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Coordinated Optimization of Shunting Task Sequencing and Wagon Placement Timing in Single-Locomotive District Stations

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Abstract: In a district station equipped with only a single shunting locomotive, the efficient organization of shunting operations is crucial. To enhance operational efficiency and reduce wagon transit dwell time, this study constructs a coordinated optimization model aiming to jointly determine the sequencing of break-up and marshalling operations and the timing of wagon placement and removal operations. The model integrates detailed wagon flow connection relationships, time window constraints, yard reorganization requirements, and resource exclusivity. It defines four hierarchical optimization objectives: maximizing the number of trains that actually achieve full-axle capacity among those required to be full-axle during the shift, maximizing the number of wagons dispatched, maximizing the number of freight loadings completed, and improving plan robustness by ensuring an even distribution of buffer time periods. To solve this model, a multi-stage search algorithm is designed to generate feasible task sequences while satisfying the complex operational constraints. Furthermore, a case study based on an actual district station was conducted to validate the feasibility of the model and algorithm. The results demonstrate that the model can generate operational schemes that maximize the number of full-axle trains, increase the volume of wagons loaded and dispatched, and maintain scheduling performance stability, thereby providing a practical method for optimizing shunting operation organization in single-locomotive district stations.

Keywords: break-up and marshalling sequence; district station; single-locomotive; timing of wagon placement and removal

1 INTRODUCTION

A district station is a critical node on the railway transportation line. Compared to a marshalling yard, a district station is generally smaller in scale and primarily handles non-classification transit wagon operations, along with a limited number of classification-involved transit wagon operations and loading/unloading wagon operations. Classification-involved transit wagons and wagons for loading/unloading arrive with break-up trains or partially reclassified transit trains. Classification-involved transit wagons depart the station after completing arrival technical operations, break-up operations, accumulation, marshalling operations, and departure technical operations. Wagons for loading/unloading, after completing arrival technical operations and break-up operations, are temporarily stored in the shunting yard. They await a suitable time to be hauled by the shunting locomotive to the freight yard or industrial sidings (placement operations). After completing loading or unloading operations, they are hauled back to the shunting yard (removal operations) by the shunting locomotive, then continue with marshalling operations and departure technical operations before leaving the station. In contrast to marshalling yards, district stations typically employ fewer shunting locomotives, and some with minimal switching operations may be equipped with only one such locomotive. In this type of district station, all operations - including break-up, marshalling, wagon placement and removal, and yard reorganization - are performed by a single shunting locomotive. Additionally, the locomotive itself requires necessary maintenance, and the switching crew has fixed meal breaks. Therefore, scientifically and rationally scheduling the sequence of various tasks is essential to enhance the station's overall throughput capacity, reduce wagon transit dwell time, and ensure punctual transportation operations. The complexity of this scheduling challenge is reflected in the following aspects:

Mutual exclusion and conflict between operations: The shunting locomotive cannot perform two tasks simultaneously, and the sequence of operations affects the continuity of wagon flows and the progress of loading/unloading operations.

Uncontrollable duration of certain operations: The time required for wagon placement and removal is influenced by the progress of freight loading/unloading, while the efficiency of break-up operations depends on the number of cars in the train and the number of break-up moves. Thus, the schedule must incorporate sufficient flexibility to accommodate unexpected situations.

Limited time windows: The departure times of self-composed originating trains are fixed, requiring the station to complete wagon allocation and corresponding technical operations before the scheduled departure time.

Rigid interruption constraints: Crew meal breaks and locomotive maintenance are rigid requirements that cannot be cancelled and must be scheduled within specified periods, potentially disrupting the continuity of critical tasks.

Scholars domestically and internationally have conducted considerable research on problems related to shunting operations at stations. Guo et al. [1] transformed the wagon placement and removal problem into a single-machine scheduling problem and the shortest circle problem in a Hamilton graph. They solved it using the Hungarian algorithm and a broken circle method, with extended algorithms handling complex scenarios combining placement, transfer, and removal. Guo et al. [2] aimed to minimize locomotive running and waiting time, established a universal model for wagon placement and removal in mixed-shaped freight yards, proposed methods for judging reverse operations and batching, and solved it with an improved simulated annealing algorithm, verifying its superiority and universality. Li et al. [3] addressed the multiple-solution issue in the sequence optimization of shunting for wagon placement and removal by proposing a dual-objective model minimizing total shunting time and wagon-hours, solved via a three-stage strategy incorporating an improved ant colony algorithm and genetic algorithm crossover. Chen et al. [4] addressed the issue that time-departure-priority schemes struggle to ensure full-axle trains. By analyzing time parameters and employing a single-machine scheduling approach, they minimized the impact of sequence adjustment, proposed adjustment conditions, and introduced a time-pass theory. Adlbrecht et al. [5] investigated the optimization of train marshalling by a shunting engine (instead of humping). They established a Mixed Integer Programme (MIP) model, whose solutions improved efficiency by 10% on average compared to a real-world heuristic, and statistically analyzed the relationship between instance characteristics and marshalling effort. Chen et al. [6] investigated the optimization of track utilization in the arrival yard of a marshalling station considering Arrival and Break-up Coordination Operation (ABCO). They established a nonlinear integer programming model aiming to minimize shunting route crossovers. Application results showed a 49.1% reduction in average track occupation time and improved balance in track utilization. Tomii et al. [7] treated shunting scheduling as a special Resource Constrained Project Scheduling Problem (RCPSP). They proposed an efficient algorithm combining probabilistic local search and PERT to dynamically reduce the solution space, and verified its speed and effectiveness with practical data. Cui et al. [8] formulated the shunting locomotive scheduling problem in a marshalling station as a single-machine scheduling problem with distinct due windows, aiming to minimize the number of delayed trains. They proposed an adjustment algorithm for break-up and make-up sequences and validated its effectiveness using data from Fuyang North Station. Yang et al. [9] believe that by using an improved genetic algorithm to optimize operational schemes in marshalling yards, considering temporal requirements, it can effectively handle disassembly, marshalling, and flow connection operations, thereby enhancing transportation efficiency and resource utilization. Wang et al. [10] take the shunting locomotive as the core, regard breaking up, marshalling, taking-out and placing-in operations along with locomotive activities as a whole, and build a bi-level programming model to solve wagon-flow allocation and shunting locomotive utilization problems. Zhang et al. [11] employ a tripartite graph isomorphism network based deep reinforcement learning method to achieve joint decision-making for hump operations and classification track assignment, realizing railcar itinerary optimization in marshalling yards with significantly improved disassembly-assembly efficiency and algorithm generalization capability. Lin et al. [12] propose a non-linear binary programming model and a simulated annealing based heuristic approach to achieve integrated optimization of traffic routing and formation plan, minimizing accumulation, reclassification, and transportation costs. Guo et al. [13] employ production scheduling theory to achieve unified modeling of railroad yard operations, establishing a standardized one shunting engine-one hump model that addresses the lack of uniformity in description methods and experimental standards within the field. Li et al. [14] employ linear regression based on shunting hooks to dynamically estimate break-up and marshalling time, establishing a dynamic wagon-flow allocation model aimed at minimizing total dwell time at stations, with an improved genetic algorithm effectively enhancing the optimization results. Li et al. [15] establish a bi-objective model for integrated optimization of wagon-flow routing and train formation plan, employing an improved heuristic algorithm to achieve reclassification workload balance at technical stations and minimize operational costs. Zhao et al. [16] propose an integrated optimization method for train and engine routing and scheduling in receiving/departure yards, employing pattern assignment and rolling horizon algorithm to simultaneously resolve route allocation and timing scheduling problems, effectively reducing operational conflicts. Hu et al. [17] construct coordinated hump and assembly sequencing models, revealing the interaction mechanism between disassembly and marshalling sequences under multi-locomotive operations, demonstrating the critical role of system capacity coordination in improving overall efficiency. Li et al. [18] develop a simulation platform for the placing-in and taking-out wagons system in branch-shaped freight networks, deconstructing three operational subsystems and two shunting modes to validate the effectiveness of strategy application and system performance enhancement. Han et al. [19] propose an integrated optimization method for train makeup and resource scheduling, employing MILP-CP hybrid modeling and logic-based Benders decomposition algorithm with three types of cuts to accelerate solving, effectively improving marshalling yard operational efficiency. Yang et al. [20] conducted a study on the resilience assessment of integrated transportation networks, which also provided new insights for formulating shunting operation plans for stations. That is, when developing station shunting operation schemes, it is necessary to consider the resilience of the schemes to withstand the impacts of uncontrollable factors.

From the aforementioned literature, it is evident that previous research has primarily focused on the coordinated operations of multiple shunting locomotives, algorithm improvements, or the optimization of individual operations such as break-up, marshalling, placement, and removal. There is a lack of in-depth exploration into the coordinated optimization mechanism between the sequencing of break-up and marshalling operations and the timing of wagon placement and removal under the configuration of a single shunting locomotive. This research gap limits the further enhancement of operational efficiency and plan stability in single-locomotive district stations. Therefore, based on existing research, this paper constructs a coordinated optimization model for the sequencing of break-up and marshalling operations and the timing of wagon placement and removal in a single-locomotive operation scenario. The innovative aspects of this model are as follows: Firstly, it breaks from the traditional model that determines the sequence of break-up and marshalling operations solely based on the chronological order of train arrivals or departures. Instead, it plans the sequence with the core principle of "optimizing the efficiency of subsequent operational connections". Secondly, it abandons fixed scheduling for wagon placement and removal operations, instead flexibly determining their timing according to the established sequence of station break-up and marshalling operations. Thirdly, to enhance the disturbance resistance and stability of the operational plan, buffer times are specifically incorporated into the overall schedule to absorb potential unexpected delays during operations. The aim is to comprehensively improve station operational efficiency and plan robustness.

