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Research Article

Optimization of the Shunting Operation Plan at Electric Multiple Units Depots

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The number of standard electric multiple units (EMUs) in China has increased from 1003 in 2013 to 3256 in 2018. For maintaining all EMUs in time, the high-speed rail system with the fast-developing number of EMUs is facing growing pressure. The maintenance and cleaning capacity of an EMU depot can be improved by a better shunting operation planning (SOP). This paper considers an SOP problem at EMU depots, which may have two types of yards, namely, stub-end and through. Every track at an EMU depot has two sections and can accommodate two short standard EMUs of 8 railcars or one long EMU of 16 railcars. As the SOP is currently handled manually by dispatchers, this paper proposes two integer linear programming models for two types of yards for daily planning and dispatching, which aim at minimizing the total delay time of all EMUs during the planning horizon. A Reduced Variable Neighborhood Search (RVNS) algorithm is designed to improve the solution efficiency. The results of the numerical experiment show that the RVNS algorithm can yield an optimal maintenance plan in a few seconds for depots of different layout types and can be applied to a computer-aided planning system. The track utilization rate of the maintenance yard with the stub-end type is higher than that of the through type. The stub-end type may be more suitable for the current schedule, as its total track utilization rate is much lower than the through type.

1. Introduction

An electric multiple units (EMU) is a passenger train consisting of multiple-unit railcars powered by electricity. By the end of 2018, China Railway had owned a total of 3,256 standard EMUs of 8 railcars, providing more than 2500 couples of passenger services every day [1]. Following the specific regulations to ensure the safety of train operations, EMUs are regularly maintained. There are five levels of maintenance cycles, and each level refers to different running lengths or service time of EMUs. For example, each EMU must carry out the first-level of maintenance after running 5500 km or on service for 48 h, according to the latest maintenance regulation [2]. To reduce the growing pressure of maintaining EMUs in time, China Railway has built more than 60 EMU depots to provide maintenance service. Those depots are divided into two classes. Class I depots mainly focus on high-level maintenance. Class II depots only complete the first two levels of maintenance.

Each EMU depot has various functions, such as maintenance, cleaning, and temporary storage for the Class II depots. Those functions are performed in maintenance yards, washing yards, and temporary storage yards correspondingly, which are equipped with individual facilities for different tasks. A typical shunting operation planning (SOP) at an EMU depot includes operation sequencing and track assignment. The operation sequencing determines the work sequence among different yards and the occupation time. An EMU may first accept maintenance after its arrival at the depot and then accept washing and temporary storage before leaving the depot. It may also be washed first and then accept maintenance and temporary storage. Similarly, it can follow the other work orders. Deciding the tracks for each EMU is called track assignment, according to the time point of each

EMU entering or leaving each yard. Different from the traditional track assignment problems following the rule that one track can only be occupied by one EMU at any time, most tracks at EMU depots can service two short EMUs (S-EMUs) of 8 railcars or a long EMU (L-EMU) of 16 railcars. Those features add complexity to the SOP problem.

The capacity of an EMU depot is closely relevant to its track utilization rate, which can be increased by optimizing the shunting operation plan that determines the operation sequences and the track occupation simultaneously. Nowadays, the shunting operation plan for EMUs is manually made, which becomes very challenging as the increasing pressure of maintenance. Infeasible shunting operational plans may be made and cause delayed departure or missed train services. It is necessary to develop a computer-aided planning system to improve the efficiency of planning. (a) This paper proposes two integer linear programming models for two types of yards, namely, stub-end and through. (b) It considers the section assignment, which was rarely studied in the previous literature. Two short EMUs can occupy one track simultaneously, which greatly improves the track utilization rate. (c) It designs a Reduced Variable Neighborhood Search (RVNS) algorithm to improve the solution efficiency. Class II EMU depots in China with different yard layouts can accommodate more EMUs during the given time horizon, which will help the Chinese railway reduce the pressure of the fast-growing number of EMUs.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 introduces the SOP problem, and two optimization models are formulated in this section for the SOP problem at both stub-end and through type of yards. Section 4 designs an RVNS algorithm. A numerical experiment is presented in Section 5 to test our models and algorithm. Finally, Section 6 concludes the paper with significant findings and research prospects.

2. Literature Review

Shunting is to move a train or railcars onto a different track or position in a station with or without additional traction. Hansmann et al. [3] set several parameters to classify the train shunting problem, namely, track design, track length, hump, timing, splitting, free or ordered, and blocks or pattern. According to these seven attributes, the SOP in EMU depots can be described as stacks or queue (stub-end and through), 16-bounded, 0-hump for through yards and 1-hump for stub-end yards, time windows, no-split, ordered, and 1 block or 2 blocks (a standard EMU of 8 railcars can be regarded as one block). So, the SOP problem at EMU depots is a particular part of the train shunting problem.

Few studies have been reported on the SOP at EMU depots. Wang et al. [4] studied first the SOP problem at Chinese EMU depots. They proposed nonlinear integer models aiming to minimize the unnecessary occupation time of critical tracks and the costs of shunting routes. The critical tracks include maintenance tracks and cleaning tracks. Guo et al. [5] also studied the SOP problem at a stub-end EMU depot and proposed an integer linear programming model, while they did not consider the section assignments. Wang et al. [6] proposed a shunting schedule model for EMU depots to minimize the number of shunting movements. They considered route conflicts but did not consider section utilization of tracks and different yard layouts. A particle swarm optimization (PSO) algorithm was proposed to solve the model. Tong et al. [7] analyzed the first-level maintenance capacity at EMU depots. They established the nonlinear models aiming to maximize the number of EMUs which can be maintained during the planning horizon. All those literature studies mentioned that the lengths of the EMUs should be considered. Li et al. [8] studied the EMU-to-track assignment problem, which assumes that the sequencing of shunting operation is given. This paper will optimize operation sequences and the track occupation simultaneously.

There are also few studies about shunting problems that occur in the train maintenance workshops. Lentink [9] took the lead in proposing the cleaning service scheduling problem. The goal of the problem is to clean as many train units as possible before the trains depart, to meet the cleaning start time, and to clean crew constraints. Jacobsen and Pisinger [10] considered the SOP at a railway workshop area, where the train units only accept maintenance. Before or after the maintenance, a train unit is parked at a temporary storage track. They formulated a time-space network and proposed an integer model to minimize the completion time and avoid blocking. The SOP at EMU depots is much more complicated than the SOP at the workshop area, as the latter one only considers the track assignment.

A typical shunting operation happens in railway freight hump yards, also called marshalling yards or classification yards. In the freight hump yards, inbound trains are decoupled to classification tracks. Then the railcars are pulled and assembled by shunting engines to form an outbound train. The process of decoupling and rearranging of inbound trains is called sorting. Gatto et al. [11] conducted primary algorithmic shunting research on freight trains. They focused on train sorting with the objective of minimizing the number of pulls or the number of used tracks. Boysen et al. [12] reviewed the sorting problem in hump yards. Compared with the freight trains, EMUs at Class II depots should be shunted and maintained without being decoupled and reassembled. Thus, the SOP at EMU depots is one kind of sorting problem that includes track assignment and accurate control of dwell time on tracks.

Sorting also happens at passenger stations. Compared with the sorting of the freight train, arrival and departure times of passenger trains are fixed. This is the same as the SOP at EMU depots. Freling et al. [13] proposed a solution approach, which included the matching of shunting units and the track assignment. Kroon et al. [14] put forward a model to solve the matching and parking problems in an integrated manner with stub-end tracks. In Beygo's thesis [15], an MIP model was developed to solve the parking problem that had a polynomial number of variables in the number of trains and shunt tracks. Haahr et al. [16] presented a comparison benchmark of multiple solution approaches for the train unit shunting problem. Wu et al. [17]

presented a mean-variance optimization model for track allocations and a simulated annealing algorithm to solve the problem.

