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RESEARCH ARTICLE

Reschedule the Shunting and Service Scheduling Plan After Disturbances at a Chinese High-Speed Railway Depot

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ABSTRACT Electrical Multiple Units (EMUs) need to undergo services like repairing, cleaning and wheel turning according to a train shunting and service scheduling (SSS) plan at the high-speed railway depot. Disturbances in the timetable at the station and overtime services affect the original SSS plan. Therefore, frequent modifications to the original SSS plan and rescheduling of some EMUs are required to recover the feasibility of the plan. This paper considers a rescheduling method for integrating train shunting, service scheduling and routing at EMU depots with various layouts. In this paper, the movement process of EMUs at depots is represented with the help of a two-layer time-space network. A heuristic algorithm for rescheduling is designed. Case studies based on a real-world depot show that the heuristic can repair the original SSS plan in 180 seconds while ensuring that the new SSS plan is as close as possible to the original SSS plan.

INDEX TERMS Maintenance, rescheduling, service scheduling, time-space network, train unit shunting.

I. INTRODUCTION

In railway operation management, Electrical Multiple Units (EMUs) must undergo different maintenance services depending on the distance and time of running to ensure safety. Effectively organizing maintenance for EMUs can enhance the stability and efficiency of railway operations. The low-level maintenance or daily maintenance [1], happens at an EMU depot (also called the shunting yard), which is usually near a station. An EMU depot contains a storage yard, a cleaning yard, a repair yard and may also have a suction yard, a wheel turning yard, and so on. Each yard has one or more parallel tracks to provide parking or services for EMUs. Figure 1 shows a simplified topology of an EMU depot in China. It consists of a storage yard, a cleaning yard, a repair yard and a wheel turning yard. The first-level daily maintenance usually takes 1-2 hours, and the second-level daily maintenance takes several hours, but usually not more than 12 hours. This daily maintenance of EMUs happens at the depot and includes several kinds of services such as repair, cleaning, sewage suction and wheel turning. The *service scheduling problem* at the depot determines the sequence, the starting time and finishing time of all services [2]. As defined by van den Broek et al. [2], the process of parking trains at yards, together with several related processes, is called *shunting*. The *shunting planning problem* at the depot determines the occupation sequence of the tracks and switches, the starting and departure time of the occupation, and the starting and the ending time of shunting routes. Since the maintenance services of EMUs are performed on the shunting tracks, the above two problems, service scheduling and shunting planning, cannot be addressed separately. The

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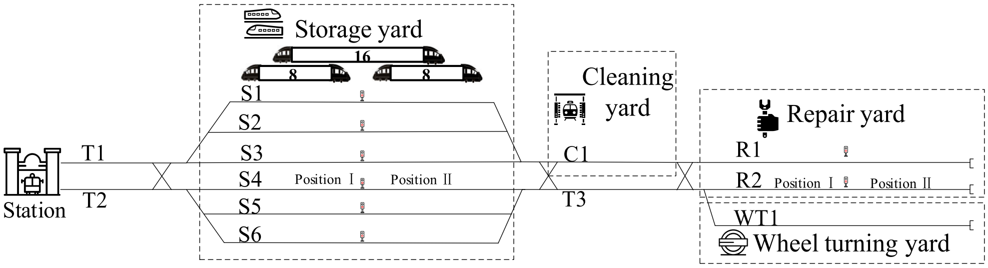


FIGURE 1. A typical layout of an EMU depot in China.

integrated problem is called the *train shunting and service scheduling* (SSS) problem. After the EMU arrives at the station at the time specified in the timetable, it enters the depot. The SSS plan of the depot is usually determined based on a fixed train timetable. However, the timetable of the station may encounter small *disturbances*, which then affect the moments at which the EMU enters and leaves the depot [3], [4]. Since the maintenance resources at the depot are limited, a perturbed EMU may affect other EMUs, e.g., subsequent EMUs dwelling on the same track or requiring the same maintenance. In addition, an EMU may encounter significant malfunctions discovered during repair services that necessitate an extension of the scheduled repair time, thereby affecting the subsequent plans for the current EMU and requiring a temporary increase in the pre-determined standard service time duration. Such *overtime service* may also lead to the infeasibility of the original SSS plan [3], [4].

At this moment, the SSS problem in China is still solved by slow manual work [5]. It is necessary to develop an applicable and fast method to assist dispatchers in rescheduling SSS plans in case of disturbances. Our focus is on computer-aided rescheduling of the SSS plan after disturbances at Chinese high-speed railway depots. The input data includes the original SSS plan (including the planning horizon, the arrival and departure times of each EMU, the service tasks and the required service time of each EMU, the operating cost for each operation, the occupancy information of tracks and switches), the layout of the depot and the function of each track, the safety headway time, and information about disturbances (including the EMU, the disturbance type, the disturbance start time and end time). The output data includes the new occupancy information of tracks and switches. The objective is to find a feasible SSS plan in a short period of time that is as close as possible to the original plan. For real-time applications, the solution time should be limited to 180 seconds [6], [7].

The SSS problem is a special case of the Train Unit Shunting Problem (TUSP). Trains are composed of one or more train units, and each train unit consists of several railcars. The combination of train unit parking, routing and matching at yards is called the *Train Unit Shunting Problem* (TUSP) [2]. *Parking* is to assign trains to tracks at the right time, *routing* is to let the train move to another place without blockage, and *matching* is to assign several train units to trains according to the required train composition and train unit order. Considering trains may have to accept services like regular repair and cleaning at some stations and depots, a more complex problem is combining *the TUSP with service scheduling*, which is called TUSPwSS [2].

Our SSS problem is mostly related to the TUSPwSS. In China, there are two types of trains in terms of length, namely long train units with 16 railcars and short train units with 8 railcars. A train unit can be operated as a single train regardless of its length. Also, two short train units can be coupled as a long train. Different from the typical TUSPwSS problem studied in The Netherlands and other countries, the SSS problem in China does not have to consider the train coupling, decoupling and matching sub-problem [1], [5], because the EMUs in China have fixed carriages. Therefore, the SSS problem in China is a special case of the TUSPwSS. However, solving the existing TUSP with or without service scheduling or coupling and decoupling is still a challenging problem.

In the following literature review, the current research status on the TUSP in Europe is presented first. Following that, the existing studies on the SSS by Chinese scholars are discussed. Subsequently, the research on rescheduling is introduced, and a brief introduction of the objective function settings in the existing literature is provided. Finally, an overview and summary of the existing work is also included.

For the TUSP, Haahr et al. [8] develop a constraint programming formulation, a column generation approach, and a randomized greedy construction heuristic to solve the train unit matching and parking problem at the shunting yard. van den Broek [9] considers a complete version of the TUSPwSS, including all sub-problems. The objective is to minimize the weighted penalties of violated constraints, such as route crossing and track capacity constraints, as well as penalties for delays and shunting movements. van den Broek et al. [2] improve their previous approach by allowing simultaneous routing. Another recent approach is presented by Kamenga [10], who undertakes a comprehensive approach by jointly modelling and solving the TUSPwSS at both the station and depot levels. He focuses more on matching and parking. However, in large depots in China, there are usually many more service tracks. Every night, $15 \sim 30$ trains require services that include cleaning and repair. Therefore, the Chinese version of TUSP needs to focus more on service scheduling and the corresponding parking plan.

TABLE 1. A literature review on TUSP and SSS.

Reference	Parking	Routing	Matching	Servicing	Rescheduling	Instances	Layout of depot	Solution approach
Haahr, et al. [8]	√	√				Nld, Den	General	CP, MIP, H,
van den Broek [9]	√	√	√	√		Nld	General	H
van den Broek, et al. [2]	√	√	√	√		Nld	General	H
Kamenga [10]	√	√	√	√		Fr	General	MIP
Wang, et al. [5]	√	√		√*		Chn	Specific, typical^{**1}	ILP
Xu and Dessouky [1]	√	√		√*		Chn	Specific, typical^{**2}	ILP, LR
He, et al. [11]	√	√		√*		Chn	Specific, typical^{**3}	H, PSO
He, et al. [4]	√			√*		Chn	Specific, typical^{**3}	AILS
This paper	√	√		√	√	Chn	General	H

MIP: Mixed integer programming; H: Heuristic; CP: Constraint programming; ILP: Integer linear programming; LR: Lagrangian relaxation; RVNS: Reduced variable neighbourhood search; GA: Genetic algorithm; PSO: Particle swarm optimization; AILS: Adaptive iterative local search.

For instances, Nld, Den, Fr and Chn stand for the Netherlands, Denmark, France and China, respectively.

*: Only considering the first-level maintenance that includes two service tasks, namely repair and cleaning.

**: All tracks in ^{**1} are last-in-first-out tracks. Repair tracks in ^{**2} are last-in-first-out tracks, which helps to model the problem from the inbound-outbound layers network. Repair tracks in ^{**3} are last-in-first-out tracks. The layouts of depots in ^{**2} and ^{**3} are longitudinal yard configurations.