2 MODEL FORMULATION

2.1 Model Assumptions

(1) Sufficient technical operation capacity for train arrivals and departures, adequate receiving-departure track

capacity, and sufficient wagon capacity in the marshalling yard tracks.

(2) Sufficient freight yard loading/unloading capacity, allowing combined placement and removal operations. Loading operations can commence immediately after unloading is completed.

(3) At the beginning of the shift, the shunting locomotive is idle, no switching operations are in progress, and all trains in the marshalling yard have been completely broken up.

(4) The station has no connected sidings (industrial tracks), and no placement/removal operations for locomotive depots or rolling stock maintenance depots are considered.

(5) The empty wagons generated after unloading at the station are sufficient to meet the loading demands of the station.

(6) Maintenance operations and switching crew meal breaks do not occur simultaneously.

(7) Trains arrive at the station strictly according to the arrival plan; uncertainty or fluctuations are not considered.

2.2 Definition of Indexes and Numbers

The trains to be broken up arriving at this station are sorted in ascending order of their arrival times, with a corresponding index of i (i = 0, 1, 2, …, m), where i = 0 represents the freight cars on hand in the yard from the previous shift. The self-made outbound trains within this shift are sorted in ascending order of their departure times, with a corresponding index of j (j = 1, 2, …, n, n + 1), where j = n + 1 represents the freight cars on hand in the yard at the end of this shift. The placement and removal operations within a shift are indexed by u (u = 1, 2, …, k). The symbol u' appearing later also serves as an index for placement and removal operations, denoting a different operation batch from u. Yard reorganization operations are indexed by v (v = 1, 2, …, c); locomotive preparation operations are indexed by w (w = 1, 2, …, β); meal breaks for the switching crew are indexed by a (a = 1, 2, …, φ); and the inserted buffer time periods are indexed by ε (ε = 1, 2, ..., ξ). Special note: The numbering rule for placement and removal operations is as follows: within a shift, the start times of all placement and removal operations are scheduled first, and then the operations are numbered sequentially in ascending order of their start times, with the first operation numbered 1, and so forth. The numbering rules for yard reorganization operations, preparation operations, meal breaks, and buffer time periods follow the same principle as for placement and removal operations. Destinations are indexed by s (s = 1, 2, …, p). The freight cars requiring loading/unloading operations arriving at this station (abbreviated as: loading/unloading cars) include types such as boxcars, gondola cars, tank cars, etc. The type of loading/unloading car is denoted by q (q = 1, 2, …, e). At the start of this shift, there are still d (d = 0, 1, 2, …, l, l + 1, …, l') loading/unloading batches in the freight yard. Freight cars delivered to the freight yard by the same placement and removal operation constitute one batch. Among the d batches: batch d = 0 indicates that the freight cars have completed loading/unloading and have been retrieved back to the shunting yard; batch d = 1 indicates that the freight cars have completed loading/unloading and are awaiting retrieval by the shunting locomotive - if empty cars are included, it signifies that these empty cars need to be retrieved back to the shunting yard for placement as empties. Batches d = 2, 3, …, l indicate several batches that have completed unloading and are undergoing loading - if empty cars are included, it signifies that these empty cars need to be retrieved back to the shunting yard for placement as empties. Batches d = l+1, l+2, …, l' indicate several batches awaiting loading, awaiting unloading, or undergoing unloading. The loading directions for cars in batches 1 to l were determined in the previous shift; the loading directions for cars in batches l+1 to l' are undetermined. The task sequence index for this shift is h (h = 1, 2, 3, …, r), where $r = m + n + k + c + \beta + \varphi + \xi$. The symbol h' appearing later also denotes a task sequence index, serving the same purpose as h, primarily to distinguish from h and represent two different task sequences.

2.3 Constraints

(1) Mutual exclusion constraint of tasks

The station has only one shunting locomotive, which consequently undertakes all tasks including break-up, make-up, placement and removal, and yard reorganization. Therefore, only one task can be performed at any given time. In addition, non-productive tasks such as locomotive preparation operations and meal breaks for the switching crew also require dedicated time periods. Furthermore, to enhance the robustness and stability of the operational plan, buffer time periods are explicitly inserted into the overall schedule to absorb potential unexpected delays during execution. The aforementioned operations, meal breaks, and buffer time periods must not overlap temporally. Let the start time of this shift be T^K, and the end time be T^{END}. Within the interval [T^K, T^{END}], h time periods are inserted, each corresponding to one task, meaning there are h tasks. The constraint that must be satisfied is:

$$\sum_{h=1}^{r} y_{i,h} = 1 \quad \forall i \in \{1, 2, ..., m\} \tag{1}$$

$$\sum_{h=1}^{r} y_{j,h} = 1 \quad \forall j \in \{1, 2, ..., n\} \tag{2}$$

$$\sum_{h=1}^{r} y_{u,h} = 1 \quad \forall u \in \{1, 2, ..., k\} \tag{3}$$

$$\sum_{h=1}^{r} y_{v,h} = 1 \quad \forall v \in \{1, 2, ..., c\} \tag{4}$$

$$\sum_{h=1}^{r} y_{w,h} = 1 \quad \forall w \in \{1, 2, ..., \beta\} \tag{5}$$

$$\sum_{h=1}^{r} y_{a,h} = 1 \quad \forall a \in \{1, 2, ..., \varphi\} \tag{6}$$

$$\sum_{h=1}^{r} y_{\varepsilon,h} = 1 \quad \forall \varepsilon \in \{1, 2, ..., \xi\} \tag{7}$$

$$\sum_{i=1}^{m} y_{i,h} + \sum_{j=1}^{n} y_{j,h} + \sum_{u=1}^{k} y_{u,h} + \sum_{v=1}^{c} y_{v,h} + \sum_{w=1}^{\beta} y_{w,h} + \sum_{a=1}^{\varphi} y_{a,h} + \sum_{\varepsilon=1}^{\xi} y_{\varepsilon,h} = 1 \quad \forall h \in \{1, 2, ..., r\} \tag{8}$$

$y_{i,h}$ is a 0-1 variable indicating whether the h-th task in the current shift is the break-up operation for arriving train i. If yes, its value is 1; otherwise, it is 0. $y_{j,h}$, $y_{u,h}$, $y_{v,h}$, $y_{w,h}$, $y_{a,h}$, and $y_{\varepsilon,h}$ are similarly defined as 0-1 variables. Specifically, $y_{j,h}$ indicates whether the h-th task is the make-up operation for outbound train j; $y_{u,h}$ indicates whether the h-th task is the u-th placement and removal operation; $y_{v,h}$ indicates whether the h-th task is the v-th yard reorganization operation; $y_{w,h}$ indicates whether the h-th task is the w-th locomotive preparation operation; $y_{a,h}$ indicates whether the h-th task is the arrangement for the a-th meal break of the switching crew; and $y_{\varepsilon,h}$ indicates whether the h-th time period is allocated as the ε-th buffer time period. If affirmative, the value of the above variables is 1; otherwise, it is 0. Eqs. (1) to (7) represent the constraint that all tasks must be allocated to specific time periods for completion. Eq. (8) ensures that only one task can be performed in any single time period. The temporal constraints between various tasks are as follows:

$$T_h^K + t_h^Z \le T_{h+1}^K \quad \forall h \in \{1, 2, ..., r-1\} \tag{9}$$

In Eq. (9), T_h^K denotes the start time of the h-th task in the current shift. The notations $T_{i,h}^K$, $T_{j,h}^K$, $T_{u,h}^K$, $T_{v,h}^K$, $T_{w,h}^K$, $T_{a,h}^K$, and $T_{\varepsilon,h}^K$, which appear subsequently in this paper, also represent the start time of the h-th task in the current shift. Furthermore, these notations simultaneously specify the content of the operation: $T_{i,h}^K$ indicates that the h-th task is the break-up operation for arriving train i; $T_{j,h}^K$ indicates that the h-th task is the make-up operation for outbound train j; $T_{u,h}^K$ indicates that the h-th task is the execution of the u-th placement and removal operation; $T_{v,h}^K$ indicates that the h-th task is the execution of the v-th yard reorganization operation; $T_{w,h}^K$ indicates that the h-th task is the execution of the w-th locomotive preparation operation; $T_{a,h}^K$ indicates that the h-th time period is allocated for the a-th meal break of the switching crew; $T_{\varepsilon,h}^K$ indicates that the h-th time period is allocated as the ε-th buffer time period. The duration of the h-th task is denoted by t_h^Z, and T_{h+1}^K represents the start time of the (h + 1)-th task. Eq. (9) specifies that the start time of the (h + 1)-th task must be greater than or equal to the end time of the h-th task. The value of t_h^Z is determined as follows:

$$t_h^Z = T^J \times y_{i,h} + T_j^B \times y_{j,h} + T^{QS} \times y_{u,h} + T^{ZLC} \times y_{v,h} + T^{ZBS} \times y_{w,h} + T^{CFS} \times y_{a,h} + T^{HC} \times y_{\varepsilon,h} \ \forall i, j, u, v, w, a, \varepsilon, h \tag{10}$$

In Eq. (10): T^J denotes the duration of the break-up operation for arriving trains. T_j^B denotes the duration of the make-up operation for outbound train j. T^{QS} denotes the duration of placement and removal operations. T^{ZLC} denotes the duration of yard reorganization operations. T^{ZBS} denotes the duration of locomotive preparation operations. T^{CFS} denotes the duration of meal breaks. T^{HC} denotes the duration of buffer time periods. The sum of the durations of all tasks must not exceed the total working time of the current shift. The start time of the first task cannot be earlier than the shift start time, and the end time of the last task cannot be later than the shift end time. Therefore:

$$\sum_{h=1}^{r} t_h^Z \le T^{END} - T^K \tag{11}$$

$$T^K \le T_1^K \tag{12}$$

$$T_r^K + t_h^Z \le T^{END} \tag{13}$$

In Eqs. (11) to (13): T_1^K denotes the start time of the first task. T_r^K denotes the start time of the last task.