In the field of trams, Blasum et al. [18] made an assignment of different types of trams to depart with the aim of minimizing morning shunting movements at a stub-end depot. Winter and Zimmermann [19] presented binary program models to minimize the number of shunting movements or the number of mismatches. Like the scheduling problem at tram depots, the SOP at EMU depots must guarantee the departure in the morning without blocking. The sequencing and track assignment should be solved at both tram depots and EMU depots, but the EMU should transfer among different yards to complete maintenance and washing tasks.

Moreover, in the field of production scheduling in manufacturing systems, the partial flexible job-shop scheduling problem (PFJSP) should be referred. Like the SOP, PFJSP should determine machine selection and operation sequencing. In the PFJSP, a set of jobs are processed on a set of machines within a given processing time. Different from the total flexible job-shop scheduling problem (TFJSP) (Kacem et al. [20]), only part of the machines is available to be specified for some operations in the PFJSP. Kacem et al. [20] transformed the PFJSP to the TFJSP by adding "infinite processing times" to the unavailable machines and solved the TFJSP instead. Chen et al. [21] mainly focused on the JSP with parallel machines and reentrant process. Genetic Algorithm and Grouping Genetic Algorithm are developed to deal with machine selection and operation sequencing, respectively, aiming to minimize the total tardiness, total machine idle time, and makespan. For more details about the PFJSP, we recommend the review of Chaudhry and Khan [22]. There are also some differences between the SOP and the PFJSP. For example, each job in the PFJSP has a prespecified processing order, and the operation time on the machines is fixed and known in advance. However, in the SOP problem, the operation sequence and the track time of one EMU are not fixed and need to be solved. Notably, one track can accommodate two S-EMUs at the same time, but each machine can only perform one operation of one job at a time. Therefore, the existing literature on PFJSP or TFJSP cannot be fully applied to the SOP problem.

3. The SOP Problem at EMU Depots

After arrival, an EMU may enter the maintenance yard directly, or enter the washing yard directly, or enter the temporary storage yard waiting for maintenance and cleaning. The shunting operation sequence of each EMU at the depot may be as follows;

(1) Temporary storage ⟶ washing ⟶ maintenance

(2) Temporary storage ⟶ maintenance ⟶ washing

(3) Maintenance ⟶ temporary storage ⟶ washing

(4) Maintenance ⟶ washing ⟶ temporary storage

(5) Washing ⟶ maintenance ⟶ temporary storage

(6) Washing ⟶ temporary storage ⟶ maintenance

As the numbers of tracks in the maintenance and washing yard are limited, it is almost impossible to complete the operations at the depot without one temporary storage operation. Therefore, the two operation sequences, namely, arrival ⟶ washing ⟶ maintenance ⟶ departure and arrival ⟶ maintenance ⟶ washing ⟶ departure, are only theoretically possible. More than one temporary storage operations may be needed. So, some other possible sequences could be temporary storage ⟶ maintenance ⟶ washing ⟶ temporary storage, or temporary storage ⟶ maintenance ⟶ temporary storage ⟶ washing ⟶ temporary storage, or others. This paper will focus on the first listed six scenarios, and only one temporary storage is considered for simplifying this problem.

The existing EMU depots have different types of layouts, such as Shanghai South EMU Depot with transversal and stub-end yard configuration, Xining EMU Depot with longitudinal and through yards configuration, and other EMU depots with a combination of transversal and longitudinal yards configuration like Shanghai Hongqiao EMU Depot. We assume that all EMU depots are with transversal yards configuration to simplify this SOP problem. The track assignment in each yard decides the track occupation for each EMU. Different from the other track assignment problems, most tracks at EMU depots have two sections, which can accommodate an L-EMU or two separate S-EMUs. For the second scenario that two S-EMUs share the same track, the procedures of EMUs to enter and leave the track are quite different between the through yard and the stub-end yard, as shown in Figure 1. In a through type of yard, when two S-EMU share the same track at the same time, take Figure 1(a) as an example, EMU-i must leave the Track-4 earlier if it arrives earlier than EMU-k. We assume that bidirectional movements of two S-EMUs at a through yard are not allowed because they may result in complicated shunting operations and potential safety hazards. And we also assume that the EMUs go back to one side of the depot through an additional connection track. In a stub-end yard, as shown in Figure 1(b), if both EMU-k and i use Track-4 at the same time, EMU-i must arrive at Track-4 earlier and leaves later than EMU-k. In brief, two S-EMUs follow the "first-in-first-out (FIFO)" rule in through yards and "first-in-last-out (FILO)" rule in stub-end yards when sharing the same track at the same time. Please note that if an S-EMU occupies Section II of any track, another EMU cannot occupy Section I even though it is empty for both through and stub-end types of yards. The L-EMUs follow the general rule that one track can only be occupied by one EMU at any time.

Let I denote a set of EMUs and let i be its index. The sets of S-EMUs and L-EMUs are defined as I_s and I_l, respectively, so we have $I = I_s \cup I_l$. Define J as the set of works (also called operations) including washing, maintenance, and temporary storage and let j be its index. Each work is carried out in the corresponding yard. The set of tracks for each

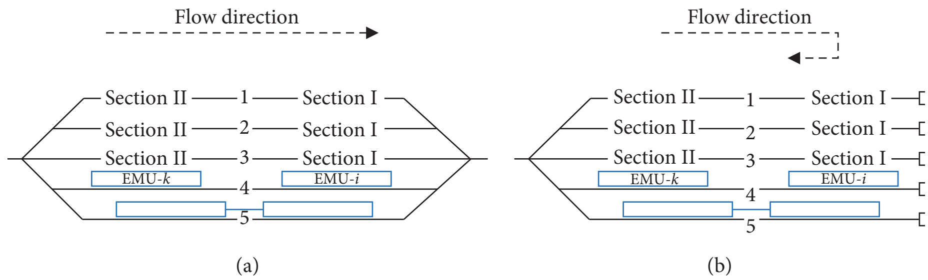

FIGURE 1: Two kinds of yard layouts at EMU depots. (a) The through yard. (b) The stub-end yard.

work j is defined as H_j. For modeling convenience, two dummy EMUs are added, $i=0$ and $i=n+1$. With these, each real EMU can be a preorder EMU of one EMU and a postorder EMU of another EMU. If without dummy EMUs, the real EMU without the preorder or postorder EMUs will not satisfy all the following constraint sets, such as the constraint set (4). Similarly, two dummy works are added, $j=0$ and $j=m+1$. Each real work can be a preorder work of one work and a postorder work of another work. As shown in Figures 2 and 3, the SOP problem can be described as two sequencing problems. It is assumed that a_i and d_i are the arrival time and departure time of EMU-i at the depot. o_{ij} is the standard operation time of EMU-i to perform Work-j. All the notations are presented in Table 1.