Many Chinese researchers have also studied the SSS planning problem. Wang et al. [5] put forward an ILP model for depots with parallel yards and solve it using the Gurobi solver. He, et al. [11] solve the SSS problem using metaheuristics, GA and PSO, respectively. He et al. [4] improve their previous work in He et al. [11] by considering the stochastic uncertainties at depots, which mainly refer to the disturbances of servicing/ arrival/departure times. They design an adaptive iterative local search algorithm to solve the robust scheduling problem. However, both He et al. [11] and He et al. [4] suppose all tracks are identical and without the double-position configuration, which simplifies the actual problem and is inconsistent with the actual situation in China. Xu and Dessouky [1] construct a two-layer time-space network customized for first-level maintenance (only repair and clean services). The differences between the network in Xu and Dessouky [1] and our network will be detailed at the end of Section III-A1.

In railway timetabling or platforming, there is much literature on rescheduling after disturbances. The survey paper by Cacchiani et al. [12] is recommended. According to Cacchiani et al. [12], disturbances are relatively small perturbations of the railway system that can be handled by just modifying the timetable. There are several rescheduling measures, including re-time, re-order, re-track and re-route [13], [14], which means modifying the arrival/departure times, the arrival/departure orders, the platforming track and the route inside or between stations. For the SSS problem, different yards can be regarded as different stations in the timetabling problem. In this paper, re-time, re-order and re-track measures will be used.

For the objective function of rescheduling for timetabling or platforming, most of literature minimize the total deviation between the scheduled and actual arrival/departure time, and minimize the total deviation between the scheduled platform tracks and actual platform tracks [15]. For the SSS problem, there is no need to consider passengers. Moreover, the service sequences are flexible, which means the sequences of occupancy yards are also flexible in the SSS problem, not like the fixed sequences of passing stations in the timetabling problem [16]. Therefore, there is no need to minimize the total deviation between the scheduled and actual arrival/departure time at different yards in the SSS problem. Considering that the initial SSS plan usually undergoes extensive calculations and human adjustments with human or depot rules before being finalized, the original SSS plan is regarded as a well-thought-out plan. The plans for drivers and maintenance workers, which are based on the original SSS plan, also require considerable time to develop. Due to the computational time limit for real-time rescheduling, a rescheduled plan that closely aligns with the original SSS plan can reduce the randomness. This would also reduce the impact on subsequent planning for drivers and maintenance workers. For example, subsequent planning for drivers and maintenance workers may only require minor adjustments to task durations, without the need for extensive changes to the task locations. Therefore, in this paper, in order to avoid extensive modifications to the original SSS plan, the tracks used in the original SSS plan should also be used as much as possible.

To give an overview, several related papers are summarized in Table 1. "$\surd$" indicates the paper has considered that aspect. The main conclusions from Table 1 are discussed below. As shown in Table 1, although there is a lot of relevant literature, the considered subproblems and assumptions in different papers result in differences in the complexity and applicability of the issues. Even though some papers address similar depots and the comprehensiveness as this paper, the focus here is on rescheduling the shunting and service scheduling plan after disturbances, requiring a rapid solution (in less than 180s). Other papers typically involve planning from scratch, which is typically much more time-consuming.

This paper makes the following contributions to the literature. First, to the best of our knowledge, our study is the first to put forward a rescheduling method for the SSS plan at high-speed railway depots on the microscopic level. Compared with platforming problem rescheduling, the SSS rescheduling problem at EMU depots needs to consider multiple track occupations when moving between different yards. Moreover, the length of EMUs and the configuration of the track need to be considered. Second, a two-layer time-space network is designed for the considered problem. Routing conflicts can be avoided during rescheduling by setting incompatible arc sets. Different from the two-layer time-space network at Xu and Dessouky [1], where a specific type of layout was analysed, our time-space network is suitable for most types of layouts of depots. In our time-space network, the shunting level and dwelling level depict the states of EMUs at the depot. The time duration of shunting with movement direction changes (saw-moves) is also considered, which is neglected in most of the literature. Third, we propose a heuristic to find the new schedule in a short time for EMUs affected by disturbances. A solution framework based on local search is designed. Compared with existing methodologies on train rescheduling that all trains need to be planned together, a pool of EMUs at the depot that need to be rescheduled is established and updated after one iteration. A tailored rule of building all possible sequences of the pool is designed. The classic label-setting dynamic programming algorithm is also modified and integrated into the heuristic.

The rest of this paper is organized as follows. In Section II, a detailed description of the considered problem is provided. In Section III, the heuristic solution method based on a two-layer time-space network representation is described. A real-world case study is conducted to confirm the effectiveness of our solution method in Section IV. Conclusions and future research are discussed in Section V.

II. PROBLEM DESCRIPTION

The railway planning problem has three levels. Strategic-level planning is long-term, typically covering several months to years. The strategic level is for determining or evaluating the capacity of the depot. Tactical-level planning involves mid-term or partial long-term decisions, typically covering a time range from one week to several months. The tactical level is for making an SSS plan from scratch [1], [2]. Operational-level planning is short-term, typically covering hours to days. This includes the daily train shunting and specific service arrangements to meet the daily operational needs of the depot. Although this paper is on the operational level to reschedule when small disturbances happen, a problem description for the SSS planning without disturbances on the tactical level is presented first, in Section II-A. Then, a problem description for the SSS rescheduling with disturbances on the operational level is presented in Section II-B.

A. THE SSS PLANNING WITHOUT DISTURBANCES ON THE TACTICAL LEVEL

In the SSS planning, during a planning horizon (4 h, 8 h or 12h, usually at night), a number of EMUs are scheduled to undergo different services with unfixed sequence and it should be decided how these EMUs are moved around the yards (and to and from the depot) to determine a feasible path for each EMU and in order to minimize the total operating cost. The assumptions of our study are as follows: (a) There are enough shunting drivers and service workers available in the depot, that is, the task assignment of drivers and service workers is not considered in this paper and can be solved after getting the TUSP or SSS plan [17], [18]. This assumption is also proposed in most papers when solving TUSP and SSS; (b) Once a service has started, it cannot be interrupted. This is also known as the common assumption "no pre-emption" in job shop scheduling. (c) If there exists shunting route(s) linking two adjacent track/position nodes without changing EMU's direction, only one main shunting route will be considered [19], [20]. (d) To reduce the frequent occupancy of service tracks, EMUs cannot enter service tracks without undergoing service.

According to the two types of EMU length, the storage track and the repair track usually have two *positions*, which are indicated in Figure 1 above. Position I (II) is the position closer to (further from) the depot entrance and exit. For constructing the time-space network, the tracks and positions were nodalised to the different nodes shown in Figure 2. For example, the black cube "t1-2" indicates Position II of Track S1. Each track with a double-position configuration can accommodate two short EMUs simultaneously or one long EMU. Compared with the normal train platforming problem [21] or track allocation problem [22] where one track can only be parked on by one train, the parking sub-problem of depots is thus more difficult than at stations. Since the cleaning track and transit track are mainly occupied by moving trains, there are no double positions on these tracks. The cleaning tracks and the transit tracks are considered as track nodes (red cubes in Figure 2). Moreover, in and out nodes are set for train arrival and departure (orange cubes in Figure 2). Finally, integrated track nodes (blue cubes in Figure 2) are

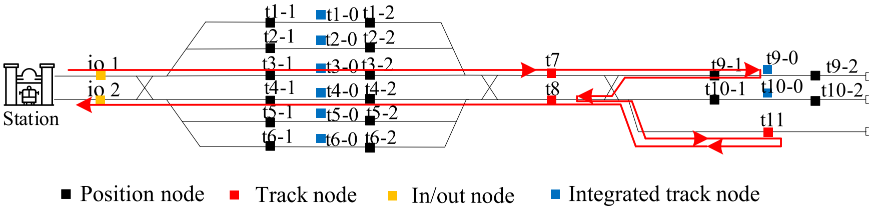
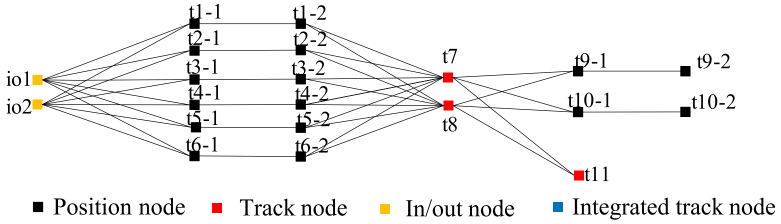
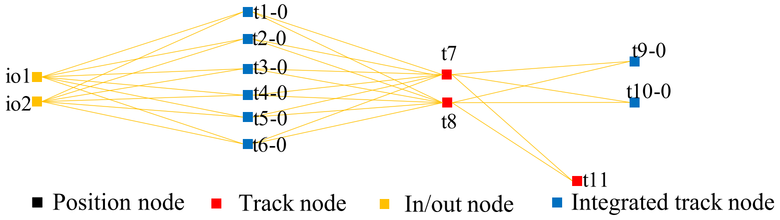


FIGURE 2. The layout of the depot after nodeization.



(a): physical network for short EMUs



(b):physical network for long EMUs

FIGURE 3. The physical network for short and long EMUs.

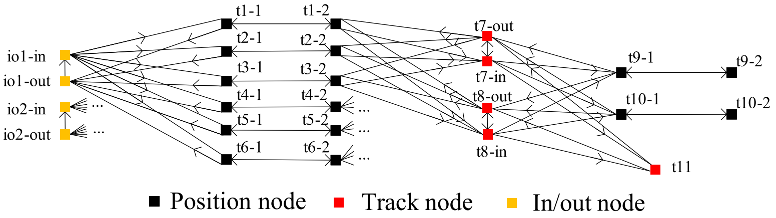
added to represent the whole track with double positions where long EMUs will park. All cubes marked in Figure 2 form the physical nodes of the EMU depot. The route shown by the red arrow in Figure 2 is an example of the EMU shunting process between the various service tracks at the depot. The EMU enters the depot from io1, and then accepts cleaning, repair, wheel turning, storage, and finally leaves the depot from io2.