(2) Constraints related to break-up and make-up operations

$$T_i^{EJT} = T_i^{DD} + T^{DJS} \tag{14}$$

$$T_j^{LB} = T_j^{CF} - T^{CJ} - T_j^B \tag{15}$$

Eq. (14) represents the constraint on the earliest break-up time for an arriving train to be broken up. Here, T_i^{EJT} denotes the earliest break-up time for arriving train i; T_i^{DD} denotes the arrival time of train i at the station; and T^{DJS} denotes the technical operation duration for arriving trains. Eq. (15) represents the constraint on the latest make-up time for a self-made outbound train. Here, T_j^{LB} denotes the latest start time for making up outbound train j; T_j^{CF} denotes the departure time of outbound train j; and T^{CJ} denotes the technical operation duration for outbound trains prior to departure.

The actual break-up start time for arriving train i cannot be earlier than the earliest break-up time of train i. This constraint is given by Eq. (16).

$$T_i^{EJT} \le T_{i,h}^K \quad \forall i \in \{1, 2, ..., m\}, \forall h \tag{16}$$

The actual make-up start time for outbound train j cannot be later than the latest make-up time of this train. This constraint is given by Eq. (17).

$$T_j^{LB} \ge T_{j,h}^K \quad \forall j \in \{1, 2, ..., n\}, \forall h \tag{17}$$

(3) Locomotive preparation and meal break constraints

$$\left[T_{w,h}^{K}, T_{w,h}^{K} + T^{ZBS}\right] \subseteq \left[T_{w}^{FK}, T_{w}^{FJ}\right] \quad \forall w, h \tag{18}$$

Eq. (18) specifies that the w-th locomotive preparation operation must be completed within its designated time interval. In the equation: $\left[T_{w}^{FK}, T_{w}^{FJ}\right]$ represents the designated time interval for the locomotive preparation operation, where T_{w}^{FK} denotes the start time of the interval and T_{w}^{FJ} denotes the end time of the interval.

$$\left[T_{a,h}^{K}, T_{a,h}^{K} + T^{CFS}\right] \subseteq \left[T_{a}^{FK}, T_{a}^{FJ}\right] \ \forall a, h \tag{19}$$

Eq. (19) specifies that any meal break must occur within its designated time interval. In the equation: $\left[T_{a}^{FK}, T_{a}^{FJ}\right]$ represents the designated meal break time interval, where T_{a}^{FK} denotes the start time of the interval and T_{a}^{FJ} denotes the end time of the interval.

(4) Wagon flow constraints

Transit wagons arriving at this station need to be allocated for wagon flow to the station's departure trains. Transit wagons that do not meet the wagon flow allocation requirements for the current shift are temporarily stored at the station. Wagons arriving at the station for loading/unloading operations, after being unloaded, are either directly allocated for wagon flow to the departure trains of the current shift, or are allocated after being loaded. Loading/unloading wagons that do not meet the wagon flow allocation requirements for the current shift are temporarily stored at the station. The wagon flow constraints can be expressed as:

$$L_{i,s} = \sum_{j=1}^{n+1} x_{i,s,j} \quad \forall i, s \tag{20}$$

$$L_{i,q} = \sum_{j=1}^{n+1} \sum_{s=1}^{p} x_{i,q,j,s} + \sum_{j=1}^{n+1} x'_{i,q,j} \quad \forall i, q \tag{21}$$

$$x_{d,q,s} = \sum_{j=1}^{n+1} x_{d,q,j,s} \ \forall q, s; \forall d \in \{0, 1, ..., l\} \tag{22}$$

$$x'_{d,q} = \sum_{j=1}^{n+1} x'_{d,q,j} \quad \forall q; \forall d \in \{0, 1, ..., l\} \tag{23}$$

$$L_{d,q} = \sum_{j=1}^{n+1} \sum_{s=1}^{p} x_{d,q,j,s} + \sum_{j=1}^{n+1} x'_{d,q,j} \quad \forall q; \forall d \in \{l+1, l+2, ..., l'\} \tag{24}$$

Among them:

$$x_{i,s,j}, x_{i,q,j,s}, x'_{i,q,j}, x_{d,q,j,s}, x'_{d,q,j} \in \{0, 1, 2, 3, ...\} \tag{25}$$

In Eq. (20): $L_{i,s}$ denotes the number of cars destined for direction s in arriving train i; $L_{i=0,s}$ denotes the classification flow in direction s stored at the station at the end of the previous shift; $x_{i,s,j}$ denotes the car flow provided by the group of cars destined for s in arriving train i for outbound train j from this station; $x_{i,s,n+1}$ denotes the number of classification cars in direction s from arriving train i stored at the station at the end of this shift.

In Eq. (21): $L_{i,q}$ denotes the number of freight cars of type q in arriving train i that require loading/unloading operations; $L_{i=0,q}$ denotes the number of cars awaiting delivery to the freight yard for loading/unloading at the end of the previous shift; $x_{i,q,j,s}$ denotes the number of loaded cars in direction s provided for outbound train j by freight cars of type q from arriving train i that are subsequently sent to the freight yard for unloading; $x'_{i,q,j}$ denotes the number of empty cars provided for outbound train j by freight cars of type q from arriving train i that are subsequently sent to the freight yard for unloading; $x_{i=0,q,j,s}$ denotes the number of loaded cars in direction s provided for outbound train j by freight cars of type q stored in the classification yard at the beginning of this shift, which are sent to the freight yard for unloading during this shift; $x'_{i=0,q,j}$ denotes the number of empty cars provided for outbound train j by freight cars of type q stored in the classification yard at the beginning of this shift, which are sent to the freight yard for unloading during this shift; $x_{i,q,n+1,s}$ denotes the number of loaded cars that have not been dispatched by the end of this shift; $x'_{i,q,n+1}$ denotes the number of empty cars that have not been dispatched by the end of this shift.

In Eqs. (22) to (23), $x_{d,q,s}$ represents the number of loaded cars of type q destined for direction s in the d-th loading/unloading batch, where $d \in \{1, 2, \dots, l\}$. $x_{d,q,j,s}$ denotes the portion of $x_{d,q,s}$ that supplies the number of loaded cars destined for direction s to outbound train j in the current shift; specifically, it is the number of loaded cars of type q from the d-th loading/unloading batch destined for direction s that are provided to outbound train j. $x'_{d,q}$ represents the number of empty cars of type q in the d-th loading/unloading batch that are not used for loading, where $d \in \{1, 2, \dots, l\}$. $x'_{d,q,j}$ denotes the portion of $x'_{d,q}$ that supplies the number of empty cars to outbound train j in the current shift; specifically, it is the number of empty cars of type q from the d-th loading/unloading batch provided to outbound train j. $x_{d,q,n+1,s}$ and $x'_{d,q,n+1}$ represent the loading/unloading cars on hand in the yard at the end of the current shift.

In Eq. (24): $L_{d,q}$ denotes the number of loading/unloading cars of type q in the d-th loading/unloading batch, where $d \in \{l+1, l+2, \dots, l'\}$.

Eq. (25) constrains all variables to only take values of 0 or positive integers.

(5) Succession constraints for placement and removal operations

Wagons for loading/unloading can only be hauled to the freight yard after completing break-up operations, and can only be hauled back to the shunting yard after completing loading/unloading operations. The constraints for wagon placement are as follows:

$$f_{i,q,u}=\begin{cases}1 & i=0\vee\left(T_{i,h}^{K}<T_{u,h'}^{K}\wedge i\in\{1,2,...,m\}\right)\\0 & \text{otherwise}\end{cases}\quad\forall q,u;\forall h\neq h' \tag{26}$$

In Eq. (26): $f_{i,q,u}$ indicates whether the loading/unloading cars of type q from arriving train i can be transported to the freight yard by the u-th placement and removal operation. If yes, its value is 1; otherwise, it is 0. For the freight cars that were on hand in the shunting yard at the end of the previous shift and require transportation to destinations for loading/unloading, their break-up operations have been completed before the start of the current shift. Therefore, the value of $f_{0,q,u}$ is always 1.

The constraint that the loading/unloading cars of type q from arriving train i, after being transported to the freight yard by the u-th placement and removal operation, are retrieved back to the shunting yard by the u'-th placement and removal operation is as follows:

$$\psi_{i,q,u,u'}=\begin{cases}1 & T_{u,h}^{K}+t_{h}^{Z}+T^{XC}+T^{ZC}\leq T_{u',h'}^{K}\\0 & \text{otherwise}\end{cases}\quad\forall i,q,u,u',h,h';\forall h\neq h';\forall u\neq u' \tag{27}$$

$$\psi'_{i,q,u,u'}=\begin{cases}1 & T_{u,h}^{K}+t_{h}^{Z}+T^{XC}\leq T_{u',h'}^{K}\\0 & \text{otherwise}\end{cases}\quad\forall i,q,u,u',h,h';\forall h\neq h';\forall u\neq u' \tag{28}$$

In Eq. (27): $\psi_{i,q,u,u'}$ indicates whether the q-type freight cars from arriving train i, which are delivered to the freight yard via the u-th placing and retrieval operation for unloading first and then loading, can be retrieved back to the marshalling yard by the u'-th retrieval operation. If they can be retrieved, the value is 1; otherwise, it is 0. T^{XC} represents the duration of the unloading operation, and T^{ZC} represents the duration of the loading operation. In Eq. (28), $\psi'_{i,q,u,u'}$ indicates whether the q-type freight cars from arriving train i, which are delivered to the freight yard via the u-th placing and retrieval operation for unloading, can be retrieved back to the marshalling yard by the u'-th retrieval operation. If they can be retrieved, the value is 1; otherwise, it is 0.