The SOP problem makes the following major operation sequence and track decisions:

(1) The shunting operation sequence of EMU-i (x^i_{jp}) is 1 if EMU-i performs Work-j before p and 0 otherwise

(2) The track assignment of Track-h (y^h_{ik}) is 1 if EMU-i is serviced on Track-h before EMU-k and 0 otherwise

(3) The section assignment of Track-h (z^h_i) is 1 if S-EMU-i occupies Section I of Track-h and 0 if occupies Section II

(4) The start time to service EMU-i on any track for Work-j and the departure time from Track-h are denoted as e_{ij} and f_{ij}, respectively

(5) The delay time of EMU-i to leave the EMU depot is denoted as T_i

From the problem statement and notations that just presented, the SOP problem at the through EMU depots can be formulated as follows (called SOP-T):

$$\min \sum_{i=1}^{n} T_i, \tag{1}$$

$$\text{s.t.} \sum_{0\le p\le m, j\ne p} x^i_{pj} = 1, \quad \forall i \in I,\ j \in J \cup \{m+1\}, \tag{2}$$

$$\sum_{1\le p\le m+1, j\ne p} x^i_{jp} = 1, \quad \forall i \in I, j \in J \cup \{0\}, \tag{3}$$

$$\sum_{h\in H_j} \sum_{1\le k\le n+1, k\ne i} y^h_{ik} = 1, \quad \forall i \in I, j \in J, h \in H_j, \tag{4}$$

$$\sum_{h\in H_j} \sum_{0\le k\le n, k\ne i} y^h_{ki} = 1, \quad \forall i \in I, j \in J, h \in H_j, \tag{5}$$

$$\sum_{0\le i\le n} y^h_{i(n+1)} = 1, \quad \forall j \in J, h \in H_j, \tag{6}$$

$$\sum_{1\le i\le n+1} y^h_{0i} = 1, \quad \forall j \in J, h \in H_j, \tag{7}$$

$$y^h_{ik} + y^t_{qi} \le 1, \quad \forall i,k,q \in I, j \in J, h \in H_j, t \in H_j, t \ne h, \tag{8}$$

$$e_{ij} \ge a_i, \quad \forall i \in I, j \in J, \tag{9}$$

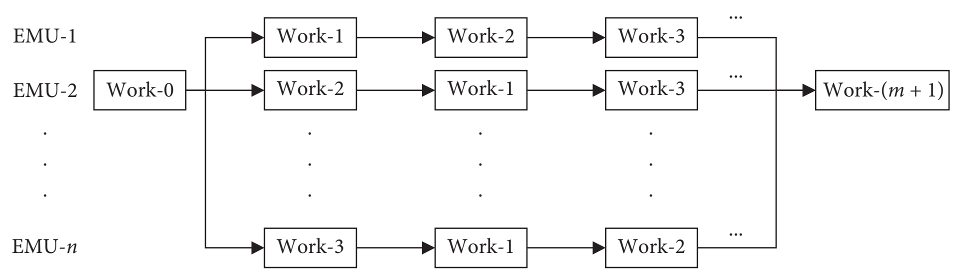

Figure 2: The operation flow of each EMU.

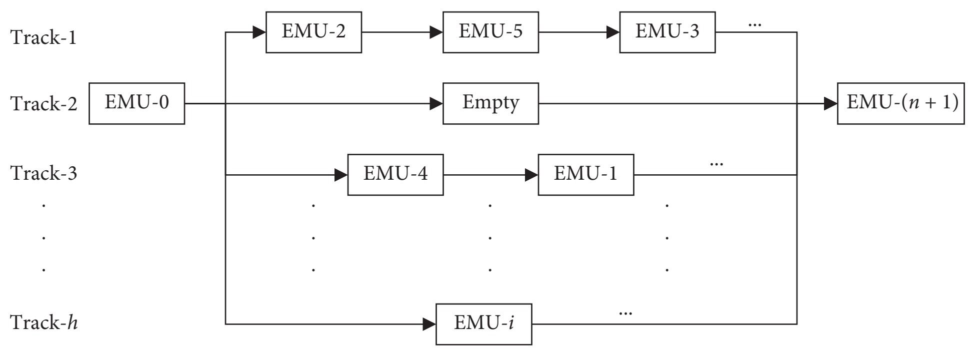

Figure 3: The occupancy flow of each track in one yard.

Table 1: Notations used in the models.

Notations	Definition
Set	
I	The set of all EMUs, dummy EMUs not included
I_s	The set of S-EMUs, $I_s \subset I$
I_l	The set of L-EMUs, $I_l \subset I$
J	The set of works, dummy works not included
H_j	The set of tracks for Work-j
Parameters	
a_i	The arrival time of EMU-i
d_i	The departure time of EMU-i from the depot
o_{ij}	The standard operation time of EMU-i for Work-j
Decision variables	
e_{ij}	The time of EMU-i to enter any track for Work-j
f_{ij}	The time of EMU-i to depart any track for Work-j
T_i	The delay of EMU-i departing the depot
x^i_{jp}	Binary variable, $x^i_{jp}=1$ if EMU-i performs Work-j before Work-p, $x^i_{jp}=0$ otherwise
y^h_{ik}	Binary variable, $y^h_{ik}=1$ if EMU-i occupies Track-h before EMU-k, $y^h_{ik}=0$ otherwise
z^h_i	Binary variable, $z^h_i=1$ if S-EMU-i occupies Section I, $z^h_i=0$ if occupies Section II

$$f_{ij} \leq d_i + T_i, \quad \forall i \in I, j \in J, \tag{10}$$

$$-M\left(1 - x^i_{jp}\right) \leq e_{ip} - f_{ij}, \quad \forall i \in I, j, p \in J, \tag{11}$$

$$e_{ip} - f_{ij} \leq M\left(1 - x^i_{jp}\right), \quad \forall i \in I, j, p \in J, \tag{12}$$

$$f_{ij} - d_i \geq M\left(x^i_{j,m+1} - 1\right), \quad \forall i \in I, j \in J, \tag{13}$$

$$o_{ij} \leq f_{ij} - e_{ij}, \quad \forall i \in I, j \in J, \tag{14}$$

$$\sum_{1 \leq j \leq m} o_{ij} \leq d_i + T_i - a_i, \quad \forall i \in I, \tag{15}$$

$$e_{kj} - f_{ij} \geq M\left(y^h_{ik} - 1\right), \quad \forall i \in I, k \in I_l, j \in J, h \in H_j, \tag{16}$$

$$e_{kj} - f_{ij} \geq M\left(y^h_{ik} - 1\right), \quad \forall i \in I_l, k \in I, j \in J, h \in H_j, \tag{17}$$

$$\sum_{1 \leq k \leq n+1, k \neq i} y^h_{ik} \geq z^h_i, \quad \forall i \in I_s, j \in J, h \in H_j, \tag{18}$$

$$y^h_{ki} \leq z^h_i, \quad \forall k \in I_l \cup \{0\}, \forall i \in I_s, j \in J, h \in H_j, \tag{19}$$

$$y^h_{ik} \leq z^h_i + z^h_k, \quad \forall i, k \in I_s, j \in J, h \in H_j, \tag{20}$$

$$z^h_i + z^h_k \leq M\left(1 - y^h_{ik}\right) + 1, \quad \forall i, k \in I_s, j \in J, h \in H_j, \tag{21}$$

$$e_{kj} - f_{ij} \geq M\left(y^h_{ik} - z^h_i - 1\right), \quad \forall i, k \in I_s, j \in J, h \in H_j, \tag{22}$$

$$e_{kj} - f_{ij} \geq M\left(y^h_{ik} + z^h_i - 2\right), \quad \forall i, k \in I_s, j \in J, h \in H_j, \tag{23}$$

$$\begin{aligned} &f_{kj} - f_{ij} \geq M\left(y^h_{ik} + z^h_i - 2\right), \quad \forall i, k \in I_s, j \in J, h \in H_j, \\ &e_{ij}, f_{ij}, T_i \geq 0, \quad \forall i \in I, j \in J, \\ &x^i_{jp}, y^h_{ik} \in \{0, 1\}, \quad i, k = 0, 1, ..n+1, \; j, p = 0, 1, ..m+1, \; \forall h \in H_j. \end{aligned} \tag{24}$$