After connecting nodes with directional or bidirectional arcs, the physical network without integrated track nodes in Figure 3(a) for short EMUs and the physical network without position nodes in Figure 3(b) for long EMUs are obtained.

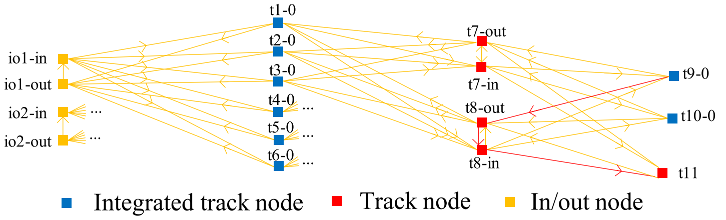
When an EMU is going to be shunted to another parallel track, such as from the repair track R1 to the wheel turning track WT1 in Figure 1, it has to change its direction at transit track L1. The reversal of direction is called a saw-move [9]. The saw-moves are also time-consuming and should only be performed if necessary. For the tracks where saw-moves are allowed (e.g., cleaning nodes, in/out nodes and nodes of transit tracks), node i is replaced by two dummy *saw-move nodes*, respectively, i-in and i-out, allowing us to distinguish the direction of movement. The modified physical network of each EMU can be modified based on the original physical network and is shown in Figure 4. For instance, the complete route of a saw-move of a long EMU from the repair tracks R1 (node t9-0) to the wheel turning track WT1 (node t11) is t9-0 →t8-out →t8-in →t11, as shown in red arrows in Figure 4.

The train shunting process is closely related to service scheduling. Like the Open Shop scheduling problem [2], the service sequence is not fixed for one EMU and should be decided depending on the states of other EMUs. This paper considers the flexible sequence scheduling of multiple sequences. When the number of services increases, the number of all possible operation processes will increase exponentially, and the uncertainty and complexity of the problem will be greatly increased. In addition, compared with the services, the unnecessary storage operation will increase the drivers' work, and add pressure on the bottlenecks of the depot and affect the capacity utilization. Therefore, in the process of daily service scheduling at the depot, it is necessary to reduce unnecessary storage and the corresponding shunting operations, which will be considered by adding the cost into operation time-space arcs. Moreover, extra dwelling on the current track after completing service is usually not allowed on cleaning tracks and wheel turning tracks, however, allowed on repair tracks and some tracks of other types, e.g., sewage suction tracks. This means that the total time at the repair track may be longer than the standard service time, which adds more complexity to the SSS problem.

The direction of arcs can be modified according to the type of tracks, i.e., first-in-first-out tracks (FIFO), last-in-first-out tracks (LIFO) and free tracks (both sides can be the entrances and exits). As can be seen in Figure 1, the tracks are of different type. The storage tracks and cleaning



(a): physical network for short EMUs



(b):physical network for long EMUs

FIGURE 4. **The modified physical network with saw-move nodes for short and long EMUs.**

tracks are free-type. The repair tracks and wheel turning tracks are LIFO. Considering the capacity and function of the track, the shunting movement should let the train be correctly serviced and not cause track/position conflicts or switch conflicts. On the one hand, track/position conflicts happen when the route of EMU is blocked on the track or position occupied by other EMUs. For example, on the repair track in Figure 1, the route of short EMU on t9-2 will be blocked by the other short EMU on t9-1. On the other hand, switch conflicts happen when two routes share the same switch segment, which should be solved on the microscopic level [1], [10]. Inspired by Zhang et al. [23], the route conflict on the microscopic level on the switch areas is considered by pre-processing before solving. That is, the conflict relationship between routes is pre-calculated after constructing the time-space network (which is discussed in Section III-A2) and considered as input for the solution process.

A route needs to be carried out by a shunting operation. After a shunting is finished, the driver needs to walk to the next shunting task location. There is a limited number of shunting drivers at the depot, although the number is assumed to be sufficient in this study. Frequent shunting leads to an elevated workload for the driver and increases the risk of conflicts at bottlenecks. The method presented in Xu and Dessouky [1] does not allow to minimize or limit the number of shunting operations (i.e. shunt from track A to track B), because one time-space arc in Xu and Dessouky [1] refers to shunting from one track to one switch node or from one switch node to another switch node. Our method considers the fixed penalty cost of a shunting operation and aims to reduce the number of shunting operations.

B. THE SSS RESCHEDULING WITH DISTURBANCES ON THE OPERATIONAL LEVEL

Typical disturbances to EMU depot operations can be classified into two categories. The first category pertains to disturbances influenced by the station timetable, involving changes in the arrival and departure times of EMUs when they enter or exit the depot. The scheduling planners of the depot are warned of these disturbances in advance.

The second category is the overtime service. Typically, at the very moment severe malfunctions are detected, the scheduling planners of depot are informed of the extended repair duration.

When a disturbance occurs at a certain moment, the following points need to be noted:

1) In order to keep the plans of as many EMUs as possible unchanged, the plans of the EMU in which the disturbance occurs and the EMUs that may be affected need to be rescheduled. While the plans of the other EMUs remain unchanged. EMUs also need to be kept on the original track as much as possible when rescheduling.
2) At the time the disturbance information is available, the plans prior to the start moment of the disturbance have already been executed, and the plan that is in progress needs to be continued and completed. For example, Figure 5 shows the Gantt chart of track occupancy for repair track R2 with a disturbance. EMU-1 and EMU-8 are short EMUs, where EMU-1 occupies Position I and EMU-8 occupies Position II. EMU-3 is a long EMU. EMU-1 should originally leave the current track at the moment 150, but at the moment 100, a severe malfunction is detected. It will only leave at the moment 200. The repair track R2 is a LIFO track. EMU-8 must wait for EMU-1 to leave R2 before it can leave. Therefore, both EMU-8 and EMU-3 are affected by EMU-1 and need rescheduling. The ongoing repair services of EMU-1 and EMU-8 need to be completed and then rescheduling starts.
3) The order of rescheduling is of great importance. A common rule referred as **Rule I** for specifying the order of rescheduling for tracks with disturbance is

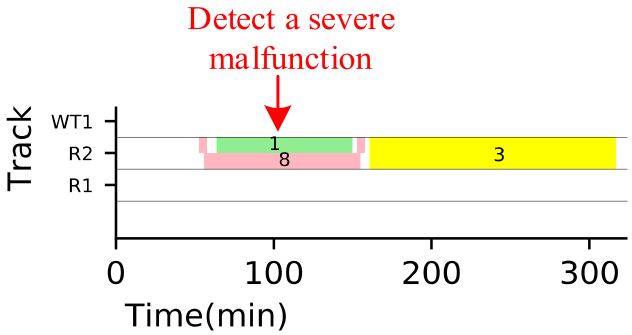


FIGURE 5. The Gantt chart of track occupancy for repair track R2 with a disturbance.

used in reality by dispatchers and also adopted in this paper:

Rule I: The EMU that is directly disturbed are the first in order, and then the other EMUs that are indirectly disturbed at the same track are rescheduled in the order of their occupancy of the track.

For the example in Figure 5, the order of rescheduling is EMU-1, EMU-8, EMU-3. If EMU-3 is rescheduled first and then kept unchanged, EMU-1 and EMU-8 can not undergo overtime service or overtime stay. It should be noted that the EMUs parked on track R2 after EMU-3 are not classified into the indirectly disturbed EMUs, because they are not definitely disturbed if EMU-3 changed the repair track R2 to other tracks when rescheduling.

III. SOLUTION METHOD

A. TIME-SPACE NETWORK FORMULATION

The time-space network or time-space-state network approach has been widely used in recent years for the optimization of the vehicle routing problem [24], [25] and railway scheduling problems [23], [26]. In this section, time is discretized for each physical node and a two-layer integrated directed acyclic time-space network $G = (V, A)$ is constructed based on the state of the EMUs at the depot. Section III-A1 first explains how to construct the time-space network, and Section III-A2 illustrates how to map the space-time networks of different EMUs to the same physical resource, avoiding resource conflicts as well as route blockages. The objective function is presented in Section III-A3.

1) TIME-SPACE NETWORK

Inspired by Caprara et al. [27], each node i that can take services and dwelling is transformed into nodes i^1 and i^2 with two different states, namely shunting state and dwelling state. When parking is not allowed at node i, such as dummy start and end nodes, in/out nodes, and nodes of transit tracks, node i has only node i^1 of the shunting state. Let N^1 be the set of shunting nodes, $i^1 \in N^1$, let N^2 be the set of dwelling nodes, $i^2 \in N^2$ and let $N = N^1 \cup N^2$ be the set of all nodes that represent the "space" dimension of the time-space network. When $\overline{o}$ denotes the dummy origin vertex, and $\overline{d}$ denotes the dummy destination vertex, all vertices in the time-space network can be expressed as $V = \left\{\overline{o}, \overline{d}\right\} \cup \{(i^w, t) \mid i^w \in N, t = 0, 1, \ldots, T, w = 1, 2\}$, with u, v as the indices. After the temporal discretization, define the time instant set T, $T = \{0, 1, \ldots, |T|\}$. The vertex set V represents the set of time-space vertices (n, t), including the space dimension $n \in N$ and the time dimension $t \in T$. Let the space-time arc $(n, t) \rightarrow (m, \tau)$ $(u \rightarrow v$ for short) denote the link of vertex (n, t) to vertex (m, τ). Different from Xu and Dessouky [1] who used a two-layer network to distinguish the two directions of train movements at the depot, the shunting layer in this paper has both directions of movements using the arcs of bidirectional physical links. After assigning a cost to the space-time arc $u \rightarrow v$, the SSS problem is then transformed into a multi-commodity network flow problem. The process of EMU's movements at the depot can be viewed as a network flow path and the scheduling plan can be achieved by calculating the minimum cost flow.