To determine whether the loading operations at the freight yard can be completed before the end of the current shift, a variable $\eta_{i,q,u}$ is introduced. $\eta_{i,q,u}$ indicates whether the q-type freight cars from arriving train i, which are delivered to the freight yard via the u-th placing and retrieval operation, can complete loading within the current shift. If they can, the value is 1; otherwise, it is 0. Refer to Eq. (29).

$$\eta_{i,q,u}=\begin{cases}1 & f_{i,q,u}=1\wedge T_{u,h}^{K}+t_{h}^{Z}+T^{XC}+T^{ZC}\leq T^{END}\\0 & \text{otherwise}\end{cases}\quad\forall i,q,u,h \tag{29}$$

For the loading and unloading freight cars stored at the freight yard from the previous shift: the time constraints for retrieving the freight cars that are first unloaded and then loaded at the freight yard back to the marshalling yard are given in Eq. (30); the time constraints for retrieving the freight cars that are only unloaded at the freight yard back to the marshalling yard are given in Eq. (31). The condition for determining whether loading can be completed within the current shift is given in Eq. (32).

$$\psi_{d,q,u'}=\begin{cases}1, & T_{d,q}^{ZXE}\leq T_{u',h}^{K}\\0, & \text{otherwise}\end{cases}\quad\forall q,u';\forall d=\{1,2,...,l'\} \tag{30}$$

$$\psi'_{d,q,u'}=\begin{cases}1, & T_{d,q}^{XCE}\leq T_{u',h}^{K}\\0, & \text{otherwise}\end{cases}\quad\forall q,u';\forall d=\{1,2,...,l'\} \tag{31}$$

$$\eta_{d,q}=\begin{cases}1, & T^{K}<T_{d,q}^{ZXE}\leq T^{END}\\0, & \text{otherwise}\end{cases}\quad\forall q,\forall d\in\{2,3,...,l'\} \tag{32}$$

In Eqs. (30) to (32): $\psi_{d,q,u'}$ indicates whether the freight cars of batch d using q-type freight cars for loading can be retrieved back to the marshalling yard by the u'-th placing and retrieval operation. If they can, the value is 1; otherwise, it is 0. $\psi'_{d,q,u'}$ indicates whether the q-type freight cars of batch d after unloading can be retrieved back to the marshalling yard by the u'-th placing and retrieval operation. If they can, the value is 1; otherwise, it is 0. $T_{d,q}^{ZXE}$ represents the completion time of the loading operation for the freight cars in batch d that are first unloaded and then loaded. $T_{d,q}^{XCE}$ represents the completion time of the unloading operation for batch d. $\eta_{d,q}$ indicates whether the q-type freight cars of batch d can complete loading within the current shift. If they can, the value is 1; otherwise, it is 0.

(6) Time constraints for wagon flow connection

Time constraints for the wagon flow connection of classified transit cars:

$$g_{i,j}=\begin{cases}1, & T_{i,h}^{K}+t_{h}^{Z}\leq T_{j,h'}^{K}\\0, & \text{otherwise}\end{cases}\quad\forall i,\forall j,\ \forall h\neq h' \tag{33}$$

In Eq. (33), $g_{i,j}$ indicates whether the transit cars from arriving train i can connect in time to outbound train j.

The time constraints for the connection of loading and unloading freight cars arriving in the current shift and those stored from the previous shift awaiting delivery to the marshalling yard to outbound trains are given in Eqs. (34) to (35). The time constraints for the connection of freight cars from loading and unloading batch d to outbound trains in the current shift are given in Eqs. (36) to (37).

$$g_{i,q,j} = \begin{cases} 1 & f_{i,q,u} \times \psi_{i,q,u,u'} = 1 \wedge T^K_{u',h} < T^K_{j,h'} \\ 0 & \text{otherwise} \end{cases} \quad \forall i,q,j,u,u',h,h'; \forall h \neq h', u \neq u' \tag{34}$$

$$g'_{i,q,j} = \begin{cases} 1 & f_{i,q,u} \times \psi'_{i,q,u,u'} = 1 \wedge T^K_{u',h} < T^K_{j,h'} \\ 0 & \text{otherwise} \end{cases} \quad \forall i,q,j,u,u',h,h'; \forall h \neq h', u \neq u' \tag{35}$$

$$g_{d,q,j} = \begin{cases} 1, & d = 0 \vee (\psi_{d,q,u'} = 1 \wedge T^K_{u',h} < T^K_{j,h'} \wedge d \in \{1, 2, ..., l'\}) \\ 0, & \text{otherwise} \end{cases} \forall q,j,u',h,h'; \forall h \neq h' \tag{36}$$

$$g'_{d,q,j} = \begin{cases} 1, & d = 0 \vee (\psi'_{d,q,u'} = 1 \wedge T^K_{u',h} < T^K_{j,h'} \wedge d \in \{1, 2, ..., l\}) \\ 0, & \text{otherwise} \end{cases} \forall q,j,u',h,h'; \forall h \neq h' \tag{37}$$

In Eqs. (34) to (35): $g_{i,q,j}$ indicates whether the q-type freight cars from arriving train i, which are first unloaded and then loaded at this station, can connect to outbound train j; $g'_{i,q,j}$ indicates whether the q-type freight cars from arriving train i, which are only unloaded at this station, can connect to outbound train j.

In Eqs. (36) to (37): $g_{d,q,j}$ indicates whether the q-type freight cars from batch d after loading can connect to outbound train j; $g'_{d,q,j}$ indicates whether the q-type freight cars from batch d after unloading can connect to outbound train j.

(7) Non-violating marshalling constraint

Only wagon groups destined for direction s or empty wagons of type q can be marshaled into departure train j if train j requires wagon groups for direction s or empty wagons of type q; otherwise, it constitutes an irregular marshalling operation. Only wagons of type q can be assigned for loading operations to direction s if direction s requires wagons of type q for loading; otherwise, it constitutes an irregular loading operation. The constraints are as follows:

$$b_{i,s}, b_{i,q}, b_{d,q} \in \{0, 1\} \tag{38}$$

$$f_{q,s}, f_{s,j}, f'_{q,j} \in \{0, 1\} \tag{39}$$

$$x_{i,s,j} \le b_{i,s} \times M \quad \forall i,s,j \tag{40}$$

$$x_{i,s,j} \le f_{s,j} \times M \quad \forall i,s,j \tag{41}$$

$$x_{i,s,j} \le g_{i,j} \times M \quad \forall i,s; \forall j \in \{1, 2, ..., n\} \tag{42}$$

$$x_{i,q,j,s} \le b_{i,q} \times M \quad \forall i,q,j,s \tag{43}$$

$$x_{i,q,j,s} \le f_{q,s} \times M \quad \forall i,q,j,s \tag{44}$$

$$x_{i,q,j,s} \le f_{s,j} \times M \quad \forall i,q,s; \forall j \in \{1, 2, ..., n\} \tag{45}$$

$$x_{i,q,j,s} \le g_{i,q,j} \times M \quad \forall i,q,s; \forall j \in \{1, 2, ..., n\} \tag{46}$$

$$x'_{i,q,j} \le b_{i,q} \times M \quad \forall i,q,j \tag{47}$$

$$x'_{i,q,j} \le f'_{q,j} \times M \quad \forall i,q; \forall j \in \{1, 2, ..., n\} \tag{48}$$

$$x'_{i,q,j} \le g'_{i,q,j} \times M \quad \forall i,q; \forall j \in \{1, 2, ..., n\} \tag{49}$$

$$x_{d,q,j,s} \le b_{d,q} \times M \quad \forall d,q,j,s \tag{50}$$

$$x_{d,q,j,s} \le f_{q,s} \times M \quad \forall d,q,j,s \tag{51}$$

$$x_{d,q,j,s} \le f_{s,j} \times M \quad \forall i,q,s; \forall j \in \{1, 2, ..., n\} \tag{52}$$

$$x_{d,q,j,s} \le g_{d,q,j} \times M \quad \forall i,q,s; \forall j \in \{1, 2, ..., n\} \tag{53}$$

$$x'_{d,q,j} \le b_{d,q} \times M \quad \forall d,q,j \tag{54}$$

$$x'_{d,q,j} \le f'_{q,j} \times M \quad \forall i,q; \forall j \in \{1, 2, ..., n\} \tag{55}$$

$$x'_{d,q,j} \le g'_{d,q,j} \times M \quad \forall i,q; \forall j \in \{1, 2, ..., n\} \tag{56}$$

Eqs. (38) to (39) are logical constraints. $b_{i,s}$ indicates whether arriving train i contains a car group destined for direction s; $b_{i,q}$ indicates whether arriving train i contains q-type loading/unloading freight cars; $b_{d,q}$ indicates whether the loading/unloading operation of batch d involves q-type freight cars; $f_{q,s}$ indicates whether direction s requires q-type freight cars for loading; $f_{s,j}$ indicates whether outbound train j requires a car group destined for direction s; $f'_{q,j}$ indicates whether outbound train j requires q-type empty cars. All the above variables are 0-1 variables; if the answer is "yes", the value is 1, otherwise it is 0. Eqs. (40) to (42) indicate that for the transit flow from arriving train i to be marshaled into outbound train *j*, arriving train *i* must contain car group *s*, outbound train *j* must require car group *s*, and arriving train *i* must be able to connect to outbound train *j*. M is a sufficiently large positive integer. Eqs. (43) to (46) represent the constraints for the *q*-type freight cars from arriving train *i*, which are first unloaded and then loaded, to be marshaled into outbound train *j*. Eqs. (47) to (49) represent the constraints for the *q*-type freight cars from arriving train *i*, after being unloaded, to be marshaled into outbound train *j*. Eqs. (50) to (53) represent the constraints for the *q*-type freight cars from batch *d*, which are first unloaded and then loaded, to be marshaled into outbound train *j*. Eqs. (54) to (56) represent the constraints for the *q*-type freight cars from batch *d*, after being unloaded, to be marshaled into outbound train *j*.