The objective function (1) of the SOP-T model minimizes the total delay time of all EMUs. Constraint sets (2) and (3) decide the operation sequence of each EMU. Figure 2 can help to understand those two constraint sets. Similarly, constraint sets (4) and (5) decide the service sequence of each track for EMUs. Please note that each EMU must go through all the operations at the depot, while not all the tracks must be used during the planning horizon, such as the Track-2 in Figure 3; this is guaranteed by constraint sets (6) and (7). Figure 3 can help to understand constraint sets (4)~(7). Constraint set (8) ensures that each EMU can only be serviced one time in each yard for the corresponding operation. An EMU may enter the same yard twice without this constraint, for example, equations $y^1_{3,2} = 1$ and $y^2_{1,3} = 1$ may all hold, and EMU-3 can occupy track 1 and track 2 one time each in the same yard. Constraint sets (9)~(13) guarantee the start time and end time of each work for all EMUs. Constraint set (14) ensures that the dwell time of each EMU on tracks must be longer than the standard operation time of each work. Constraint (15) ensures that the total dwell time of each EMU at the depot must be longer than the total operation time. Constraint sets (16) and (17) ensure that an L-EMU cannot occupy the same track together with any other EMU at the same time. Constraint sets (18)~(21) guarantee section occupancy policy for EMUs. Constraint set (18) means that one EMU utilizes a track if it occupies any section of this track. Constraint set (19) ensures that the S-EMU will occupy Section I after the previous L-EMU or dummy EMU takes the same track. Constraint sets (20) and (21) ensure that if the previous S-EMU occupies Section II, the S-EMU behind cannot enter the same track until the previous one departed, and the second EMU should move to Section I after the previous EMU has been departed. At the same time, Constraint sets (20) and (21) also ensure that if the previous S-EMU occupies Section I, the second S-EMU can occupy Section II directly. Constraint set (22) together with constraint sets (23) and (24) ensure that two S-EMUs can be assigned to the same track.

For the stub-end yard, the occupancy sequence of two sections in one track by two S-EMUs can be prescribed by constraint set (25). While the constraints can only handle time conflict between two EMUs, three or more EMUs may occupy the same track successively with time conflict. So, we present constraint sets (26) and (27) to present the time relationship among three consecutive EMUs. Constraint set (26) ensures that the third S-EMU must move to Section I after the first EMU leaves the track, if three S-EMUs occupy the same track successively. Constraint set (27) ensures that the L-EMU can enter a track only after all the previous two S-EMUs move out of this track:

$$f_{ij} - f_{kj} \geq M\left(y_{ik}^{h} + z_{i}^{h} - 2\right), \quad \forall i, k \in I_s, j \in J, h \in H_j, \tag{25}$$

$$e_{qj} - f_{ij} \geq M\left(y_{ik}^{h} + y_{kq}^{h} + z_{q}^{h} - 3\right), \quad \forall i, k, q \in I_s, j \in J, h \in H_j, \tag{26}$$

$$e_{qj} - f_{ij} \geq M\left(y_{ik}^{h} + y_{kq}^{h} - 2\right), \quad \forall i, k \in I_s, q \in I_l, j \in J, h \in H_j. \tag{27}$$

Then, the model for SOP at EMU depots with stub-end yards (SOP-S) can be formulated by replacing constraint set (24) in the SOP-T with constraint sets (25)~(27).

Different from the study of Wang et al. [3], the delay time (T_i) is allowed in our models. If the objective value is equal to 0, then we get an optimal solution, which means that all EMUs can depart on time after maintenance. If the total delay time is a positive number, a feasible solution with delay departure of EMUs is obtained. Then the dispatcher can improve operation efficiency or reduce the operation time (i.e., the washing time) to make sure that all the EMUs can depart on time.

4. RVNS Algorithm

We used Cplex12.9 to perform computational experiments of different scales, the solution time increased exponentially with the growing number of EMUs and tracks. For an example of 10 EMUs and 10 tracks, only about 6s of computation time was required. For 20 EMUs and 20 tracks, it took tens of minutes to yield the optimal solution. The number of tracks in most China's Class II EMU depots ranges from 10 to 40, with maintenance and cleaning tracks accounting for around 20%, while there are also some EMU depots such as the Shanghai Hongqiao EMU Depot with about 90 tracks. CPLEX may need couple of hours to get solutions and cannot meet the need of real-time dispatching at EMU depots. Therefore, we have designed an RVNS algorithm for this problem. The RVNS algorithm starts with several neighborhood structures and searches in the neighborhood structures in turn until reaching the stopping criterion.

4.1. Model Simplification: Two S-EMUs Regarded as a Dummy Long EMU (DL-EMU). After testing the models by CPLEX, we found that the proposed approach may lead to a large total busy time of tracks, as the models cannot constrain the S-EMUs to share the same track at the same time as much as possible (see the numerical experiment). So, this paper proposes a special method of "two S-EMUs regarded as a Dummy Long EMU (DL-EMU)" to simplify the model. For example, two S-EMUs that arrived at the depot successively are coupled and regarded as a DL-EMU. If the number of arriving S-EMUs is odd, there will be a single S-EMU left unpaired. The arrival time of the DL-EMU is the arrival time of the S-EMU that arrives earlier, and the departure time of the DL-EMU is the departure time of the S-EMU that departs later, that is, "arrive early and depart late." For example, as shown in Table 2, S-EMU-1 and 2 are "bundled" together to form the DL-EMU-1. The arrival time and departure time of DL-EMU-1 are 19:00 and 06:30 the next day, respectively.

It should be noted that the time standards of operations for each DL-EMU are still the time standards of S-EMUs. In the RVNS algorithm, there is no need of decision variables for section assignments. And it is only necessary to change the sections of the two S-EMUs in different operations, so that the time requirements at the through or stub-end depot can be satisfied. We assume that the DL-EMU can change the section occupancy of the two S-EMUs during the shunting process. After completing one operation, we can swap the sections of the two S-EMUs for the next operation. Take Figure 4 as an example, Tracks 1, 2, and 3 and Tracks 4 and 5 are located at different yards. On Track-1, S-EMU-1 and S-EMU-2 are invisibly connected, which means DL-EMU-1 looks like a real L-EMU when be shunted. The section occupations of those two S-EMUs stay the same on Track-5. On Track-2, S-EMU-4 can leave the Track-2 and then enter the Track-4 without waiting for S-EMU-3. In this way, the section occupation of S-EMU-3 and S-EMU-4 is swapped. If S-EMU-3 arrives and departs earlier than S-EMU-4, the DL-EMU-2 should take the swap operation as shown in Figure 4. Similarly, at a through depot, the DL-EMUs may swap sections before the last operation, so that the S-EMU can leave the depot without being blocked. In conclusion, two S-EMUs may have to swap sections before starting the last operation based on the departure time and the yard layouts.

After processing in this way, the models can be simplified without considering sections and yard layouts. However, a new problem arose. For example, in Table 2, the departure time of S-EMU-1 is covered up by the departure time of DL-EMU-1. So, it is possible that S-EMU-1 cannot complete the last operation before the departure time. Similarly, it is possible that S-EMU-2 cannot complete the first operation and then start the second operation. We set two parameters and some additional constraints to avoid this situation. Set b_i as the later arrival time of DL-EMU-i that equals to the arrival time of the S-EMU arrives later and set c_i as the earlier departure time of DL-EMU-i that equals

Table 2: The schedule of the two S-EMUs and the generated DL-EMU.