A summary of the notation used is given in Table 2.

In the two-layer time-space network of EMU e, there are the following types of arcs:

a: STARTING ARC

For any $i^1 \in N^{\mathrm{in}} \cap N^e$, there are one or more starting arcs $a = \overline{o} \rightarrow (i^1, a_e)$ for an EMU to enter the network, $c_{ea} = 0$.

b: ENDING ARC

For any $i^1 \in N^{\mathrm{out}} \cap N^e$, there are one or more ending arcs $a = (i^1, d_e) \rightarrow \overline{d}$ for an EMU to depart from the network, $c_{ea} = 0$.

c: SHUNTING ARC

For any $i^1, j^1 \in N^1 \cap N^e$, if there exists physical directional links between node i^1 and node j^1, there are shunting arcs $a = (i^1, t) \rightarrow (j^1, t'), t' = t + t_{ij}, t \geq a_e, t' \leq d_e, c_{ea} = c_{ea}^{\mathrm{shu}} t_{ij}$. Traversing the shunting arc means to pass through a physical link.

d: SERVICE ARC

For any $i^1 \in N^1 \cap N^e \backslash N^{\mathrm{sto}}$, $i^2 \in N^2 \cap N^e \backslash N^{\mathrm{sto}}$, there are service arcs $a = (i^1, t) \rightarrow (i^2, t')$, $t' = t + t_{ep}^{\mathrm{ser}}$, $t \geq a_e$, $t' \leq d_e$, $c_{ea} = c_{ep}^{\mathrm{ser}} * t_{ep}^{\mathrm{ser}} + c^{\mathrm{fix}}$. Traversing the service arc means to finish a service. c^{fix} denotes the fixed penalty cost parameter of a shunting operation. One shunting operation requires a dedicated driver to operate in practice. Saving the shunting operation helps to avoid too much driver work and relieve the pressure on bottlenecks at the depot. One shunting operation may contain multiple shunting arcs, and thus the fixed penalty cost cannot be divided and added into the cost of a single shunting arc. Therefore, the fixed penalty cost of shunting operation before service is calculated into the cost of service arcs.

e: STORAGE ARC

For any $i^1 \in N^1 \cap N^e \cap N^{\mathrm{sto}}$, $i^2 \in N^2 \cap N^e \cap N^{\mathrm{sto}}$, there are storage arcs $a = (i^1, t) \rightarrow (i^2, t)$, $a_e < t < d_e, c_{ea} =$

TABLE 2. Definition of notations.

Set	
E	Set of EMUs, e as the index
N	Set of nodes, n, m, i^1, i^2 as the indices
N^1	Set of shunting nodes, $i^1 \in N^1$
N^2	Set of dwelling nodes, $i^2 \in N^2$
N^{sto}	Set of nodes for storage
N^{pos}	Set of position nodes
$N^{\text{int-tra}}$	Set of integrated track nodes
N^{in}	Set of entrance nodes
N^{out}	Set of exit nodes
N^e	Set of nodes of EMU e. For short EMU e, $N^e = N \backslash N^{\text{int-tra}}$, and for long EMU e, $N^e = N \backslash N^{\text{pos}}$, according to Figure 3.
T	Set of time instant, t as the index
B	Set of switches of the depot, including the dummy switches, b as the index
P	Set of service type, p as the index
P^e	Set of service type of EMU e, p as the index
V	Set of time-space vertices, u, v as the indices
A	Set of time-space arcs, $u \rightarrow v$ or a as the index
A^e	Set of arcs in the time-space network of EMU e
A^1_{nt}	Incompatible arc set for vertex (n, t), $n \in N^2 \backslash N^{\text{int-tra}}$
A^2_{nt}	Incompatible arc set for vertex (n, t), $n \in N^1 \backslash N^{\text{int-tra}}$
A_{bt}	Incompatible arc set for critical switch b at time instant t, $b \in B$
Ψ_n	Incompatible node set for node n
$\bar{o}$	Dummy origin vertex
$\bar{d}$	Dummy sink vertex
Parameter	
a_e	Arrival time of EMU e
d_e	Departure time of EMU e
t_{ij}	The time traversing through the physical arc $i \rightarrow j$
t_h	The safety headway time
c_{ea}	Cost of arc a for EMU e
c^{shu}_{ea}	Cost per unit time of shunting arc a for EMU e
c^{ser}_{ep}	Cost per unit time of service arcs of service type p for EMU e
c^{dwe}_{ep}	Cost per unit time of dwelling arcs of service type p for EMU e
c^{dwesto}_{e}	Cost per unit time of dwelling arcs of storage for EMU e
c^{fix}	Fixed cost per shunting operation
t^{ser}_{ep}	Standard time of service type p for EMU e
p_n	Service type of node n
Decision Variable	
$x^e_{u,v}$	=1 if arc $u \rightarrow v$ is traversed by EMU e, =0 otherwise.

c^{fix}. Traversing the storage arc means to enter a storage track and start storage. The fixed penalty cost of shunting before storage is calculated into the cost of storage arcs.

f: DWELLING ARC

For any $i^2 \in N^2 \cap N^e$ and i^2 is allowed for dwelling, there are dwelling arcs $a = (i^2, t) \rightarrow (i^2, t+1)$, $a_e < t < d_e - 1$. If $i^2 \notin N^{\text{sto}}$, $c_{ea} = c^{\text{dwe}}_{ep}, p = p_{i^2}$; if $i^2 \in N^{\text{sto}}$, $c_{ea} = c^{\text{dwesto}}_e$. Traversing the dwelling arc means to park at the current location after finishing the service for service tracks and to park at the storage track. Note that the cleaning nodes and wheel turning nodes are not allowed for dwelling and do not belong to any dwell arc.

g: STATE TRANSFER ARC

For any $i^2 \in N^2 \cap N^e$, $i^1 \in N^1 \cap N^e$, there are state transfer arcs $a = (i^2, t) \rightarrow (i^1, t)$, $a_e < t < d_e, c_{ea} = 0$. Traversing the state transfer arc means to finish parking and start shunting. Note that the shunting fixed penalty cost can alternatively be added into the cost of state transfer arcs instead of service arcs.

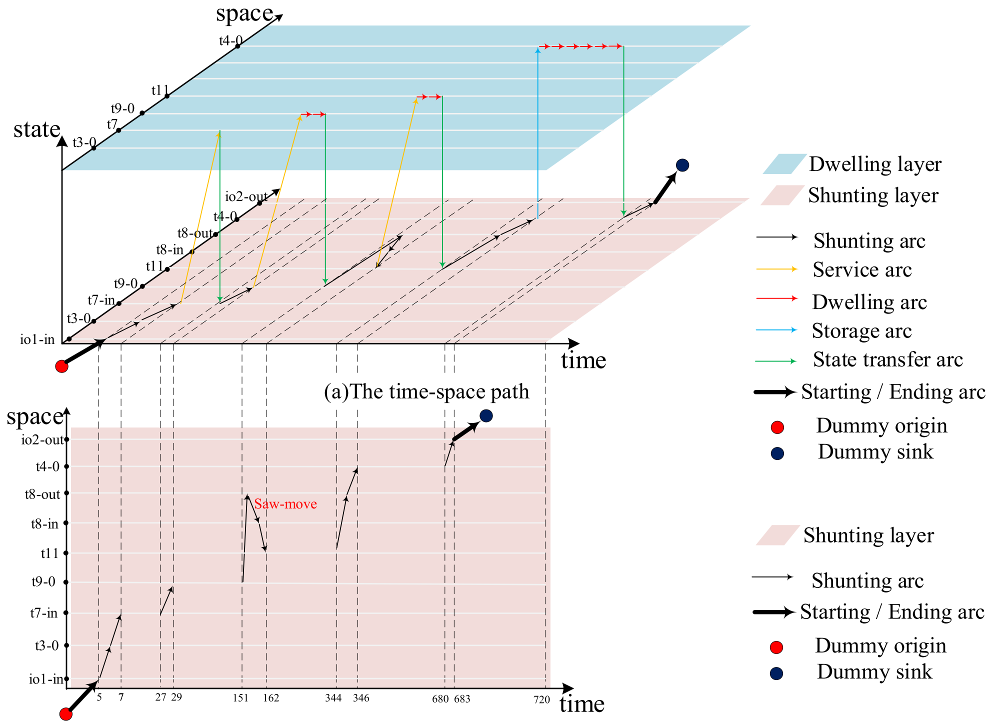
h: DUMMY ARC

For any $i^1 \in N^{\text{in}} \cap N^e, j^1 \in N^{\text{out}} \cap N^e$, there are dummy arcs $a = (i^1, a_e) \rightarrow (j^1, d_e)$. A train traversing the dummy arc means the service task of this train cannot be performed due to the capacity of the depot. The cost of cancelling services for one EMU is high, so let $c_{ea} = c_e^{\text{dwesto}} * (d_e - a_e) + \sum_{p \in P^e} (c^{\text{ser}}_{ep} * t^{\text{ser}}_{ep} + c^{\text{fix}})$.