(8) Loading and empty car distribution constraints

$$\sum_{d=2}^{l'}\sum_{j=1}^{n+1} x_{d,q,j,s} + \sum_{i=0}^{m}\sum_{j=1}^{n+1} x_{i,q,j,s} \le z_{s,q} \quad \forall s,q \tag{57}$$

$$\sum_{d=2}^{l'}\sum_{q=1}^{e}\sum_{j=1}^{n+1}\sum_{s=1}^{p}\left(x_{d,q,j,s}\times\eta_{d,q}\right)+\sum_{i=0}^{m}\sum_{q=1}^{e}\sum_{j=1}^{n+1}\sum_{s=1}^{p}\left(x_{i,q,j,s}\times\eta_{i,q,u}\right)\ge Z^{ZC} \tag{58}$$

$$\sum_{d=0}^{l'} x'_{d,q,j} + \sum_{i=0}^{m} x'_{i,q,j} = z'_{j,q} \quad \forall q; \forall j \in \{1, 2, ..., n\} \tag{59}$$

$$\sum_{d=0}^{l'}\sum_{q=1}^{e}\sum_{j=1}^{n} x'_{d,q,j} + \sum_{i=0}^{m}\sum_{q=1}^{e}\sum_{j=1}^{n} x'_{i,q,j} = Z^{PK} \tag{60}$$

In Eq. (57), the number of loaded cars of type *q* for direction *s* must not exceed the specified loading volume for that direction. $z_{s,q}$ represents the allowable number of loaded cars of type *q* for direction *s*. Eq. (58) indicates that the actual number of cars loaded during the current shift must not be lower than the specified minimum loading volume. Z^{ZC} represents the minimum required number of loaded cars for the current shift. Eq. (59) specifies that the actual number of empty cars distributed for a designated outbound train must equal the required number. $z'_{j,q}$ represents the required number of type *q* empty cars to be marshaled into outbound train *j*. Eq. (60) states that the total number of empty cars actually distributed during the current shift must equal the required number. Z^{PK} represents the total required number of empty cars to be distributed in the current shift.

(9) Full-axle, wagon flow allocation, and loading priority constraints

The full-axis constraint for departure train *j* is as specified in Eq. (61). The constraint for determining whether an outbound train is full-axle is given in Eq. (62).

$$0 \le L_j - \left(\sum_{i=0}^{m}\sum_{s=1}^{p} x_{i,s,j} + \sum_{d=0}^{l'}\sum_{q=1}^{e}\sum_{s=1}^{p} x_{d,q,j,s} + \sum_{d=0}^{l'}\sum_{q=1}^{e} x'_{d,q,j} + \sum_{i=0}^{m}\sum_{q=1}^{e}\sum_{s=1}^{p} x_{i,q,j,s} + \sum_{i=0}^{m}\sum_{q=1}^{e} x'_{i,q,j}\right) \le M\left(1-B_j\right) \forall j \in \{1, 2, ..., n\} \tag{61}$$

$$y_j = \begin{cases} 1, & \sum_{i=0}^{m}\sum_{s=1}^{p} x_{i,s,j} + \sum_{d=0}^{l'}\sum_{q=1}^{e}\sum_{s=1}^{p} x_{d,q,j,s} + \sum_{d=0}^{l'}\sum_{q=1}^{e} x'_{d,q,j} + \sum_{i=0}^{m}\sum_{q=1}^{e}\sum_{s=1}^{p} x_{i,q,j,s} + \sum_{i=0}^{m}\sum_{q=1}^{e} x'_{i,q,j} = L_j \\ 0, & \sum_{i=0}^{m}\sum_{s=1}^{p} x_{i,s,j} + \sum_{d=0}^{l'}\sum_{q=1}^{e}\sum_{s=1}^{p} x_{d,q,j,s} + \sum_{d=0}^{l'}\sum_{q=1}^{e} x'_{d,q,j} + \sum_{i=0}^{m}\sum_{q=1}^{e}\sum_{s=1}^{p} x_{i,q,j,s} + \sum_{i=0}^{m}\sum_{q=1}^{e} x'_{i,q,j} < L_j \end{cases} \quad \forall j \in \{1, 2, ..., n\} \tag{62}$$

Eq. (61) specifies that the marshalling volume of outbound train *j* must not exceed its full-axle capacity. In the equation, B_j is a 0-1 variable; $B_j = 1$ indicates that outbound train *j* must depart at full-axle capacity, otherwise it may depart without being full-axle. L_j represents the full-axle capacity of outbound train *j*. In Eq. (62), y_j is a 0-1 variable indicating whether outbound train *j* is full-axle. If it is full-axle, the value is 1; otherwise, it is 0.

If $B_j > B_{j'}$ or $\left(B_j = B_{j'}\right)\wedge\left(T_j^{CF} < T_{j'}^{CF}\right)$, then the wagon flow allocation and loading priority for outbound train *j* is higher than that for *j'*, i.e.:

$$Y_j^Z > Y_{j'}^Z \ \forall j \in \{1, 2, ..., n\}; \forall j \ne j' \tag{63}$$

Eq. (63) indicates: Y_j^Z and $Y_{j'}^Z$ represent the wagon flow allocation and loading priority for outbound trains *j* and *j'*, respectively.

(10) Yard organization constraint

In the marshalling yard, yard reorganization is typically required after every 3 to 5 break-up operations. The constraint conditions that must be satisfied are given in Eq. (64). Eq. (64) specifies that tasks *h'* and *h''* are both yard organization operations, and that 3 to 5 breaking-up operations should be scheduled between two consecutive yard organization operations.

$$T_{v,h'}^K < T_{v',h''}^K \ \text{and} \ 3 \le \sum_{i=1}^{m}\sum_{h=h'+1}^{h''-1} y_{i,h} \le 5 \quad \forall v,v' \in \{1, 2, ..., c\}; \forall h',h'' \in \{1, 2, ..., r\} \tag{64}$$

2.4 Objective Functions

The primary optimization objective is to maximize the number of actual full-axle trains among those requiring full-axle departure. See Eq. (65).

$$\max Z_1 = \sum_{j=1}^{n}\left(B_j \times y_j\right) \quad (65)$$

Based on the primary optimization objective, the secondary optimization objective is to maximize the number of cars dispatched in the current shift. See Eq. (66). Building upon the secondary optimization objective, the tertiary optimization objective is to maximize the number of loaded cars in the current shift. See Eq. (67).

$$\max Z_2 = \sum_{i=0}^{m}\sum_{s=1}^{p}\sum_{j=1}^{n} x_{i,s,j} + \sum_{d=0}^{l'}\sum_{q=1}^{e}\sum_{j=1}^{n}\sum_{s=1}^{p} x_{d,q,j,s} + \sum_{d=0}^{l'}\sum_{q=1}^{e}\sum_{j=1}^{n} x'_{d,q,j} + \sum_{i=0}^{m}\sum_{q=1}^{e}\sum_{j=1}^{n}\sum_{s=1}^{p} x_{i,q,j,s} + \sum_{i=0}^{m}\sum_{q=1}^{e}\sum_{j=1}^{n} x'_{i,q,j} \quad (66)$$

$$\max Z_3 = \sum_{d=2}^{l'}\sum_{q=1}^{e}\sum_{j=1}^{n+1}\sum_{s=1}^{p}\left(x_{d,q,j,s} \times \eta_{d,q}\right) + \sum_{i=0}^{m}\sum_{q=1}^{e}\sum_{j=1}^{n+1}\sum_{s=1}^{p}\left(x_{i,q,j,s} \times \eta_{i,q,u}\right) \quad (67)$$

Based on the tertiary optimization objective, the fourth optimization objective is to ensure that the first $\xi - 1$ buffer periods are distributed as evenly as possible within the range from 1 to h_ξ, with intervals as large as possible. h_ξ represents the sequential position of the ξ-th buffer period among all tasks. This objective can be transformed into minimizing the variance between the actual intervals and the ideal interval. See Eq. (68).

$$\min Z_4 = \frac{1}{\xi}\sum_{\varepsilon=1}^{\xi}\left(h_\varepsilon - h_{\varepsilon-1} - \left\lceil \frac{r}{\xi} \right\rceil\right)^2 \quad (68)$$

where: h_ξ represents the sequential position of the ε-th buffer period among all tasks, with $h_0 = 0$. $\frac{r}{\xi}$ represents the ideal interval for distributing ξ buffer periods among r tasks, rounded up if not divisible. Eq. (68) ensures that the first $\xi - 1$ buffer periods are distributed as evenly as possible within the range from 1 to h_ξ, while also ensuring that the intervals between buffer periods are as close as possible to the ideal interval.

3 ALGORITHM DESIGN

3.1 Generate Initial Task Sequence Schemes

In the station, the arrival times T_i^{DD} of m arriving trains and the departure times T_j^{CF} of n outbound trains are known. The times T_w^{FK} for preparation operations and T_a^{FK} for meal breaks during a shift are also known. The breaking-up operations of arriving trains, the marshalling operations of outbound trains, the preparation operations, and the meal breaks are sorted in ascending order based on T_i^{DD}, T_j^{CF}, T_w^{FK}, and T_a^{FK}, resulting in the first task sequence, referred to as Scheme 1. Scheme 1 comprises a total of $m+n+\beta+\varphi$ tasks. Define the initial scheme set as Q_1, and add Scheme 1 to Q_1. Generate two random variables θ and τ, where $\theta \in \mathbb{N}^+$ and $\theta < m+n+\beta+\varphi$, and $0 < \tau < 1$. Also, define a parameter λ where $0 < \lambda < 1$. Based on Scheme 1, take the θ-th task as the starting point. If $\tau > \lambda$, swap the θ-th task and the (θ+1)-th task; if $\tau \le \lambda$, do not swap them. Then, generate the variable τ randomly again. Determine the relationship between τ and λ: if τ is larger, swap the (θ+1)-th task and the (θ+2)-th task; otherwise, do not swap. Continue this process until determining whether to swap the $(m+n+\beta+\varphi-1)$ -th task with the last task. This generates a new task sequence. Check if this new sequence is identical to any sequence in set Q_1. If it is different, add the new sequence to Q_1, and this new sequence becomes Scheme 2. If it is identical, it cannot be added to Q_1. Generate several different schemes using the above method and store them in set Q_1.