Index	Arrival time	Departure time (the next day)
S-EMU-1	19:00	06:00
S-EMU-2	19:30	06:30
DL-EMU-1	19:00	06:30

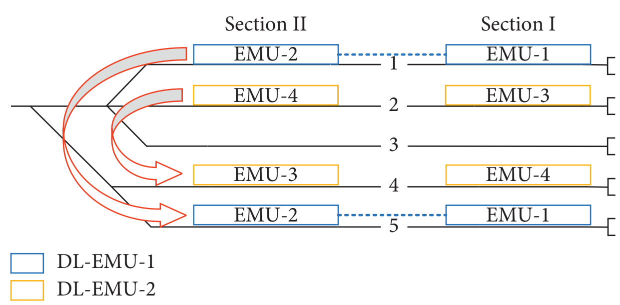

Figure 4: Swap sections and do not swap sections in the process of shunting.

to the departure time of the S-EMU departs earlier. For the DL-EMU-1 in Table 2, $b_1 = 19{:}30$ and $c_1 = 06{:}00$ the next day. Set I as the set of all EMUs, DL-EMUs included, dummy EMUs (i=0 and $i = $ n+1) not included. Set I_{dl} as the set of DL-EMUs, $I_{dl} \subset I$.

Additional constraints are as follows:

$$e_{kj} - f_{ij} \geq M\left(y_{ik}^{h} - 1\right), \quad \forall i, k \in I, j \in J, h \in H_j, \tag{28}$$

$$e_{ij} - b_i - o_{ij} \geq M\left(x_{1,j}^{i} - 1\right), \quad \forall i \in I_{dl}, j \in J, \tag{29}$$

$$c_i - f_{ij} - o_{ij} \geq M\left(x_{j,m+1}^{i} - 1\right), \quad \forall i \in I_{dl}, j \in J. \tag{30}$$

Then the simplified model for the SOP problem at EMU depots (SOP-Simplified) can be formulated by replacing constraint sets (16)~(24) in the SOP-T with constraint sets (28)~(30). Constraint set (28) ensures that the later EMU can enter a track only after the previous EMU has left the track. Constraint set (29) ensures that S-EMUs can complete the first operation before starting the second operation. Constraint set (30) ensures that S-EMUs can complete the last operation before the departure time.

4.2. Procedures of the RVNS Algorithm. The general procedure of RVNS is described in Hansen et al. [23]. First, generate several neighborhood structures. Set the stopping criterion and the initial solution. Second, search in one of the neighborhood structures to find the local optimal solution. If cannot find the solution better than the initial solution, try another neighborhood structure until the algorithm ends. The RVNS is more effective in very large instances than the Variable Neighborhood Search. In recent years, many researchers have used RVNS to solve scheduling problems, such as Remde et al. [24] and Zheng et al. [25].

The RVNS algorithm for SOP is designed as follows (as shown in Figure 5):

(i) Step 1: bundle two S-EMUs as a DL-EMU until the remaining one single S-EMU is left or all the S-EMUs are paired and reorder all EMUs. Then, set the standard operation time and the earlier departure time for all DL-EMUs. The algorithm terminates at T_{max} CPU time, as it is more important to get a feasible solution within an acceptable time than to get an optimal solution.

(ii) Step 2: generate the initial solution by selecting the operation sequence randomly from the six scenarios for each EMU. The initial solution must satisfy constraint sets (2) and (3). G is set to be the objective value of the best solution of each iteration. G can be obtained by solving the simplified model based on the given sequences.

(iii) Step 3: generate the neighborhood N. v is the index of the neighbor in N. Set $v = 0$, $V = |N|$. Each neighbor is the operation sequences of all EMUs. Inspired by Zheng et al. [25], we use two methods to generate new neighbor: (a) insert: cut the operation sequence of a random EMU, and insert (paste) it in another random position of the sequence list of the initial solution; (b) swap: swap operation sequences of random two EMUs. The operation sequences of the two EMUs should be different.

(iv) Step 4: based on the simplified model, use the CPLEX to find the objective value G_v of neighbor v.

(v) Step 5: if G_v is smaller than G, then $G = G_v$ and go to Step 7. Otherwise, go to Step 6.

(vi) Step 6: after trying all the neighbors in the neighborhood N, if cannot find the solution with the objective value of 0, then go to Step 2. Otherwise, $v = v + 1$, go to Step 4.

(vii) Step 7: if $G = 0$ or CPU-Time $\geq T_{max}$, the solution with the minimum objective value is the final solution, go to Step 8. Otherwise, go to Step 6.

(viii) Step 8: get the operation plan of all S-EMU data based on the schedule of all DL-EMUs. A complete shunting operation plan is produced.

5. Numerical Experiment

In this section, we take the real data of a Chinese EMU depot as a numerical experiment to verify the proposed approaches. This is a through Class II depot, which has 4 maintenance tracks, 3 cleaning tracks, and 8 temporary storage tracks, as shown in Figure 6. Each track has two sections.

The planning horizon of this experiment is about 13 hours. Table 3 lists the arrival time and departure time of each EMU. There are 9 S-EMUs and 8 L-EMUs. The converted times (a_i and d_i) are listed in Table 3 in an integer format rather than a 24-hour format. We took 19:00 as the start point and set it to 0 as the converted time, and then the other time can be converted according to the time differences between arrival/departure time and 19:00.

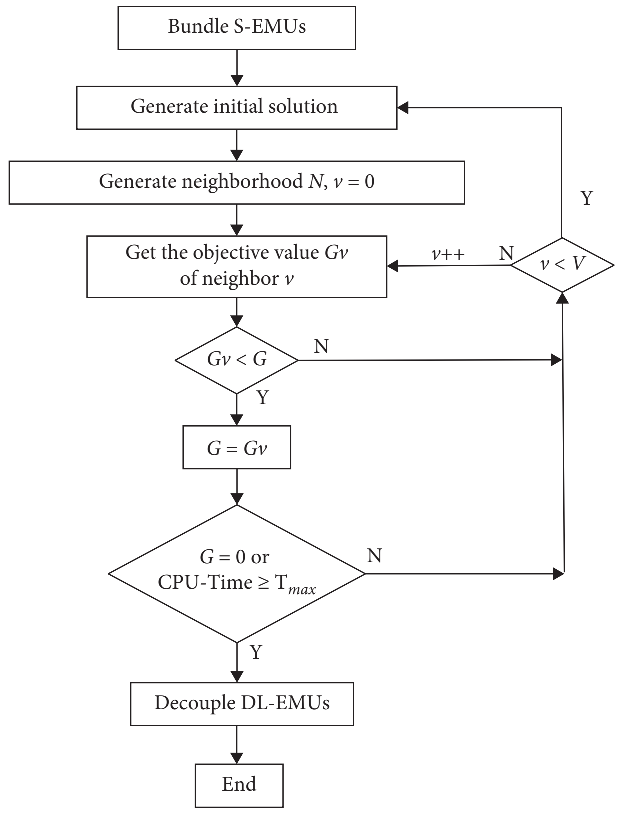

Figure 5: Procedure of the algorithm.