The arcs set A^e in the time-space network of EMU e are the concatenation of (1)(2)(3)(4)(5)(6)(7) and (8) above.

With the time-space network, the movement process of each EMU can be described by the time-space path within its network. Take the whole moving process of a long EMU shown in red arrows in Figure 2 as an example. Figure 6 (a) is the time-space path and Figure 6 (b) shows the projection of the time-space path on the shunting layer. The EMU undergoes a cleaning and repair service and then proceeds to the WT1 for wheel turning through saw-move shunting, finally parks at S4 and waits to depart from the depot.

Under the assumption that EMUs cannot enter service tracks without undergoing services, when using a single-layer space-time network, EMUs might occupy service tracks for additional short-term shunting. If the two-layer time-space network is merged into one-layer network, although the complexity of the network can be reduced, there is no guarantee that the EMU will be shunted first, and then perform service or storage, and finally allow extra dwelling. The order of traversing arcs is disrupted. To address this, the dwelling arc is assigned after the service/storage arc, ensuring that service/storage always precedes dwelling. The service arc and the storage arc serve as a bridge between the two-layer networks. Before performing the dwelling arc, the EMU must go through the shunting arc → service arc/storage arc to reach the dwelling layer, ensuring the order in which the EMUs move. This is also the essence of the time-space network, which is to embed complex constraints into the construction of the network. Once the network is successfully constructed, there is no need to add additional constraints on the sequence constraints related to the movement of EMUs. It should be noted that the starting and ending times of the service arc do not imply the actual start and end times of the service. In fact, the starting time of the service arc is the moment of entering the track, and the ending time of the last dwelling



(a)The time-space path

(b)The projection of time-space path on the shunting layer.

FIGURE 6. **The whole time-space path of a long EMU at the depot.**

arc is the moment of leaving the track. Service workers can start the service at an appropriate moment after the train enters the track. Moreover, the number of shunting can be regarded as the number of times it is moved from the shunting layer to the dwelling layer. The fixed cost of each shunting is added to the cost of the service arc/storage arc. If merging to a one-layer network, the fixed cost of each shunting is not suitable to be added to the cost of any arc.

Compared with the two-layer network in Xu and Dessouky [1], our network has some advantages, referred to as "Contribution (2)" in Section I. First, as they assumed, there is no possibility of arranging storage operation(s) between train repair and cleaning in their customized network and model. In our network, the storage is allowed between two consecutive services. For example, when the EMU has finished repair and is ready to undertake cleaning, if the cleaning resources are not available, then it can only wait on the repair track. But the repair track is a relatively important equipment, unnecessary occupancy causes a large waste of resources. The actual practice is that after the EMU is cleaned, the EMU will be driven to the storage track and wait until the repair resources are available. Moreover, our time-space network will allow EMU to have different service tasks instead of being limited to two service tasks (daily repair and cleaning), and our time-space network allows track relocation, which makes it easier to get a feasible plan [2].

2) INCOMPATIBLE ARC SET FOR NODES AND SWITCHES

An arc pair is considered incompatible if both physical arcs share the same micro-segment, also known as track circuits, when the headway time is not satisfied. The microscopic track circuits are implicitly incorporated into the physical arc (i, j). To restrict resource usage, incompatible time-space arc sets are established for nodes and switches, referred to as "Contribution (1)" in Section I. The first step is to define the incompatible node set for nodes and switches, see the Appendix. Then, taking into account the headway and the mapping relationship between position nodes and integrated track nodes, the incompatible time-space arc set for vertices and critical switches is defined in the Appendix. To prepare the data, as done by Caprara et al. [21] and Zhang et al. [23] the priori incompatible time-space arc sets must be enumerated before solving.

3) OBJECTIVE FUNCTION

Once the two-layer space-time networks for each EMU are constructed, the original problem is transformed into a minimum-cost multi-commodity network flow problem. The objective function (1) is to minimize the total operating cost. As mentioned before, the total operating cost includes service cost of service arcs, the parking cost of dwelling at storage tracks and service tracks, the route cost of shunting arcs, the penalty cost for shunting and the penalty cost for cancelling EMUs.

$$\text{Min} \sum\nolimits_{e\in E} \sum\nolimits_{u\to v\in A^e} c^e_{u\to v} x^e_{u\to v} \tag{1}$$

After disturbances, for ensuring that the tracks in the original SSS plan being used as much as possible, the cost of the service arcs should be adjusted to attract EMU parking at the tracks in the original plan when rescheduling. Here,

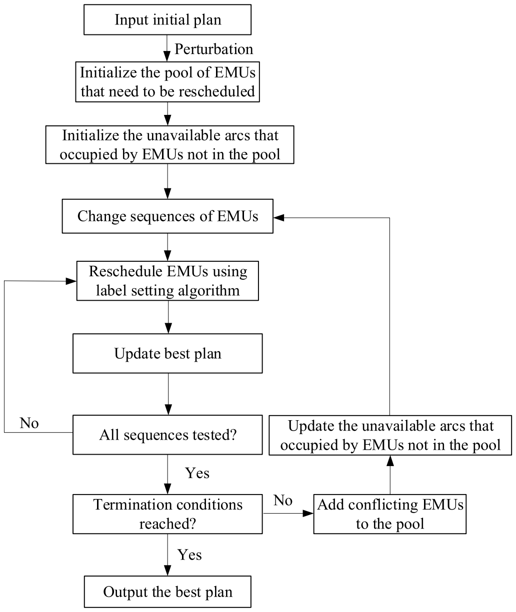


FIGURE 7. The framework of the whole approach.

if the track h is occupied in the original plan, the service arcs $u \to v$ belong to the track h, then, the cost of the service arcs $c^e_{u\to v}$ is adjusted to 0.8 times its previous cost, which will be discussed in Section IV-C.

B. SOLUTION PROCEDURE

The framework of the whole approach is shown in Figure 7. After inputting the original plan and disturbance(s) information, the pool of EMUs that need to be rescheduled is initialized. The initial pool includes all EMUs with delayed arrival and departure times, and EMUs with overtime services. Some EMUs that are definitely affected by the EMU with overtime services are also added to the pool. The sequences of the EMUs in the pool are varied to perform a local search of the rescheduling of the EMUs in the pool. Then, each sequence that obeys **Rule I** is tried. The plan of EMUs in the pool is solved using a sequential approach according to the sequence. Each solution can be regarded as a Shunt-in/Shunt -out simulation [28]. The time-space arcs in the incompatible arc set of the time-space nodes and critical switches occupied by the EMUs not in the pool and preceding rescheduled EMUs are not available for the following EMUs, which are determined according to the Appendix. The plan for each EMU can be rescheduled using the time-dependent label setting algorithm in Section III-C.

The termination conditions are reaching the maximum computational time limit or getting a feasible solution after testing all generated sequences of one pool. After all sequences of one pool are tested, if the termination conditions are not reached, one EMU that shares the same tracks with the EMUs in the pool is selected and then added to the pool and all possible sequences that obey **Rule I** of the new pool should be tested again. If the termination conditions are reached, output the best plan.

A limitation of this framework is that, particularly during high-pressure situations of the depot, the proposed framework may necessitate multiple iterations and consume additional time to attain a feasible solution. In the worst-case scenario, there is a possibility of some EMUs being cancelled, resulting in an unfeasible solution. In such scenario, manual intervention by a dispatcher becomes necessary for successful rescheduling, such as substituting machine cleaning on clean tracks for cancelled EMUs with manual cleaning on other tracks.

C. MODIFIED LABEL SETTING ALGORITHM

The classical label setting algorithm is a kind of forward dynamic programming algorithm to solve the shortest path problem of an acyclic network without negative cost. For each EMU e, a modified label setting algorithm is applied to find the shortest path in the time-space network of EMU e. Each time instant t is a stage for dynamic programming. In order to limit each service to be performed only once, information about the number of performed services needs to be introduced as part of the label, which modifies the classical label setting algorithm. Each vertex has multiple labels [29], [30]. The information stored in each label is: the vector of completed times of each service $\Pi^{\text{ope}} = \left[\pi^1, \pi^2, \ldots \pi^{|P_e|}\right]$, $\pi^p = \{0, 1, 2\}$ and the label cost c. P_e is the set of service tasks of EMU e. When searching the shortest path for EMU e, let $\Pi^{\text{ope}} = [0, 0, \ldots 0]$. If EMU e has traversed the service arc belonging to one of EMU e's service tasks, let the corresponding $\pi^p = \pi^p + 1$. When $\pi^p = 2$, the label is disqualified from continued exploration. Π^{ope} is also used to allow flexible service sequences. For a vertex with labels with different Π^{ope}, it is meaningless to judge the two labels of a vertex with different Π^{ope}. When valuing a new candidate label $L^{\text{new}} = [\Pi^{\text{ope-new}}, c^{\text{new}}]$ for vertex v, find the current label $L^{\text{current}} = [\Pi^{\text{ope}}, c^{\text{current}}]$ with $\Pi^{\text{ope-new}} = \Pi^{\text{ope}}$ from one of the current labels of vertex v. If $c^{\text{current}} > c^{\text{new}}$, let L^{new} replace L^{current}; if such a L^{current} does not exist, let L^{new} be one of the current labels of vertex v. For each label of dummy sink vertex $\overline{d}$ at time instant d_e, the label with $\Pi^{\text{ope}} = [1, 1 \ldots, 1]$ is the final label. Backtracking the final label, the shortest path can be obtained.