3.2 Insert Buffer Times and Yard Organization Operations

Set the number of yard organization operations to c, which corresponds to c tasks. Set the number of buffer periods to ξ. Each scheme in set Q_1 has $m+n+\beta+\varphi$ tasks. First, specify that the beginning of each scheme cannot be used for inserting buffer periods or yard organization operations, leaving $m+n+\beta+\varphi$ possible insertion positions. Within the range of 1 to $m+n+\beta+\varphi$, randomly generate $c+\xi$ distinct integers, which represent the insertion scheme for yard organization operations and buffer periods. The first c integers are the insertion positions for yard organization operations, and the last ξ numbers are the insertion positions for buffer periods. Store this insertion scheme in set E. Repeat the above steps to generate several insertion schemes sequentially. Check if each generated scheme already exists in E. If it does not, add the scheme to E. According to the first insertion scheme in E, insert the yard organization operations and buffer periods into the corresponding insertion positions of Scheme 1 in Q_1. Check whether the yard organization operations satisfy the constraint condition of Eq. (64). If they do, add Scheme 1 with the inserted yard organization operations and buffer periods to set Q_2 for storage. Then, repeat the above steps: insert the first insertion scheme in E into the other schemes in Q_1 sequentially, and add the schemes that satisfy the constraint condition of Eq. (64) to Q_2. After completing the insertion for the first scheme in E, proceed to insert the other schemes in E into all the schemes in Q_1 sequentially, and add the qualified schemes to Q_2.

3.3 Insertion of Placing and Retrieval Operations

It is stipulated that placing and retrieval operations can be inserted at both the beginning and the end of all task schemes in set Q_2. Consequently, each scheme possesses $m+n+\beta+\varphi+c+\xi+1$ potential insertion positions. Given that there are k placing and retrieval operations within a shift, k distinct integers are randomly generated within the range from 1 to $m+n+\beta+\varphi+c+\xi+1$. These integers constitute the first insertion scheme for the placing and retrieval operations, explicitly defining their insertion positions. This initial insertion scheme is stored in a set denoted as G. The aforementioned procedure is repeated to generate multiple insertion schemes for the placing and retrieval operations. Each newly generated scheme is checked for duplication against existing schemes within set G. If no duplicate is found, the new scheme is added to G. Finally, for each insertion scheme contained within G, the placing and retrieval operations are sequentially inserted into the corresponding schemes of Q_2. All newly generated schemes resulting from this process are stored in a new set, Q_3.

3.4 Setting the Start Times of Tasks

Using Scheme 1 from set Q_3 as an illustrative example: If the first task of Scheme 1 is the breaking-up operation of train i, its start time is defined as $T_{i,1}^{K}=T_{i}^{EJT}$; If the first task is a marshalling operation or a placing and retrieval operation, its start time is T^{K}; If the first task is a locomotive preparation operation, then $T_{w,1}^{K}=T_{w}^{FK}$; If the first task is a meal break, then $T_{a,1}^{K}=T_{a}^{FK}$.

The start time for any subsequent h-th task ($\forall h$, and $\forall h\neq 1$) is determined by the following rules based on task type:

If the h-th task is a breaking-up operation: If $T_{i}^{EJT}\leq T_{h-1}^{K}+t_{h}^{Z}$ then $T_{i,h}^{K}=T_{h-1}^{K}+t_{h}^{Z}$; If $T_{i}^{EJT}>T_{h-1}^{K}+t_{h}^{Z}$, then $T_{i,h}^{K}=T_{i}^{EJT}$.

If the h-th task is a marshalling operation: If $T_{j}^{LB}<T_{h-1}^{K}+t_{h}^{Z}$, this indicates the scheme is temporally infeasible, and it is immediately discarded; If $T_{j}^{LB}\geq T_{h-1}^{K}+t_{h}^{Z}$, then $T_{j,h}^{K}=T_{h-1}^{K}+t_{h}^{Z}$.

If the h-th task is a placing and retrieval operation, then $T_{u,h}^{K}=T_{h-1}^{K}+t_{h}^{Z}$. If the h-th task is a buffer period, then $T_{\varepsilon,h}^{K}=T_{h-1}^{K}+t_{h}^{Z}$. If the h-th task is a yard organization operation, then $T_{v,h}^{K}=T_{h-1}^{K}+t_{h}^{Z}$.

If the h-th task is the w-th preparation operation: If $T_{w}^{FK}\geq T_{h-1}^{K}+t_{h}^{Z}$, then $T_{w,h}^{K}=T_{w}^{FK}$; If $T_{w}^{FK}<T_{h-1}^{K}+t_{h}^{Z}$ and $T_{w}^{FJ}-(T_{h-1}^{K}+t_{h}^{Z})\geq T^{ZBS}$, then $T_{w,h}^{K}=T_{h-1}^{K}+t_{h}^{Z}$; If $T_{w}^{FK}<T_{h-1}^{K}+t_{h}^{Z}$ and $T_{w}^{FJ}-\left(T_{h-1}^{K}+t_{h}^{Z}\right)<T^{ZBS}$, it indicates temporal infeasibility, and the scheme is discarded.

If the h-th task is a meal break for the shunting team: If $T_{a}^{FK}\geq T_{h-1}^{K}+t_{h}^{Z}$, then $T_{a,h}^{K}=T_{a}^{FK}$; If $T_{a}^{FK}<T_{h-1}^{K}+t_{h}^{Z}$ and $T_{a}^{FJ}-(T_{h-1}^{K}+t_{h}^{Z})\geq T^{CFS}$, then $T_{a,h}^{K}=T_{h-1}^{K}+t_{h}^{Z}$; If $T_{a}^{FK}<T_{h-1}^{K}+t_{h}^{Z}$ and $T_{a}^{FJ}-\left(T_{h-1}^{K}+t_{h}^{Z}\right)<T^{CFS}$, it indicates temporal infeasibility, and the scheme is discarded.

If Scheme 1 remains valid after assigning start times to all tasks, a final check is performed: verify if the end time of the last task is less than or equal to the shift end time, i.e., if $T_{r}^{K}+t_{r}^{Z}\leq T^{END}$ holds true. If this condition is satisfied, Scheme 1 is added to set Q_4. Otherwise, it is discarded. This procedure is applied identically to all schemes within set Q_3. Those schemes meeting all requirements are added to set Q_4. Q_4 represents the set of initial feasible solutions. To ensure a sufficient number of schemes in Q_4, let the sample size parameter be C^{s} (where C^{s} is a positive integer). If $\left|Q_4\right|\geq C^{s}$, then proceed to the next step of calculation; otherwise, repeat the aforementioned steps until $\left|Q_4\right|\geq C^{s}$.

3.5 Empty Car Distribution and Wagon Flow Allocation Rules

When an outbound train requires empty car distribution, priority is given to allocating empty cars already present within the marshalling yard. If the quantity of empty cars in the marshalling yard is insufficient or unavailable, empty cars are selected from the freight yard for allocation. If multiple batches of unloading operations within the freight yard yield empty cars that are all retrievable to the marshalling yard, thus providing a source of wagon flow for empty car distribution trains, the empty cars generated from the most recent batch are prioritized for connecting to the empty car distribution train. Should the quantity from the last batch prove insufficient, empty cars from the immediately preceding batch are utilized for allocation.

Following empty car allocation, loaded car allocation is executed. Loaded car allocation is a four-step process: Step 1: Allocate wagon flow to outbound trains mandated to depart at full-axle capacity. Sources include cars currently stored in the marshalling yard, transit wagon flow arriving during the current shift, and wagon flow in the freight yard with a predetermined loading direction. Step 2: Allocate wagon flow to outbound trains not required to depart at full-axle capacity, utilizing the same sources listed in Step 1. Step 3: Allocate wagon flow to those outbound trains from Step 1 that must be full-axle but remain below capacity. Sources for this step are wagon flow in the freight yard awaiting unloading or loading at the shift's start and service cars arriving during the current shift. Step 4: Utilize any remaining wagon flow from Step 3 to allocate wagon flow to trains from Step 2 that have not yet reached full-axle capacity.

3.6 Calculate the Optimization Objective Values and the Extreme Values of Each Optimization Objective

Calculate all schemes in Q_4, solve the first optimization objective, and then sequentially solve the second to fourth optimization objectives. To determine whether the calculated results are optimal or approaching optimality, this paper compares each optimization objective value with its corresponding extreme value. Each of the four optimization objectives in this paper has an extreme value. The calculation logic for the extreme values is as follows:

The first optimization objective is to maximize the number of trains that actually achieve full-axle capacity among those required to be full-axle during the shift. Therefore, the maximum extreme value for the first objective is the number of trains required to be full-axle. For example, if the number of trains requiring full-axle operation is 3, then the maximum extreme value for the first objective is 3. The condition where all departure trains meet the specified full-axle formation count is the maximum extreme value for the second optimization objective. For example, if there are 6 departure trains, each with a specified full-axle formation count of 50 wagons, then the maximum extreme value for the second objective is 300. Disregarding all waiting times and removing the empty wagons that must be used for empty wagon distribution during the shift, the remaining number of empty wagons that can be loaded during the shift constitutes the maximum extreme value for the third optimization objective. The minimum extreme value for the fourth optimization objective is 0. However, the objective values may not necessarily reach their extremes. Firstly, the number of wagons itself may be insufficient, preventing full-axle operation. Secondly, even if the wagon count is sufficient, operational conflicts may prevent wagon groups from being connected to departure trains or loading operations in a timely manner.

