

The Sequence Optimization of the Railway Tree-Shaped Special Line's Shunting for Taking-out and Placing-in of Wagons

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Abstract: Shunting for taking-out and placing-in of wagons (STPW) is an important work of freight stations, technical stations with more cargo operations, and large intermediate stations. The sequence optimization of STPW can effectively reduce the total shunting time and reduce operating costs, which is of great significance. When the optimization goal is to minimize the total shunting time, there will be many optimal solutions. Therefore, it is necessary to introduce a second optimization objective in order to seek a more reasonable solution from numerous optimal solutions. However, there is no relevant research on this in existing literature. In response to this situation, this paper proposes two optimization objectives: the first is to minimize the total time of STPW, and the second is to minimize the wagon-hour based on minimizing the total time of STPW. Based on the above two optimization objectives, a mathematical model is established, and a three-stage optimization solution strategy is proposed. The first stage is to solve the first optimization objective by using the improved ant colony algorithm; the second stage is to introduce and improve the crossover operation of the genetic algorithm to improve the diversity of the optimal path; the third stage is to solve the second optimization objective. Finally, an example is given to verify the feasibility of the model and the solution strategy.

Keywords: ant colony; genetic algorithm; sequence of shunting for taking-out and placing-in of wagons; total shunting time; tree-shaped special line; wagon-hour

1 INTRODUCTION

Due to the particularity of railway transportation production activities, freight trains must be marshalled to transport, while loading and unloading operations are generally carried out in special lines or freight yards, which are not in the same place as the arrival, disintegration, marshalling, and departure of freight trains. Therefore, the freight trains arriving at the station need to be sent to the freight yard or special line, and they need to be taken back to the station after unloading or loading operations are completed at the freight yard or special line. Therefore, shunting for taking-out and placing-in of wagons (STPW) is an important work of freight stations, technical stations with more cargo operations, and large intermediate stations. Its efficiency directly affects the speed of wagon turnround and cargo delivery and affects the competitiveness of railways and the production and operation of enterprises. Therefore, we should make scientific and reasonable arrangements for STPW, optimize the operation organization, and constantly improve operational efficiency. The three main sub-problems of the STPW are the timing of optimizing the shunting, the number of times of optimizing the shunting, and the order of optimizing the shunting. These three problems are closely related, but they are mutually constrained. Shunting time is actually the time point for arranging the STPW, that is, combining the arrangement of the station's shunting for break-up of trains, shunting for make-up of trains, reasonably determining a STPW time, which is an important content of the stage station working plan. The number of shunting operations is mainly to determine how many shunting operations are arranged in a day and night. The so-called "reasonable" means that the total cost related to the number of shunting operations is the least. The sequence of STPW mainly studies the sequence of shunting locomotives visiting the special line or freight yard. Its main purpose is to reduce the running time of shunting locomotives, reduce production costs, and reduce carbon emissions [1]. When the three main subproblems are optimized as a whole system, the difficulty of combinatorial optimization will increase significantly. Therefore, scholars at home and abroad

mainly focus on one of the subproblems. Among these three sub-problems, the sequence optimization of STPW can effectively reduce the total shunting time and reduce the operating costs, which is of great significance. Therefore, this paper mainly optimizes the sequence of STPW. In addition, according to the layout of the loading and unloading sites, the sequence problems of STPW can be divided into two categories: STPW of radial special lines and STPW of tree-shaped special lines. Compared with the order of optimizing the STPW of the radial special line, the order of optimizing the STPW of the tree-shaped special line is more complex. To sum up, this paper mainly studies the optimization of the sequence of STPW of tree-shaped special line.