For the EMU e with arrival or departure delay, the updated arrival or departure time should be used. Its time-space path starts from the starting arc $\overline{o} \to (i^1, \overline{a_e})$, and ends from the ending arc $(i^1, \overline{d_e}) \to \overline{d}$, where $\overline{a_e}$ and $\overline{d_e}$ are the updated arrival and departure times.

For the EMU e with overtime service, after traversing the service arc with a disturbance, it should then traverse the dwell arc of the specified time until reaching the service disturbance end time. Then, time-space shortest path searching for rescheduling is performed. That is, the rescheduling starts from the state transfer arc $(i^2, \overline{a_e}) \to (i^1, \overline{a_e})$, $\overline{a_e}$ is the end time of the overtime service disturbance. A complete procedure of the modified label setting algorithm is shown in Algorithm 1.

Algorithm 1 Label Setting Algorithm

```
For each EMU $e$ do
    //Initialization
    Input initial vertex $(n, t)$
    For each time $t \in [\overline{a_e}, \overline{d_e}]$ do
        for each link $(n, m)$ do searching through the arc $a = (n, t) \rightarrow \left(m, t'\right)$, where $t' = t + t_{nm}$:
            Set $\Pi^{ope-new}(m, t') = \Pi^{ope-new}(n, t)$, then $\pi^p = \pi^p + 1$, if arc $a$ is a service arc.
            Set $c^{new}\left(m, t'\right) = c\,(n, t) + c_{ea}$.
            Create the new label $L^{new}$ with $\Pi^{ope-new}(m, t')$ and $c^{new}(m, t')$ of vertex $(m, t')$.
            If $\Pi^{ope-new}(m, t')$ with $\pi^p = 2$,
                The new label $L^{new}$ is disqualified.
            If the current label $L^{current}$ with $\Pi^{ope}\left(m, t'\right) = \Pi^{ope-new}\left(m, t'\right)$, and $c^{current} > c^{new}$.
                Replace the existing label with the new label $L^{new}$.
                Set the node precedence of $L^{new}$ of vertex $(m, t')$: $= n$.
                Set the time precedence of$L^{new}$ of vertex $(m, t')$: $= t$.
        End;
    End;
End;
Backtrace the time-space path for EMU $e$.
```

IV. CASE STUDY

In this section, an illustrative case and other computational experiments based on the Jinan Depot in China are carried out to test our two-stage approach. The heuristic algorithm was implemented in C# and tested on a laptop with an Intel i9-13900HX CPU and 40GB of memory. The datasets, including the input original plan and output rescheduled plan, algorithm codes in C#, and the Gantt chart visualization tool in Python for the case can be downloaded from https://data.mendeley.com/datasets/dscm8h6gdt/1.

The layout of Jinan Depot in China (36°39′59.4″N 116°52′46.3″E on Google Maps) is shown in Figure 8. There are 24 storage tracks (S1 ∼ S24), 2 cleaning tracks (C1, C2), 3 wheel turning tracks (WT1 ∼ WT3), 6 repair tracks (R1 ∼ R6) and 5 transit tracks (T1 ∼ T5). All storage tracks and repair tracks are with double positions. The repair tracks and track T3 are of LIFO type, and other tracks are free-type tracks. The time unit is set to 1 min. The length of the planning horizon is 840 time units (14 hours, i.e., from 18:00 to 08:00 the next day). The standard time of repair, cleaning and wheel turning for long EMUs (short EMUs) is 150, 20, 180 minutes respectively (80, 15, 120 minutes respectively). For the cost of the arcs, set $c_{ea}^{shu} = 10$, $c_{ep}^{ser} = 3$ for short EMUs and $c_{ep}^{ser} = 6$ for long EMUs, $c^{fix} = 100$, $c_{ep}^{dwe} = 3$ for short EMUs and $c_{ep}^{dwe} = 6$ for long EMUs, $c_e^{dwesto} = 2$ for short EMUs and $c_e^{dwesto} = 4$ for long EMUs. The safety headway time for tracks and switches are set to 2 min. The maximum computational time limit is set to 180 seconds [6], [7].

A. ILLUSTRATIVE CASE

During the planning horizon, 20 EMUs are scheduled: 12 EMUs with two services, 6 EMUs with 3 services, 2 EMUs only need to carry out night storage. For the EMU length, there are 4 long EMUs and 16 short EMUs. The Gantt chart of the original SSS plan is shown in Figure 9. A row in the Gantt chart represents a track. The length of the rectangle represents the occupation time of the track. The number in the rectangle is the index of the EMU. Long EMUs are represented by thick rectangles, and short EMUs are represented by thin rectangles. The green arrow indicates that the EMU has finished parking from the current track and left the depot. The upper half of the row means occupying Position I, and the lower half means occupying Position II.

TABLE 3. The information of the disturbances.

EMU	Disturbance type	Start time	End time
7	Overtime repair	150	230
17	Arrival delay	170	170

The planner at the depot is informed of two disturbances at time 150. The information of the disturbances is listed in Table 3. EMU-7 should extend the end time of repair service from time 199 to 230, which will affect the parking plan of EMU-6 and EMU-2 on track R2, as shown in the black ellipse in Figure 9. The arrival of EMU-17 is delayed from time 155 to 170, which will trigger a conflict with EMU-9 on cleaning track C1, as shown in the blue ellipse in Figure 9. The start time of the planning horizon of the rescheduling is the moment when the planner is informed of the disturbance information. Different disturbances may occur and end at different times. The start time of the disturbance of the overtime service is the time when the service worker reports the overtime service demand, and the end time is the expected end time of the overtime service. The start and end times of arrival delay (or departure delay) are equal to the updated arrival time (or delay time).

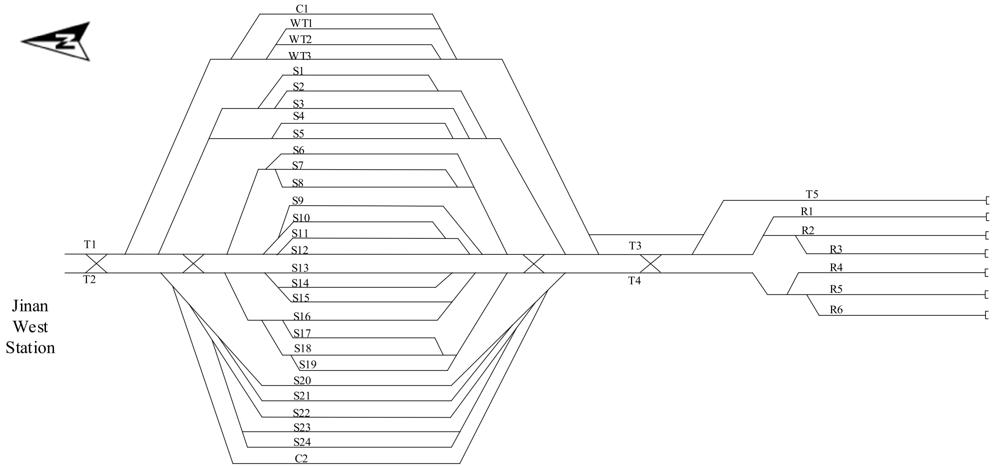


FIGURE 8. The layout of the Jinan depot in China.

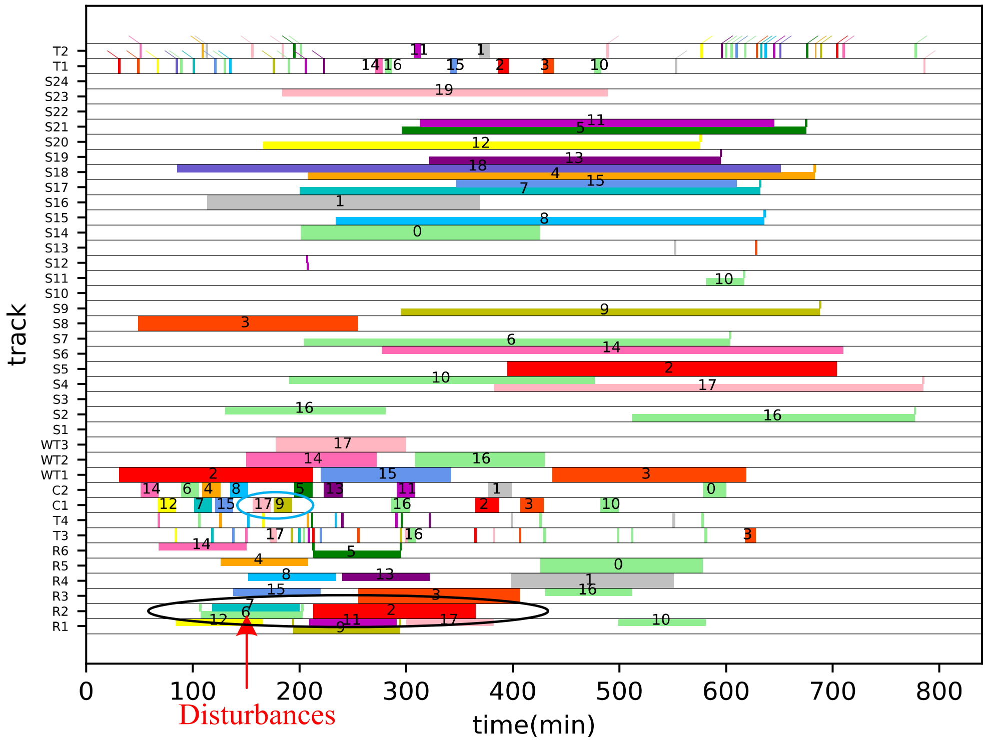


FIGURE 9. The Gantt chart of the original SSS plan.