Based on the importance of each optimization objective and the wagon flow situation, an optimization coefficient is respectively set for the first to third optimization objectives, denoted as W^{Z1}, W^{Z2}, and W^{Z3}. The value range of the optimization coefficients is greater than 0 and less than or equal to 1. Simultaneously, a stability coefficient W^s ($W^s \geq 0$) is set for the fourth optimization objective. If the ratio of the first to third optimization objective values to their corresponding extremum is greater than or equal to their respective optimization coefficients, and the fourth optimization objective value is less than or equal to the stability coefficient (Condition One), then it is determined that the optimum has been reached. If, among the first to third optimization objectives, the ratio of one objective's value to its corresponding extremum is less than its respective optimization coefficient, or if the fourth optimization objective value is greater than the stability coefficient, it indicates that the optimum may not have been reached. At this point, the aforementioned steps are cyclically repeated, adding at least C^s more feasible solutions to the Q_4 set, and then continuing to solve for the optimal solution. If Condition One is satisfied, it is determined that the optimum has been reached; or, if after C^c consecutive cycles, all optimization objective values remain unchanged, it is also determined that the optimum has been reached, and the cycle is exited.

4 CASE STUDY

4.1 Basic Data

(1) Line conditions

The station studied in this paper is the D_2 district station. Its schematic location within the railway network is shown in Fig. 1. In Fig. 1, D_1 and D_4 are marshalling stations, D_2 and D_3 are district stations, and O_1-O_{12} are intermediate stations.

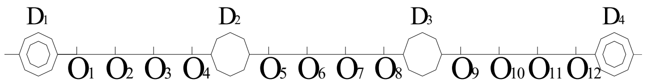

Figure 1 Schematic diagram of D_2 station's network location

(2) Operation time standards for D_2 station

The operation time standards for D_2 Station are shown in Tab. 1.

Table 1 Operation time standards for D_2 station (unit: minutes)

Time type	T^{DJS}	T^{CJ}	T^{J}	T^{B}_{j}
Duration	35	25	25	25/35
Time type	T^{XC}	T^{ZC}	T^{QS}	T^{ZLC}
Duration	60	120	40	30
Time type	T^{ZBS}	T^{CFS}	T^{HC}	
Duration	40	30	30	

In Tab. 1, for marshalling district trains, T^{B}_{j} =25 minutes; for marshalling pickup-drop trains or local transfer trains, T^{B}_{j} = 35 minutes. For placing and retrieval operations: whether it is placing alone, retrieval alone, or combined placing and retrieval, the operation time T^{QS} is 40 minutes. The preparation operation is scheduled from 20:00 to 20:40. The meal break is arranged around 24:00, with a deviation not exceeding 30 minutes before or after. Meanwhile, the shift start time T^{K} is 18:00, and the shift end time T^{END} is 06:00 the next day. The number of yard organization operations is set to 1, and the number of buffer periods is set to 3. The number of wagon placement and removal operations is set to 4. All trains departing from this station have L_j = 50.

Table 2 Marshalling plan related to this station

Departure station	Destination station	Marshalling content	Train type	Operation type
D_2	D_1	D_1 and beyond	District train	Marshalling operation
D_2	D_1	O_4-O_1	Pickup and drop train	Marshalling operation
D_2	D_3	1. D_3 and beyond 2. Empty cars, not sorted by type.	District train	Marshalling operation
D_2	D_3	O_5-O_8	Pickup and drop train	Marshalling operation
D_1	D_2	D_2 and beyond	District train, Pickup and drop train	Breaking-up operation
D_3	D_2	D_2 and beyond	District train, Pickup and drop train	Breaking-up operation

(3) Marshalling plan related to this station

The marshalling plan related to this station is shown in Tab. 2. Since the operations of non-classified transit trains do not involve reclassification at this station, the marshalling plan for non-classified transit trains is omitted in this paper.

(4) Cars in storage at the station

The status of cars in storage at the D_2 Station marshalling yard at 18:00 is shown in Tab. 3. Meanwhile, there is one batch of cars being loaded in the freight yard, scheduled to be completed by 18:30. The loading directions are: 5 covered cars for station D_1 and 5 gondola cars for station D_3. Additionally, 12 empty gondola cars are stored in the freight yard.

Table 3 Status of cars in storage at the marshalling yard at 18:00

Direction	Transit Cars (Loading/Unloading Cars)
D_1	43 (8)
O_4-O_1	35 (2)
D_3	30-Empty Gondola Cars (15)
O_5-O_8	23 (0)
Cars Awerting Delivery to Freight Yard	0 (0)

(5) Loading and empty car distribution plan

The daily empty car distribution requirement is 60 cars, of which 35 empty gondola cars are specifically assigned to be marshaled into train 32001 during this shift. The daily loading requirement is 95 cars, with at least 43 cars required to be loaded during this shift. The specific loading requirements for each direction are shown in Tab. 4.

Table 4 Loading quantities by direction

Direction	D_1	O_4-O_1	D_3	O_5-O_8
Covered cars	5	15	10	13
Gondola cars	20	15	10	7

(6) Freight train arrival and departure plan for D_2 station.

The information of self-marshaled originating trains at D_2 station is shown in Tab. 5. The self-marshaled originating trains at Station D_2 have only two destinations: D_1 and D_3. There is a total of 6 self-marshaled originating trains, comprising 3 district trains and 3 pickup and drop trains. Since the district trains are required to depart at full-axle capacity, their wagon flow allocation and loading priority are higher than those of the pickup and drop trains.

Table 5 Information of self-marshalled originating trains

Direction	Train number	Departure time
D_1	32302	19:30
	43162	21:40
	32304	4:30
	43164	5:07
D_3	32001	21:12
	43141	2:16

The information of arriving breaking-up trains at D_2 Station is shown in Tab. 6.

Table 6 Train numbers and related information of arriving breaking-up trains at D_2 station

Direction	Train number	Arrival time	Marshalling content					Types of loading/unloading cars	
			D_1	O_4-O_1	D_3	O_5-O_8	D_2	Covered cars	Gondola cars
D_1	32301	21:00	-	-	30	15	10	10	-
	43165	1:30	-	-	20	30	5	5	-
D_3	32004	18:15	-	40	-	-	15	-	15
	43148	1:00	30	15	-	-	5	-	5
	32002	4:07	-	30	-	-	25	15	10

(7) Parameter settings

C^s is set to 1000, meaning the number of initial feasible solutions must reach 1000 or more. C^c is set to 3. W^{Z1}, W^{Z2}, and W^{Z3} are set to 1, 0.9, and 0.9, respectively. W^s is set to 2.

4.2 Calculation Process

(1) Solving the first optimization objective

The Q_4 set obtained through calculation contains 1065 schemes, meaning there are 1065 schemes that satisfy all constraints. The number of trains that actually reached full-axle capacity among those required to be full-axle was calculated for these 1065 schemes. The calculation results are shown in Fig. 2. Fig. 2 is a scatter plot where the horizontal axis represents the number of schemes in Q_4, and the vertical axis represents the number of trains that actually reached full-axle capacity among those required to be full-axle. The vertical axis is divided into three regions. All points in Region 1 have a y-coordinate value of 1, while the points in Regions 2 and 3 have corresponding y-coordinate values of 2 and 3, respectively. There are 327 points in Region 3, indicating that for 327 schemes, the actual number of trains achieving full-axle capacity among those required to be full-axle is 3. The maximum value is 3, hence $\max Z_1 = 3$. Furthermore, only three departure trains are required to be full-axle, so the maximum extreme value for the first optimization objective is 3. The value of the first optimization objective equals its maximum extreme value, therefore $\max Z_1 = 3$ represents the optimal solution.

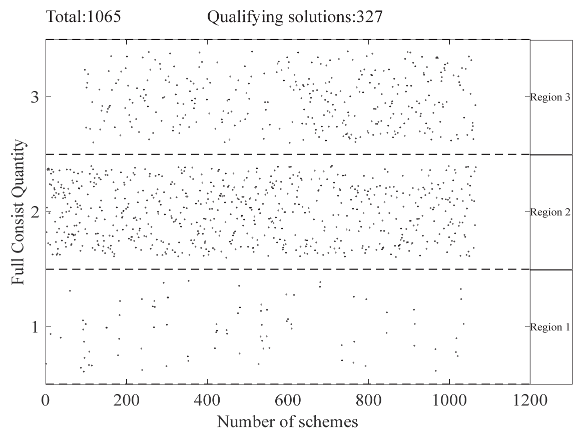

Figure 2 Number of full-axle trains among those required to be full-axle

(2) Solving the second optimization objective

There are 327 schemes that satisfy $\max Z_1 = 3$. The number of cars dispatched for all these schemes was calculated, and the results are shown in Fig. 3. In Fig. 3, the horizontal axis represents the 327 schemes, and the vertical axis represents the number of cars dispatched for each scheme. The calculation results show that all 327 schemes dispatched 288 cars, meaning $\max Z_2 = 288$. Meanwhile, a total of 6 trains are dispatched during the shift, each with a full-axle formation count of 50 wagons. Therefore, the maximum extreme value for the second optimization objective is 300. The ratio of the second optimization objective value to its maximum extreme value is 96%, which exceeds 90%, indicating that the optimal condition is achieved.