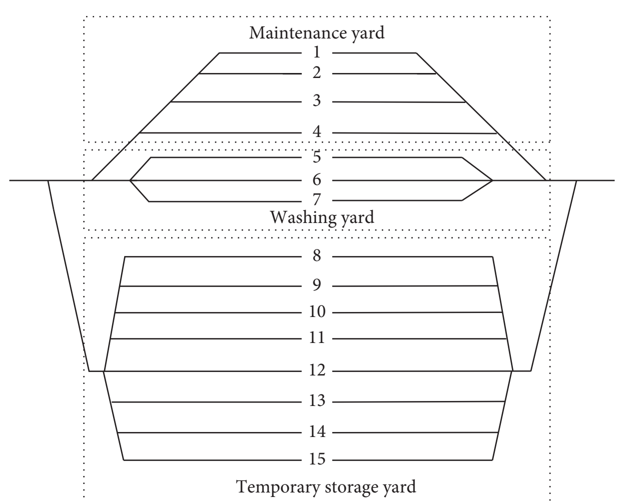

Figure 6: Layout of the EMU depot.

The maintenance time is 80 min per S-EMU and 150 min per L-EMU. The washing time is 30 min per S-EMU and 60 min per L-EMU. The temporary storage time is 40 min per S-EMU and 80 min per L-EMU. The transfer time between different yards has been included in the operation time. Actually, the transfer time between the various tracks is different. This paper does not consider the route conflicts at the trim-end of yards.

5.1. Results of the Original Models Using CPLEX. We used CPLEX 12.9 to solve those models on a PC with Intel Core i7-6700 CPU and 8 GB RAM. The CPU-Time for SOP at this EMU depot was 13 minutes, and the result is shown in Table 4. The value of the objective function was 0, which meant all the EMUs can depart on time according to the timetable. We displayed the result in a Gantt Chart format, as shown in Figure 7. The horizontal axis refers to

Table 3: The schedule of the EMUs.

Index	Arrival time	a_i (min)	Departure time (the next day)	d_i (min)	Dwell time at the depot
S-EMU-1	19:00	0	06:12	672	672
S-EMU-2	19:05	5	06:20	680	675
S-EMU-3	19:37	37	07:05	725	688
S-EMU-4	20:06	66	07:41	761	695
S-EMU-5	21:43	163	04:28	568	405
S-EMU-6	22:39	219	07:21	741	522
S-EMU-7	23:15	255	04:01	541	286
S-EMU-8	23:21	261	05:51	651	390
S-EMU-9	23:40	280	08:10	790	510
L-EMU-10	19:20	20	07:35	755	735
L-EMU-11	19:44	44	06:06	666	622
L-EMU-12	21.11	131	06:41	701	570
L-EMU-13	21:30	150	06:50	710	560
L-EMU-14	21:50	170	05:14	614	444
L-EMU-15	23:02	242	04:39	579	337
L-EMU-16	23:36	276	08:00	780	504
L-EMU-17	23:52	292	05:19	619	285

Table 4: The shunting operation plan generated by CPLEX at the through EMU depot.

Index	Maintenance			Cleaning			Storage		
	Track	Section	Dwell time	Track	Section	Dwell time	Track	Section	Dwell time
S-EMU-1	3	I	568–672	7	I	0–30	11	I	30–568
S-EMU-2	4	I	299–469	7	I	469–680	10	I	5–299
S-EMU-3	2	I	645–725	5	I	37–131	11	II	131–645
S-EMU-4	2	II	680–761	7	II	650–680	8	I	66–650
S-EMU-5	3	II	449–568	7	II	163–193	9	I	193–449
S-EMU-6	3	I	219–299	7	I	680–741	8	II	299–680
S-EMU-7	3	I	449–541	6	I	310–449	10	II	255–310
S-EMU-8	2	I	302–464	6	I	261–302	15	I	464–651
S-EMU-9	4	II	310–469	6	II	280–310	10	I	469–790
L-EMU-10	1	—	605–755	6	—	449–605	15	—	20–449
L-EMU-11	4	—	44–299	5	—	299–404	14	—	404–666
L-EMU-12	3	—	299–449	5	—	131–299	9	—	449–701
L-EMU-13	2	—	150–302	7	—	302–404	12	—	404–710
L-EMU-14	2	—	464–614	5	—	404–464	12	—	170–404
L-EMU-15	1	—	426–579	7	—	242–302	13	—	302–426
L-EMU-16	1	—	276–426	5	—	720–780	13	—	426–720
L-EMU-17	4	—	469–619	7	—	404–469	14	—	292–404

the time, and the vertical axis refers to the index of tracks. The blocks in different colors represent different EMUs, and the blocks of L-EMUs are wider than the S-EMUs. If two S-EMUs occupy the same track at the same time, the thin block above takes Section I, and the other takes Section II. There are 8 couples of S-EMUs sharing the same tracks.

If the layout of the EMU depot is set to be stub-end, and the number of tracks in each yard keeps unchanged, we can also get an optimal solution, as shown in Table 5. The solution time is 25 minutes by CPLEX. There are 10 couples of S-EMUs sharing the same tracks, as shown in Figure 8.

5.2. Results of the Simplified Model Using RVNS Algorithm. The S-EMUs are handled as shown in Table 6. The RVNS algorithm is coded in Visual Studio 2017 and runs on the same PC, and an optimal solution can be searched in 5 seconds, as shown in Table 7. Tables 8 and 9 are the shunting operation plan of S-EMUs at a through and stub-end EMU depot, respectively. The difference between those two plans is the section that S-EMUs (except S-EMU-9) occupy when accepting the last operation. At the stub-end EMU depot, all the S-EMUs (except S-EMU-9) must swap sections before starting the last operation to make sure that no blocking happens.

Figures 9 and 10 show the Gantt chart representations for the optimized shunting plan at a through EMU depot and a stub-end EMU depot, respectively. There are 12 couples of S-EMUs sharing the same tracks.

5.3. Difference between the Two Types of Yards. The capacity of a yard is relevant to its track utilization rate. A high track utilization rate means more difficult to complete all the operations. The plan horizon in this numerical

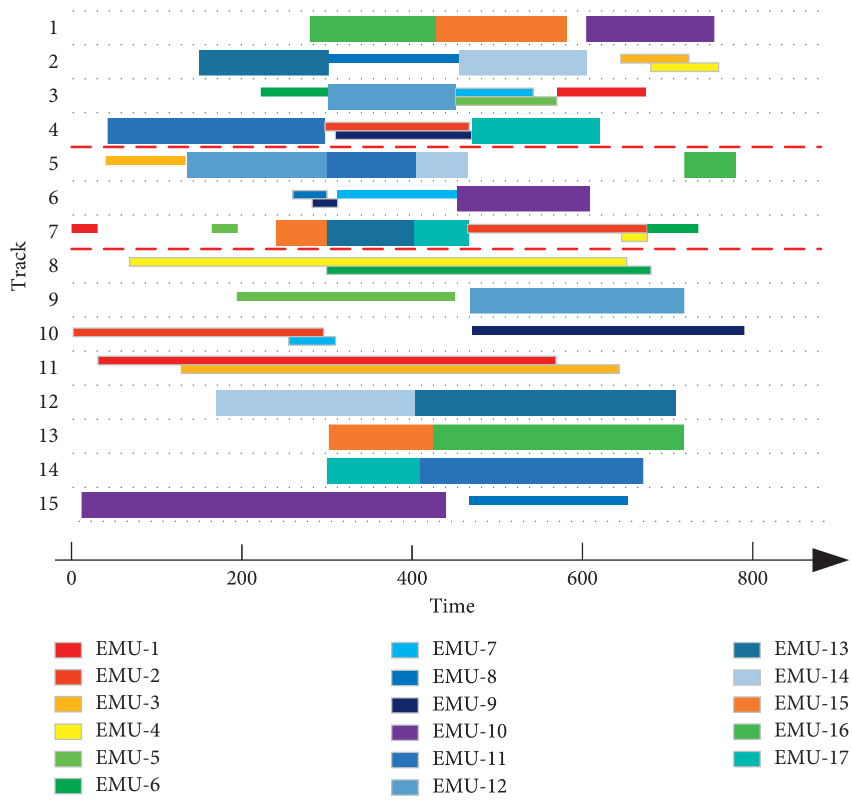

FIGURE 7: A Gantt chart representation for the optimized shunting plan generated by CPLEX at the through EMU depot.