The heuristic algorithm takes 80 seconds to get a feasible SSS plan after rescheduling. The Gantt chart of the SSS plan after rescheduling is shown in Figure 10. EMU-7, EMU-6, EMU-2 and EMU-17 are rescheduled. EMU-6 waits for EMU-7 to finish the overtime repair and leaves track R2. After finishing the wheel turning service of track WT1, EMU-2 was originally planned to stay on track R2, but due to the overtime service of EMU-7, it can only change the track to R5. In the new plan, the operation sequence of EMU-17 is adjusted to avoid conflict with EMU-9. EMU-17 carries out wheel turning first, then cleaning. Because the cost of service arcs are adjusted to take into account the original plan's tracks, only EMU-2's repair service changes tracks, while other services and storages do not change tracks, only slightly changing the time period for which the tracks are used. This makes the new SSS plan very close to the original SSS plan. As mentioned in Section III-A3, the adjustment parameter of the cost of service arcs is set to 0.8.

B. COMPUTATIONAL EXPERIMENTS

Considering the future passenger flow growth at the Jinan Depot, we further evaluated the algorithm's performance with increased numbers of EMUs and varying ratios of long and short EMUs. Table 4 summarizes the input statistics and

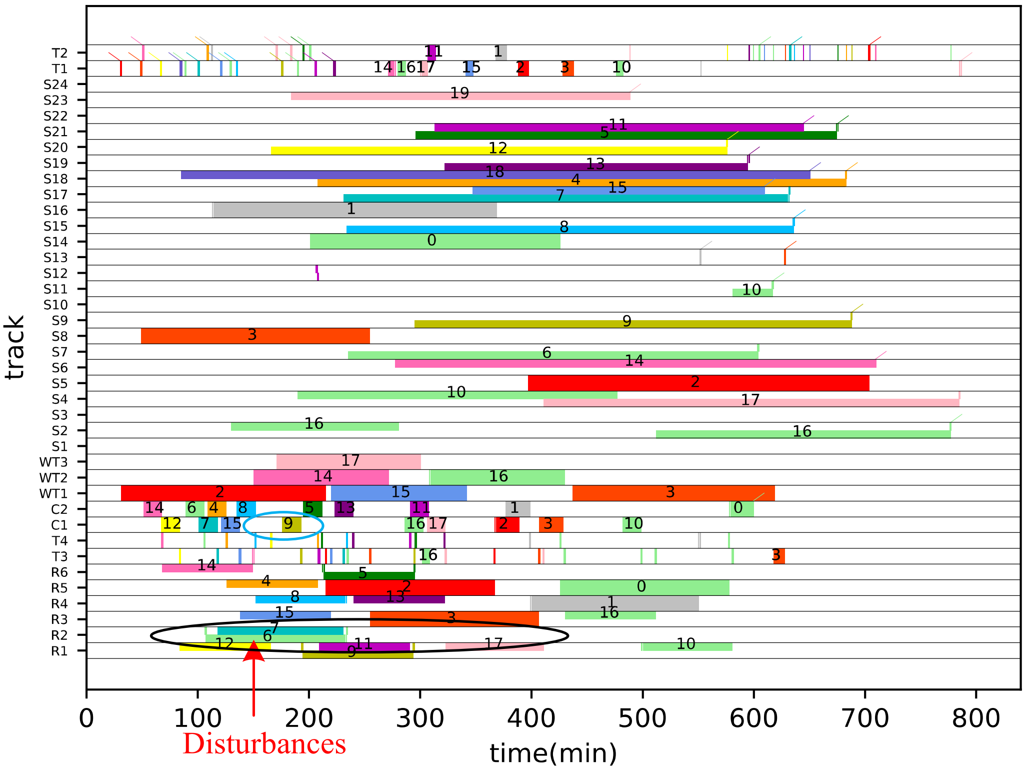


FIGURE 10. The Gantt chart of the SSS plan after rescheduling.

TABLE 4. Computational results of Jinan depot with various EMU scales.

Inst.	$\lvert E\rvert$	$\lvert E_p\rvert$		$\lvert E_{\mathrm{L}}\rvert$	$\lvert E_{\mathrm{S}}\rvert$	$\lvert E_{\mathrm{d}}\rvert$	$\lvert D\rvert$	Solution statistics		
		2	3					$\lvert E_{\mathrm{pool}}\rvert$	CT	Obj.
J-1	20	12	6	4	16	2	2	4	80	52168
J-2	20	12	6	8	12	2	2	4	56	55348
J-3	20	12	6	12	8	2	2	3	48	62756
J-4	30	18	8	6	24	3	3	6	157	78643
J-5	30	18	8	10	20	3	3	5	105	82435
J-6	30	18	8	14	16	3	3	4	85	87956

computational results of these instances. Instance J-1 is the illustrative case above. Instances J-2 ∼ J-6 are based on the real-world case with 20 and 30 EMUs, respectively. The "$\lvert E_p\rvert$" column with two sub-columns reports the number of EMUs with 2 services and 3 services respectively. The "$\lvert E_{\mathrm{L}}\rvert$" and "$\lvert E_{\mathrm{S}}\rvert$" columns report the number of long EMUs and short EMUs, respectively. The "$\lvert E_{\mathrm{d}}\rvert$" column reports the number of EMUs with disturbances, and the "$\lvert D\rvert$" column reports the number of types of disturbances. For the solution statistics, the "$\lvert E_{\mathrm{pool}}\rvert$" column denotes the number of EMUs in the final pool of EMUs that need to be rescheduled. The "CT" column specifies the computation time in CPU seconds. The "Obj." column represents the best objective value.

The result shows that with an increase in the number of EMUs with disturbances, the number of EMUs in the final pool also increases. When the numbers of EMUs with disturbances are the same, the instance with more long EMUs has a smaller number of EMUs in the final pool and a shorter

TABLE 5. Computational results of instance J-1 with various adjustment parameters for the cost of service arcs.

Inst.	μ	Solution statistics				
		$\lvert E_{\text{pool}} \rvert$	#Obj.	Num.Change_Track	CT	FEA
J-1-1	0.2	4	52168	1	92	50%
J-1-2	0.5	4	52168	1	85	75%
J-1-3	0.8	4	52168	1	80	100%
J-1-4	1.0	4	52152	5	71	100%

computational time. This is because long EMUs do not simultaneously occupy the track with other EMUs, and will have less impact on other EMUs. Moreover, the scale of time-space network of the long EMU is smaller. The computational experiments indicate that the heuristic algorithm can generate feasible rescheduling plans in less than 180 seconds, meeting the real-time application requirements. It is referred to as "Contribution (3)" in Section I.

C. SENSITIVITY ANALYSIS

In this section, a sensitivity analysis of the adjustment parameter μ for the cost of service arcs is performed. The case J-1 is selected for this analysis, with the original value of $\mu = 0.8$ being altered to 0.2, 0.5, and 1.0. The computational results of this analysis are presented in Table 5. Due to different values of μ, it becomes challenging to fairly compare the objective values. Therefore, the objective values are recalculated just for comparison based on the original costs without any adjustment. These recalculated objective values are then presented in the column labelled "#Obj.".

The "Num.Change_Track" column represents the number of track occupancy changes in the new plan compared to the original plan. The "FEA" column denotes the probability, in the local search, that the attempted sequences of the EMUs in the pool result in feasible solutions. In other words, it indicates the ratio of the number of sequences generating feasible solutions to the total number of attempts.

If set to 1.0, indicating no modifications in the original cost, all rescheduled EMUs change their storage tracks compared to the occupancies in the original plan. In total, 5 track changes occurred, significantly changing the original plan. Although the objective functions and the final plans are the same when $\mu = 0.2$, 0.5 and 0.8, there are some differences in the calculation process. As μ decreases, the "FEA" value decreases, leading to an increase in computation time. This is because, with a lower μ, EMUs tend to adhere more closely to the original plan, making it challenging to find feasible schedules. Considering the comprehensive sensitivity analysis, $\mu = 0.8$ appears to be an appropriate adjustment parameter.