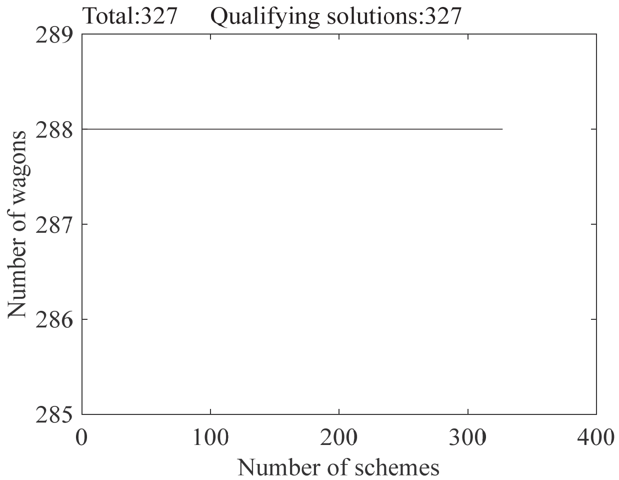

Figure 3 Calculation of dispatched cars for schemes satisfying maxZ_1 = 3

(3) Solving the third optimization objective

There are 327 schemes that satisfy $\max Z_2 = 288$. The number of loaded cars for these 327 schemes was calculated, and the results are shown in Fig. 4, which is a scatter plot. The horizontal axis represents the number of schemes, and the vertical axis represents the number of loaded cars for each scheme. Fig. 4 shows that the maximum number of loaded cars is 47, and the minimum is 32. Thus, $\max Z_3 = 47$, and there are 102 schemes that achieved a loaded car count of 47. At the freight yard, the loading operations for 10 wagons will be completed at 18:30. Simultaneously, there are 12 empty gondola cars in the freight yard, of which 5 are designated for empty wagon distribution. Disregarding waiting time, the remaining 7 wagons commence loading immediately at 18:00 and complete loading at 20:00. Therefore, a total of 17 wagons at the freight yard can complete loading before the end of the shift. For the wagons for loading/unloading arriving with the trains, disregarding waiting time, 280 minutes are required from their arrival time to the completion of loading. Calculations show that a total of 30 wagons for loading/unloading from the arriving trains can complete loading before the end of the shift. Therefore, the maximum extreme value for the third optimization objective is 47. The optimized value of the third objective equals its corresponding extreme value, achieving the optimal condition.

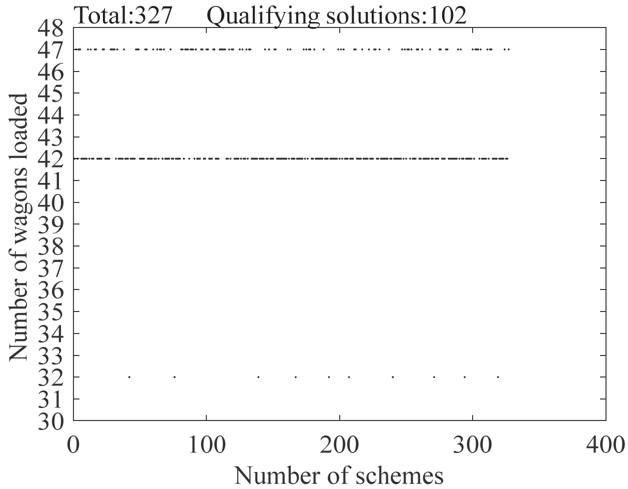

Figure 4 Calculation of maximum loaded cars

(4) Solving the fourth optimization objective

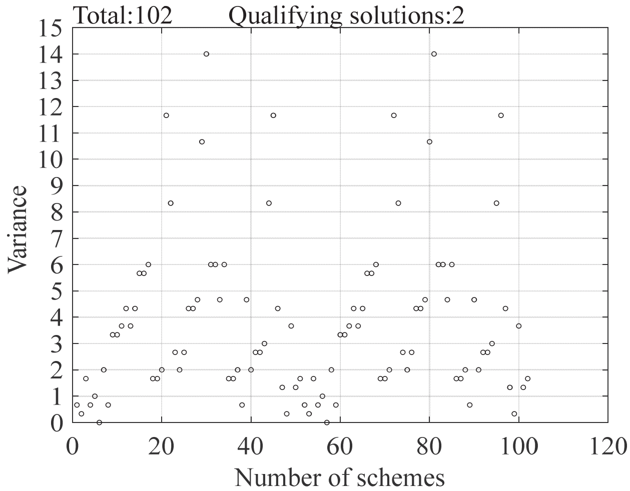

Figure 5 Variance calculation results

The fourth optimization objective was solved based on the third optimization objective. The results are shown in Fig. 5. The minimum variance obtained was 0, meaning $\min Z_4 = 0$, and two schemes achieved $\min Z_4 = 0$. The fourth optimization objective equals its corresponding extreme value, achieving the optimal condition.

4.3 Calculation Results

(1) Task sequence and schedule

Two schemes that meet the requirements were ultimately obtained through calculation. Tab. 7 shows one of the task schemes. In Tab. 7, the "Task type" column: "0" represents placing and retrieval operations; "1" represents breaking-up operations; "2" represents marshalling operations for trains that must depart at full-axle capacity; "3" represents marshalling operations for trains not required to depart at full-axle capacity; "4" represents preparation operations; "5" represents meal breaks; "100" represents buffer periods; "101" represents yard organization operations.

(2) Placing and retrieval arrangements The details of placing and retrieval operations are shown in Tab. 8.

Table 7 Task sequence and schedule

h	Task type	Train number/ Operation number	T_i^{DD} / T_j^{CF}	T_h^K	$T_h^K + t_h^Z$
1	0	0-1	-	18:00	18:40
2	2	32302	19:30	18:40	19:05
3	1	32004	18:15	19:05	19:30
4	2	32001	21:12	19:30	19:55
5	4	4-1	-	20:00	20:40
6	3	43162	21:40	20:40	21:15
7	100	100-1	-	21:15	21:45
8	0	0-2	-	21:45	22:25
9	1	32301	21:00	22:25	22:50
10	101	101-1	-	22:50	23:20
11	5	5-1	-	23:30	0:00
12	0	0-3	-	0:00	0:40
13	3	43141	2:16	0:40	1:15
14	100	100-2	-	1:15	1:45
15	1	43148	1:00	1:45	2:10
16	0	0-4	-	2:10	2:50
17	1	43165	1:30	2:50	3:15
18	2	32304	4:30	3:15	3:40
19	3	43164	5:07	3:40	4:15
20	1	32002	4:07	4:42	5:07
21	100	100-3	-	5:07	5:37

Table 8 Placing and retrieval details

Placing/Retrieval operation number	Number of cars placed	Number of cars retrieved	
		Empty cars	Loaded cars
0-1	0	5	0
0-2	15	0	17
0-3	10	0	0
0-4	5	0	15

(3) Loading arrangements

A total of 47 cars were loaded during the shift. The specific loading details for each direction are shown in Tab. 9. In Tab.9, the first three loading/unloading batches provide wagon flow sources for the departing trains of this shift. Therefore, the loading content and sequence are determined based on the priority and departure order of the trains. The fourth and fifth batches provide wagon flow sources for the next shift's departing trains. The loading principle is to prioritize trains that must depart at full-axle capacity, and any remaining capacity is allocated to trains not required to depart at full-axle capacity.

Table 9 Loading details

Loading batch	Unloading start time	Loading completion time	Loading direction\Car type\Quantity
1	-	18:30	D_1\Covered cars\5; D_3\Gondola cars\5
2	-	21:00	D_1\Gondola cars\7
3	22:25	1:25	D_1\Gondola cars\7; O_4-O_1\Gondola cars\8
4	0:40	3:40	D_3\Covered cars\10
5	2:50	5:50	D_1\Gondola cars\5

(4) Wagon flow sources

The wagon flow sources for the departing trains are shown in Tab. 10.

Table 10 Wagon flow sources for departing trains

Train number	Source	Quantity	s	Car type\Loaded cars or empty cars
32302	Cars in storage at station	50	D_1	-
32001	Cars in storage at station	45	D_3	-
	0-1	5	D_3	Gondola cars\Empty cars
43162	Cars in storage at station	37	O_4-O_1	-
	32004	13	O_4-O_1	-
43141	Cars in storage at station	23	O_5-O_8	-
	32301	15	O_5-O_8	-
32304	Cars in storage at station	1	D_1	-
	43148	30	D_1	-
	0-2	5	D_1	Covered cars\Loaded cars
	0-2	7	D_1	Gondola cars\Loaded cars
	0-4	7	D_1	Gondola cars\Loaded cars
43164	32004	27	O_4-O_1	
	43148	15	O_4-O_1	
	0-4	8	O_4-O_1	Gondola cars\Loaded cars

5 CONCLUSION

The coordinated optimization model for the sequencing of break-up and marshalling operations and the timing of wagon placement and removal at a single-locomotive district station constructed in this paper integrates detailed wagon flow connection relationships, time window constraints, yard reorganization requirements, and resource exclusivity. It hierarchically defines four priority optimization objectives, achieving dual guarantees of operational efficiency and plan robustness. The efficiency objectives, centered on "maximizing the number of trains that actually reach full-axle capacity among those required to be full-axle in the current shift", "maximizing the number of cars dispatched", and "maximizing the number of cars loaded", directly enhance the station's transportation output. The stability objective of "evenly distributed buffer periods" strengthens the anti-interference capability of the operational plan. The priority setting of these four objectives aligns with the practical operational needs of the station. Finally, case validation demonstrates that the proposed collaborative optimization model and its supporting algorithm can effectively improve the operational efficiency of district stations with a single shunting locomotive. By increasing the number of full-axle trains, the number of cars dispatched, and the number of cars loaded, while simultaneously ensuring the stability of the operational plan, this study provides theoretical support and practical references for optimizing operational organization at similar stations.

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