TABLE 5: The shunting operation plan generated by CPLEX at the stub-end EMU depot.

Index	Maintenance			Cleaning			Storage		
	Track	Section	Dwell time	Track	Section	Dwell time	Track	Section	Dwell time
S-EMU-1	2	II	502–642	7	I	642–672	13	I	0–502
S-EMU-2	3	II	524–680	5	I	325–524	10	I	5–325
S-EMU-3	2	I	502–725	6	I	302–502	12	I	37–302
S-EMU-4	3	I	66–302	6	II	302–426	12	I	426–761
S-EMU-5	4	I	163–325	6	I	524–568	15	II	325–524
S-EMU-6	4	II	219–325	5	II	325–524	15	I	524–741
S-EMU-7	4	I	325–541	7	I	255–285	13	II	285–325
S-EMU-8	4	II	325–541	5	I	261–325	12	II	541–651
S-EMU-9	3	I	524–790	5	II	280–325	15	I	325–524
L-EMU-10	1	—	579–755	6	—	20–80	14	—	80–579
L-EMU-11	1	—	104–254	5	—	44–104	11	—	254–666
L-EMU-12	3	—	325–524	5	—	524–701	15	—	131–325
L-EMU-13	4	—	546–710	7	—	486–546	9	—	150–486
L-EMU-14	2	—	170–320	7	—	554–614	8	—	320–554
L-EMU-15	1	—	426–579	6	—	242–302	12	—	302–426
L-EMU-16	1	—	276–426	7	—	426–486	10	—	486–780
L-EMU-17	2	—	352–502	7	—	292–352	13	—	502–619

experiment was 13.17 h from 19:00 to 08:10 in the next morning. All EMUs spend 34.35 Track-hours in the maintenance yard with 4 tracks, so the utilization rate in maintenance yard was 65.22% (34.35÷4÷13.17 = 65.22%). The track utilization rates of the other yards are listed in Table 10. The "Track-hours" ware only calculated once even though two S-EMUs occupy the same track. The results show that the track utilization rate of maintenance yard of stub-end type (75.73%) is much higher than through type (65.22%). In practice, the maintenance yard is usually regarded as the bottleneck of EMU Depot, and it may be more suitable to be designed as the through type. The number of EMUs that require maintenance will increase because the number of EMUs is expected to

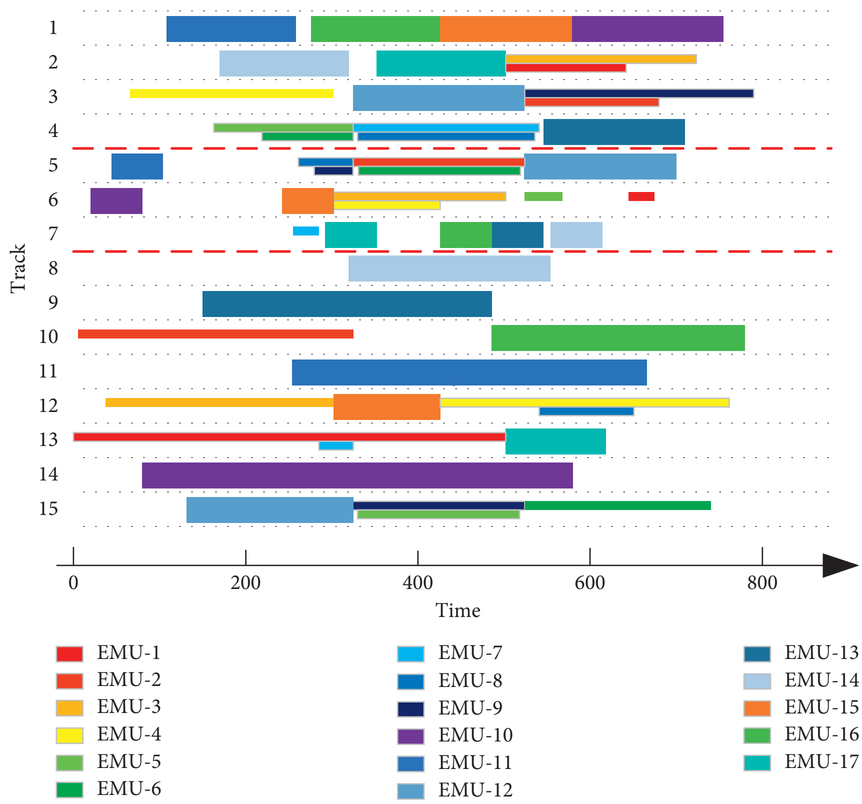

FIGURE 8: A Gantt chart representation for the optimized shunting plan generated by CPLEX at the stub-end EMU depot.

TABLE 6: The processed schedule including DL-EMUs.

Index	a_i (min)	d_i (min)	b_i (min)	c_i (min)
DL-EMU-1	0	680	5	672
DL-EMU-2	37	761	66	725
DL-EMU-3	163	741	219	568
DL-EMU-4	255	651	261	541
S-EMU-9	280	790	—	—
L-EMU-10	20	755	—	—
L-EMU-11	44	666	—	—
L-EMU-12	131	701	—	—
L-EMU-13	150	710	—	—
L-EMU-14	170	614	—	—
L-EMU-15	242	579	—	—
L-EMU-16	276	780	—	—
L-EMU-17	292	619	—	—

TABLE 7: The solution data generated by the RVNS algorithm.

Index	Maintenance		Cleaning		Storage	
	Track	Dwell time	Track	Dwell time	Track	Dwell time
DL-EMU-1	1	35–115	5	0–35	13	115–680
DL-EMU-2	4	96–176	5	37–96	9	176–761
DL-EMU-3	1	163–299	6	299–329	10	329–741
DL-EMU-4	1	321–401	5	255–321	8	401–651
S-EMU-9	3	310–456	7	280–310	15	456–790
L-EMU-10	4	605–755	6	20–80	14	80–605
L-EMU-11	2	456–606	5	606–666	15	44–456
L-EMU-12	1	551–701	5	486–551	12	131–486
L-EMU-13	3	500–650	7	650–710	11	150–500
L-EMU-14	1	401–551	7	551–614	8	170–401
L-EMU-15	4	426–579	6	329–426	10	242–329
L-EMU-16	4	276–426	5	426–486	12	486–780
L-EMU-17	2	292–442	7	442–502	11	502–619

Table 8: The shunting operation plan of S-EMUs at a through EMU depot generated by the RVNS algorithm.

Index	Maintenance			Cleaning			Storage		
	Track	Section	Dwell time	Track	Section	Dwell time	Track	Section	Dwell time
S-EMU-1	1	I	35–115	5	I	0–35	13	I	115–672
S-EMU-2	1	II	35–115	5	II	5–35	13	II	115–680
S-EMU-3	4	I	96–176	5	I	37–96	9	I	176–725
S-EMU-4	4	II	96–176	5	II	66–96	9	II	176–761
S-EMU-5	1	I	163–299	6	I	299–329	10	I	329–568
S-EMU-6	1	II	219–299	6	II	299–329	10	II	329–741
S-EMU-7	1	I	321–401	5	I	255–321	8	I	401–541
S-EMU-8	1	II	321–401	5	II	261–321	8	II	401–651
S-EMU-9	3	I	310–456	7	I	280–310	15	I	456–790

Table 9: The shunting operation plan of S-EMUs at the stub-end EMU depot generated by the RVNS algorithm.