V. CONCLUSION

In this paper, a heuristic method based on a two-layer time-space network was developed to solve the SSS rescheduling problem on the operational level. The resources occupied by EMUs without disturbances can be easily described using the time-space network and set to be unavailable when searching time-space shortest paths for other EMUs. The incompatible arc sets for nodes guarantee that there is no conflict on the tracks with double-position. The incompatible arc set for switches can avoid routing conflicts on the microscopic level. The real-world case studies demonstrated the effectiveness of the solution method. Computational experiments show that the computational time satisfies the time requirement of real-time scheduling. The new SSS plan is close to the original SSS plan by adjusting the cost of service arcs with an appropriate adjustment parameter based on the original SSS plan.

Considering that the SSS problem is a special case of the Open Shop Scheduling problem, the method proposed in this paper could be extended and implemented to some Open Shop Scheduling / Rescheduling problems.

Future research will focus on the following aspects. First, crew scheduling (drivers and maintenance workers) at the depot will be considered jointly with the SSS problem [3], [31]. Second, the robustness and resilience of shunting or routing plan is also meaningful to be considered to absorb small disturbances [3], [32].

APPENDIX

A. INCOMPATIBLE NODE SET

Ψ_{i^w} denotes the set of incompatible nodes of node i^w that establish the mapping relationship between the position nodes and the integrated track nodes of the same track.

If node i^w is a position node, Ψ_{i^w} contains node i^w as well as the integrated track node of the same track, but does not include another position node of the same track. For example, $\Psi_{t3-1^1} = \{t3-1^1, t3-1^2, t3-0^1, t3-0^2\}$ in Figure 2.

If node i^w is an integrated track node, Ψ_{i^w} contains node i^w as well as the two position nodes of the same track. For example, $\Psi_{t3-0^1} = \{t3-1^1, t3-1^2, t3-2^1, t3-2^2, t3-0^1, t3-0^2\}$ in Figure 2.

If node i^w is a track node and node i does not allow saw-move, Ψ_{i^w} contains node i^1 and node i^2 (if node i has the dwelling state). For example, $\Psi_{t11^1} = \{t11^1, t11^2\}$ in Figure 2.

If node i^w is a track node and node i allows saw-move, Ψ_{i^w} contains node i^2 (if node i has the dwelling state) and all saw-node of node i. For example, $\Psi_{t7-\text{in}^1} = \{t7-\text{in}^1, t7-\text{out}^1, t7^2\}$, $\Psi_{t8-\text{in}^1} = \left\{t8-\text{in}^1, t8-\text{out}^1\right\}$.

B. INCOMPATIBLE ARC SET FOR VERTICES

(1) headway constraint for the dwelling node $i^2 \in N^2 N^{\text{int-tra}}$ at the dwelling layer

If $i^2 \in (N^2 \backslash N^{\text{sto}}) \backslash N^{\text{int-tra}}$, at time instant t, the incompatible arc set of vertex (i^2, t) contains three sets of arcs, namely

① set of dwelling arcs
$\{(j^2, t) \rightarrow (j^2, t+1) \,|\, j^2 \in \Psi_{i^2}\}$,

② set of service arcs $\left\{\left(j^1, t_1\right) \rightarrow \left(j^2, t_2\right) \,|\, j^1, j^2 \in \Psi_{i^2}, t_1 - t^{\mathrm{h}}_{i^2} < t \leq t_2\right\}$,

③ set of departure and arrival shunting arcs
$\{(j^1, t) \rightarrow (q^1, t + t_{jq}), (q^1, t + t^{\mathrm{h}}_{i^2} + 1 - t_{qj}) \rightarrow (j^1, t + t^{\mathrm{h}}_{i^2} + 1) | j^1 \in \Psi_{i^2}, q^1 \in N^1\}$.

Considering the headway and the mapping relationship between position nodes and integrated track nodes, if $i^2 \notin N^{\mathrm{sto}}$, the incompatible arc set $A^1_{i^2 t}$ of service vertex (i^2, t) is defined as follows. For service vertex $\left(i^2, t\right)$, the total EMU flow passing through the arc in the incompatible arc set $A^1_{i^2 t}$ should be smaller than 1 to avoid conflict.

$$\begin{aligned}
A^1_{i^2 t} = &\left\{\left(j^2, t\right) \rightarrow \left(j^2, t+1\right) |\, j^2 \in \Psi_{i^2}\right\} \\
&\cup \left\{\left(j^1, t_1\right) \rightarrow \left(j^2, t_2\right) |\, j^1, j^2 \in \Psi_{i^2}, t_1 - t^{\mathrm{h}}_{i^2} < t \leq t_2\right\} \\
&\cup \{(j^1, t) \rightarrow (q^1, t + t_{jq}), (q^1, t + t^{\mathrm{h}}_{i^2} + 1 - t_{qj}) \\
&\rightarrow (j^1, t + t^{\mathrm{h}}_{i^2} + 1) | j^1 \in \Psi_{i^2}, q^1 \in N^1\}, \\
&\forall i^2 \in (N^2 N^{\mathrm{sto}}) \backslash N^{\mathrm{int-tra}}, t = 0, 1, \ldots, T - t^{\mathrm{h}}_{i^2} + 1
\end{aligned}$$

If $i^2 \in (N^2 \cap N^{\mathrm{sto}}) \backslash N^{\mathrm{int-tra}}$, no service will happen on the physical storage node i. The incompatible arc set of storage vertex (i^2, t) is defined as follows and contains three sets of arcs, namely

$$\begin{aligned}
A^1_{i^2 t} = &\left\{\left(j^2, t\right) \rightarrow \left(j^2, t+1\right) |\, j^2 \in \Psi_{i^2}\right\} \\
&\cup \left\{\left(j^1, t+1\right) \rightarrow \left(j^2, t+1\right) |\, j^1, j^2 \in \Psi_{i^2}\right\} \\
&\cup \left\{\left(j^1, t\right) \rightarrow \left(q^1, t + t_{jq}\right) |\, j^1 \in \Psi_{i^2}, q^1 \in N^1\right\} \\
&\cup \left\{\left(q^1, t + t^{\mathrm{h}}_{i^2} + 1 - t_{qj}\right) \rightarrow \left(j^1, t + t^{\mathrm{h}}_{i^2} + 1\right) |\, j^1 \in \Psi_{i^2}, \right. \\
&\left. q^1 \in N^1\right\}, \forall i^2 \in (N^2 \cap N^{\mathrm{sto}}) \backslash N^{\mathrm{int-tra}}, \\
&t = 0, 1, \ldots, T - t^{\mathrm{h}}_{i^2} + 1.
\end{aligned}$$

Since $\Psi_{i^2 : i^2 \in N^2 \backslash N^{\mathrm{int-tra}}}$ contains the integrated track nodes, the incompatible set of integrated track nodes is not necessary to be indicated.

(2) headway constraint for the shunting node and saw-move node $N^1 \backslash N^{\mathrm{int-tra}}$ at the shunting layer

If $i \in N^1 \backslash N^{\mathrm{int-tra}}, t = 0, 1, \ldots, T - t^{\mathrm{h}}_{i^1} + 1$, the incompatible arc set $A^2_{i^1 t}$ of vertex (i^1, t) contains sets of departure and arrival shunting arcs, which is defined as follows.

$$\begin{aligned}
&A^2_{i^1 t} \\
&= \left\{\left(j^1, t_1\right) \rightarrow \left(q^1, t_2\right) |\, j^1 \in \Psi_{i^1}, q^1 \in N^1, t_1 \leq t \leq t_2\right\} \\
&\quad \cup \left\{\left(q^1, t_1\right) \rightarrow \left(j^1, t_2\right) |\, j^1 \in \Psi_{i^1}, q^1 \in N^1, t_1 - t^{\mathrm{h}}_{i^1} < t < t_2\right\} \\
&\quad \forall i \in N^1 N^{\mathrm{int-tra}}, t = 0, 1, \ldots, T - t^{\mathrm{h}}_{i^1} + 1.
\end{aligned}$$

Similarly, for shunting vertex $\left(i^1 t\right)$, the total EMU flow passing through the arc in the incompatible arc set $A^2_{i^1 t}$ should be smaller than 1 to avoid conflict on the shunting layer.

C. INCOMPATIBLE ARC SET FOR CRITICAL SWITCHES

Each physical arc is associated with a set of switches it passes through. Critical switches are defined as the common switches with the maximum number of shunting arcs. The method for determining whether a switch is a critical switch is as follows: given a switch b_1, the physical arcs containing switch b_1 are filtered, and if there are no other common switches among the switch sets of these filtered physical arcs, switch b_1 is considered a critical switch, which means switch b_1 can be regarded as the representative of all the switches that these filtered physical arcs contain. If there exists another common switch b_2, then switch b_1 is not considered a critical switch if the number of physical arcs containing switch b_2 is greater than the number of physical arcs containing switch b_1.

For each critical switch $b \in B$, the incompatible arc set $A_{b,t}$ is defined as follows: $A_{b,t} = \left\{\left(i^1, j^1, t_1, t_2\right) | b \in PA_{(i,j)}, t_1 - t^{\mathrm{h}}_b < t \leq t_2, \right\}$, where $b \in PA_{(i,j)}$ indicates that the physical arc (i, j) contains switch b. To restrict occupancy at bottlenecks, the number of EMUs passing through the arcs in the incompatible arc set $A_{b,t}$ cannot exceed 1 for each $b \in B$. Parallel routes without common switches at a bottleneck area are allowed to be executed simultaneously, since the parallel route pair does not belong to the single incompatible arc set $A_{b,t}$ of each critical switch b.

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