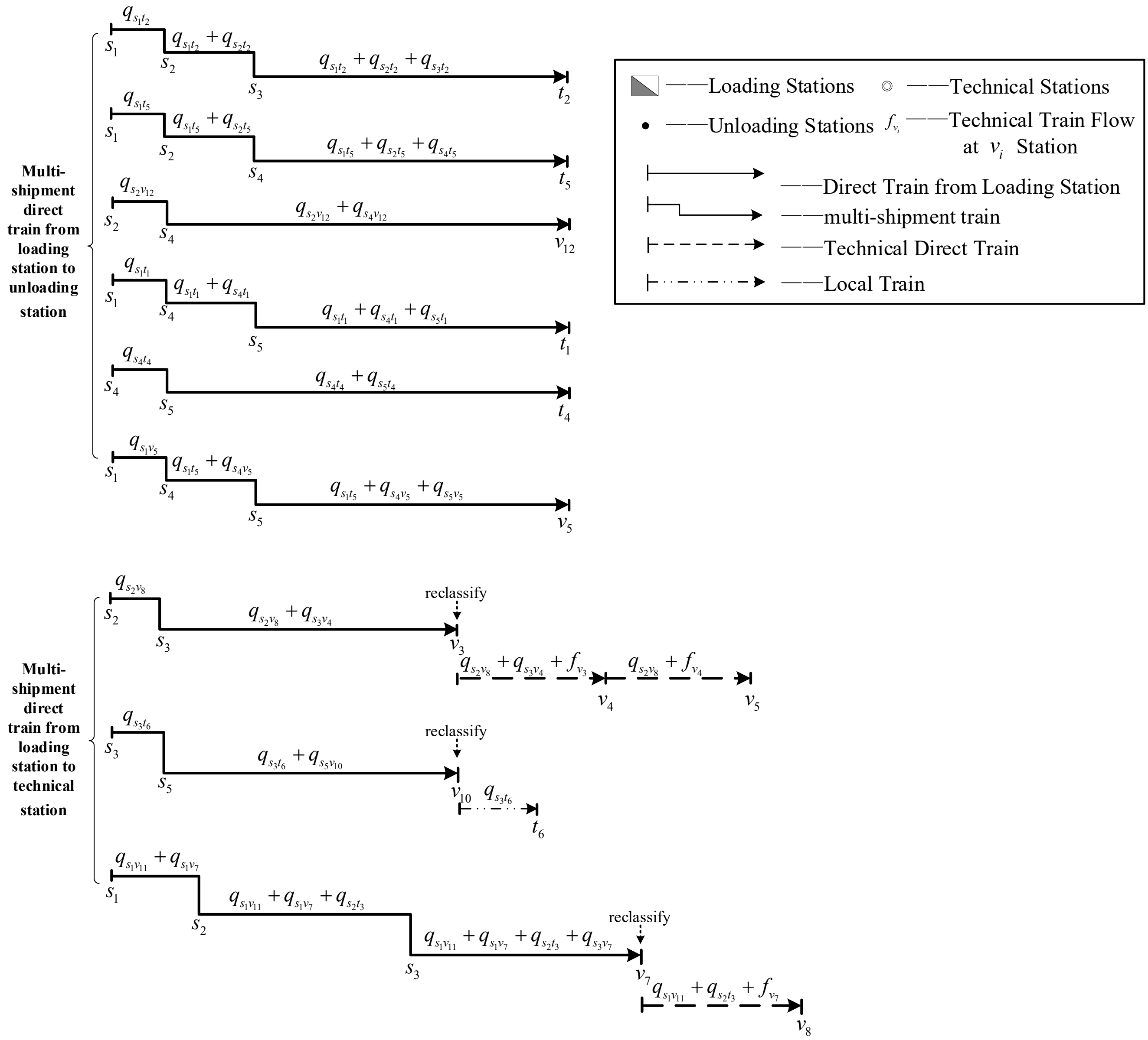

Figure 6 – Schematic diagram of the multi-shipment direct train formation plan

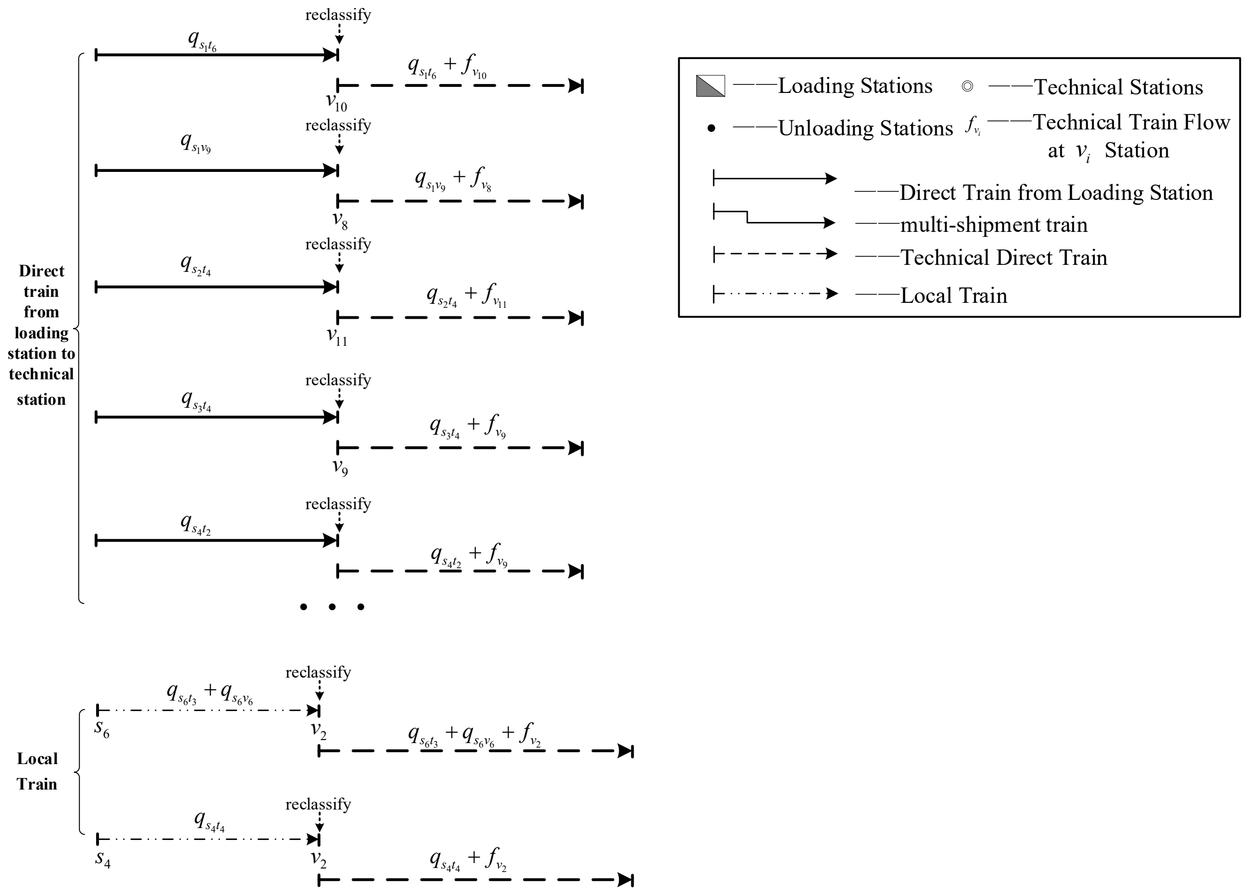

Figure 7 – Schematic diagram of other train formation plans

Due to the concentration of loading stations and the relatively low average daily traffic flow at each loading station along the northern corridor of Xinjiang coal transportation, the loading stations lack the conditions for operating direct trains from the loading station. For small traffic flows at loading stations, the only options are to organise multi-shipment direct trains or transport them to the nearest technical station using local trains.

From the multi-shipment direct train formation plan diagram, it can be observed that traffic flows destined for the same unloading station are primarily transported using multi-shipment direct trains from the loading station to the unloading station, such as $q_{s_1t_2}$, $q_{s_2t_2}$ and $q_{s_3t_2}$. In cases where the traffic flow directions are relatively concentrated but not directed to the same unloading station, transportation is mainly organised through multi-shipment direct trains from the loading station to the technical station, such as $q_{s_3t_6}$ and $q_{s_5v_{10}}$. Furthermore, all direct trains from the loading station merge with originating traffic flows from subsequent loading stations with the same unloading station to form multi-shipment direct trains from the loading station to the unloading station. Additionally, some direct trains from the loading station to intermediate technical stations also attract a portion of small traffic flows.