Index	Maintenance			Cleaning			Storage		
	Track	Section	Dwell time	Track	Section	Dwell time	Track	Section	Dwell time
S-EMU-1	1	I	35–115	5	I	0–35	13	II	115–672
S-EMU-2	1	II	35–115	5	II	5–35	13	I	115–680
S-EMU-3	4	I	96–176	5	I	37–96	9	II	176–725
S-EMU-4	4	II	96–176	5	II	66–96	9	I	176–761
S-EMU-5	1	I	163–299	6	I	299–329	10	II	329–568
S-EMU-6	1	II	219–299	6	II	299–329	10	I	329–741
S-EMU-7	1	I	321–401	5	I	255–321	8	II	401–541
S-EMU-8	1	II	321–401	5	II	261–321	8	I	401–651
S-EMU-9	3	I	310–456	7	I	280–310	15	I	456–790

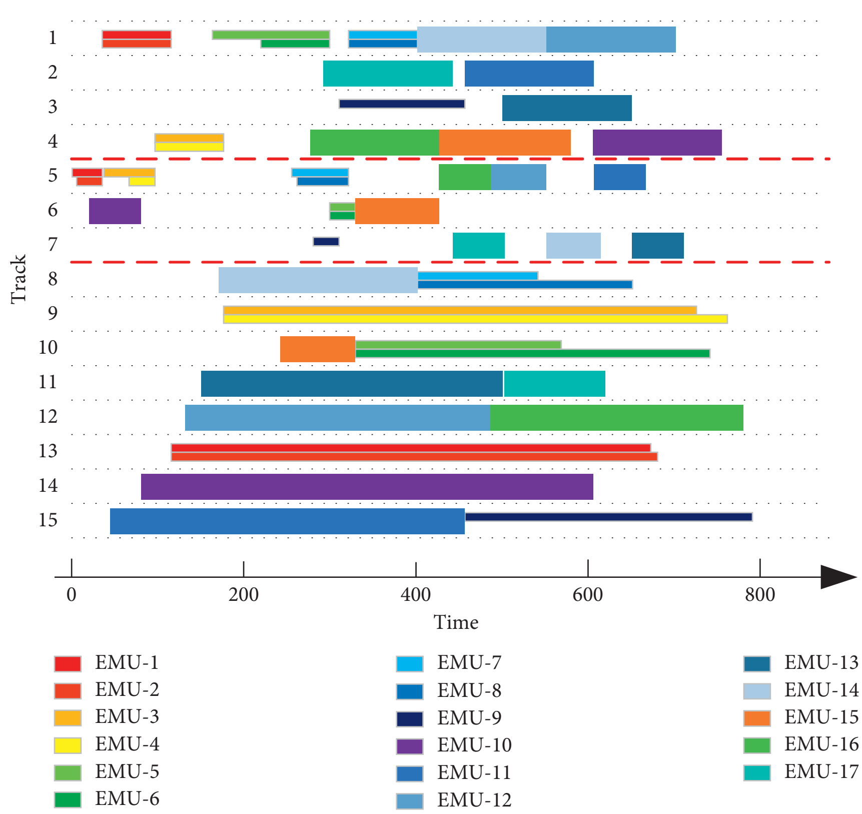

Figure 9: A Gantt chart representation for the optimized shunting plan at the through EMU depot generated by the RVNS algorithm.

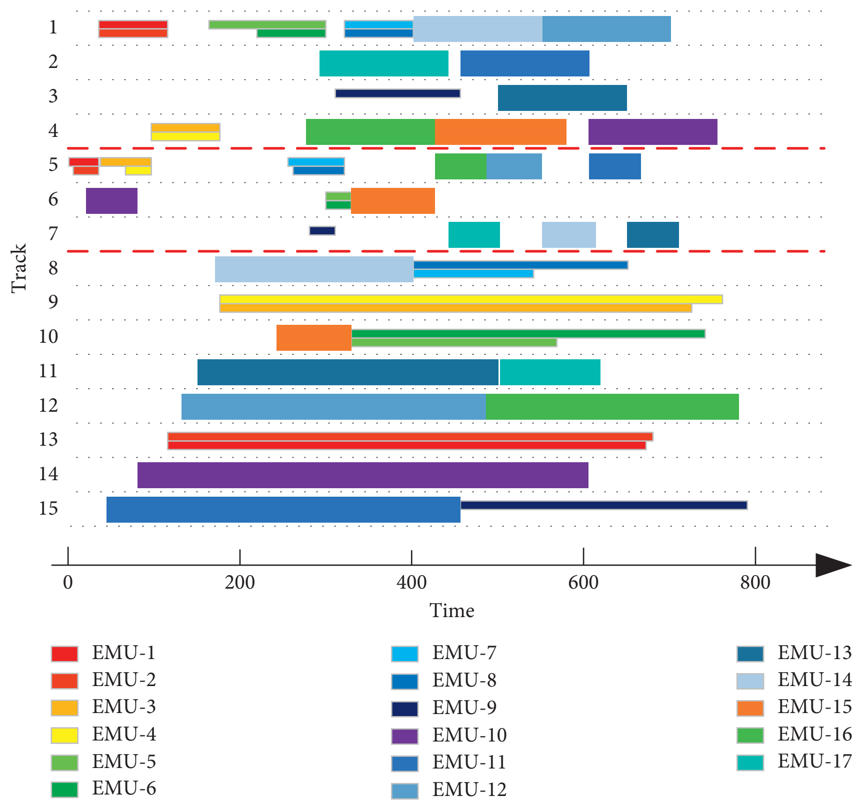

FIGURE 10: A Gantt chart representation for the optimized shunting plan at a stub-end EMU depot generated by the RVNS algorithm.

TABLE 10: The track utilization rate of each yard generated by original models.

Yard	Through		Stub-end	
	Track-hours	Utilization rate (%)	Track-hours	Utilization rate (%)
Maintenance	34.35	65.22	39.88	75.73
Washing	23.17	58.65	19.40	49.11
Temporary storage	77.70	73.77	67.47	64.05

increase. There is an urgent need to improve the utilization of tracks in the maintenance yard to meet the higher requirements for high-speed rail systems.

6. Conclusions

In this paper, we introduced the SOP problem at EMU depots and presented integer linear programming models for the problem. The yard layouts and section occupation conflicts were taken into consideration. Then, we designed an RVNS algorithm after simplifying the original models. We used a numerical experiment based on data from a Chinese Class II EMU depot to verify the proposed models and algorithm. The results showed that the proposed approach can yield a shunting operation plan by minimizing the total delay time of all EMUs in a few seconds. Through yards and stub-end yards differ from each other in the track/section assignment solutions. We found that the service capacity of the through EMU depot is larger than that of the stub-end EMU depot. The maintenance yard is always regarded as the bottleneck, and the utilization rate needs to be improved, especially for the stub-end yard.

The proposed models do not consider the transfer operations between tracks at the trim-end of yards. Route conflicts should be considered in future research studies to make the plan more executable. Moreover, two bundled S-EMUs in the simplified approach may add unnecessary waiting time to some of the S-EMUs. The method for this problem is the future topic of research.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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