In practical applications, small traffic flows are transported using multi-shipment direct trains instead of being moved to the first technical station via local or detachment trains. This approach improves transportation efficiency by avoiding the additional costs associated with merging originating traffic flows at the first technical station with technical traffic flows at that station. Furthermore, it significantly alleviates the reclassification workload at adjacent technical stations.

To highlight the optimisation effect of the integrated train formation planning scheme proposed in this study and verify the effectiveness of the optimisation model, a comparative analysis was conducted against a scheme that solely employs local or detachment trains to transport small traffic flows. To ensure the feasibility of the alternative scheme, the reclassification capacities of v_1 and v_2 were expanded to 500 (trains). The results are presented in *Table 6*.

Table 6 – Comparison of schemes

	Optimal solution value (car hours)	v_1 Station modification capacity utilisation rate (%)	v_2 Station modification capacity utilisation rate (%)
Considering multi-shipment direct train	28922.6	0	72.2
Only considering the local train	31878.7	85.6	97
Gap (%)	9.273	100	25.57

5. CONCLUSION

This study analyses the characteristics of loading station traffic flows in the northern channel of the Xinjiang coal transportation network and proposes a comprehensive optimisation problem for loading station train formation planning, considering multi-shipment direct trains. A detailed discussion is provided on the organisation of small traffic flows at loading stations. Based on this, an optimisation model for loading station train formation planning is established, incorporating multi-shipment direct trains. The model is a nonlinear 0-1 integer programming model that satisfies constraints such as the uniqueness of car flow organisation, technical station reclassification capacity, conditions for operating multi-shipment direct trains and small traffic flow organisation methods. The objective of the model is to minimise train unloading and reclassification costs during transportation. To solve the model using commercial software, linearisation techniques were applied to convert the model into a linear form. Finally, a case study of the northern Xinjiang coal transportation channel was conducted, which includes 7 loading stations, 12 technical stations and 6 unloading stations. According to the results, 6 multi-shipment direct trains were organised from loading stations to unloading stations, 3 multi-shipment direct trains to intermediate technical stations, 2 groups of traffic flows were sent to the first technical station via local trains, and 10 other groups of traffic flows were organised as direct trains from the loading station to intermediate technical stations. The total cost was 28,922.6 train-hours. Moreover, by comparing the experimental results with a scenario where only local or shuttle trains are used to transport small traffic flows, it is demonstrated that the proposed model outperforms the latter in terms of total train-hour consumption and technical station capacity utilisation, proving the effectiveness of the model.

However, during the research process, this study did not consider the impact of technical station train formation plans on the loading station train formation plans. As a result, the originating traffic flows at loading stations tend to concentrate at a certain technical station for reclassification. Therefore, future research could focus on optimising the train formation plans at both loading stations and technical stations collaboratively, to derive an overall train formation plan for the entire corridor or network.

Additionally, since the scale of the case study in this paper is relatively small, we chose to use the GUROBI solver to solve the model. However, for NP-hard problems like train formation planning, as the problem size increases, commercial solvers may no longer efficiently obtain the optimal solution. In future research, more efficient heuristic algorithms can be used to solve the TFP problem, such as the algorithms designed in references [24-27].

It is worth noting that while this paper analyses the costs associated with organising different types of trains at the loading station, the cost determination is somewhat generalised. The study assigns a fixed parameter corresponding to each organisational method without a more refined distinction. In particular, the loading and unloading costs are determined solely based on different car flow organisation methods, without considering variations in operational efficiency at different loading and unloading stations. Future research could develop a more detailed objective function that accounts for differences in loading and unloading efficiency across stations, making the optimisation results of train formation plans more realistic and applicable.

ACKNOWLEDGEMENTS

This research was supported by the National Natural Science Foundation of China (No. 72361020), Natural Science Foundation of China (No. 52462045), China National Railway Group Corporation Science and Technology Research and Development Program Project (No. K2023X019), Central Government-Guided Local Science and Technology Development Fund Project (No. 22ZY1QA005) and The Key Program of the Natural Science Foundation of Gansu Province (No. 24JRRA221).

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