Domestic and foreign scholars have conducted extensive research on the sequence optimization of STPW. In order to reasonably arrange the sequence of wagons' placing-in and taking-out in branch shaped railway siding, improve the efficiency of shunting locomotives, and accelerate the turnover of wagons. Guo et al. [2] established an optimization model for wagons' placing-in and taking-out, and designed its heuristic algorithm. Li et al. [3] set out to develop a simulation approach for evaluating and optimizing the placing-in and taking-out wagons system on the branch-shaped freight operation network (PTWS-BSFON) on the basis of economic considerations. Qi [4] constructed the optimization model of wagon placing-in and taking-out under the condition of the fluctuant travel time, then, the hybrid intelligent algorithm is presented based on stochastic simulation, neural network, and genetic theory. Guo et al. [5] established a general model for placing-in and taking-out wagons in mixed freight operation sites. Using simulated annealing algorithm as the main function, the model is solved by embedding reverse-order judgment and processing functions, the batch division function, the wagon-number-judging function in batch operation, and the function of computing time for placing-in and taking-out wagons. Guo [6] formulated an optimization model for the placing-in and taking-out of wagons in railway stations with branch-shaped goods operation sites, taking the minimization of locomotive running and waiting time for

loading and unloading as the optimization objective. A simulated annealing algorithm was regarded as the main framework to solve the optimization model. According to the characteristics that wagon's taking-out and placing-in problem has two optimization dimensions of sequence and batch. Mu et al. [7] proposed a method used to generate solutions of generic model for wagons' taking-out and placing-in problem in railway station based on some objective constraints and practical experiences; to find the reasonable sequence, moment, and batch number of taking-out and placing-in wagons in shunting operation on radial private lines. Mu et al. [8] built a model for wagons' taking-out and placing-in operation on radial private lines by combining qualitative and quantitative analysis. Then, the methods to construct and compute the solution of the model were elaborated, and an effective ant colony genetic algorithm (ACGA) was designed to search for the optimal solution. Some scholars have proposed a data mining algorithm, which is fast and efficient, and also provides a new idea to solve the vehicle routing problem [9]. With minimizing the weighted comprehensive value of the total time operation for shunting locomotive's placing-in and taking-out of wagons, total wagons' preparation time, total wagons' travel kilometers as optimization objectives, regarding the capability of locomotive and the priority that the transferring operations require between operating sites as constraints, Guo [10] established a multi-objective optimization model for scheme of wagons' placing-in and taking-out in branch-shaped operating sites according to the analysis of characteristics of the operations on placing-in and taking-out of wagons in actinoid private line. Li et al. [11] proposed a chromosome presentation and realized the genetic algorithm for the problem. Li et al. [12] studied the shunting for taking-out and placing-in of non-through wagon flow with handling capacity limited on hybrid siding. The problem is formulated as a mathematical programming model which makes minimization of shunting engine cost and wagons detention time cost as the objective function. Yang et al. [13] used genetic annealing algorithms to solve large-scale computing problems. This provides a computational approach for solving the optimal order of STPW.

From the above literature, it can be seen that most scholars transform the sequence optimization problem of STPW into a vehicle routing problem, establish corresponding mathematical models, and use heuristic algorithms to solve it. From the perspective of optimization models, most of the mathematical models established in existing literature are single objective optimization models. Even if a single literature is a multi-objective optimization model, it ultimately transforms into a single objective solution. Although the sequence problem of STPW can be described as a path planning problem, the sequence problem of STPW is a special path planning problem. When taking the minimum total time as the objective function, the loop that makes the line connecting each operation location only round-trip once is the optimal path, but the loop that makes the line connecting each operation location only round-trip once is more than one. That is to say, there is more than one optimal shunting route. Therefore, when studying the order problem of STPW, it is difficult to find a more reasonable solution in many optimal paths by only taking the minimum total time as the objective function. Therefore, it is necessary to add a second optimization objective to find a more reasonable solution. However, there is currently no relevant literature

on this topic. From the perspective of solving algorithms, when the first optimization goal is to minimize the total time, there will be many optimal solutions, but most of the existing literature's solving algorithms can only find one optimal solution. There is no relevant literature on the algorithm that can possibly find all the optimal solutions that meet the conditions. Therefore, this article conducts a multi-objective optimization for the sequence of STPW in order to find a more reasonable solution and reduce production costs. The first optimization objective is to minimize the total time of STPW, and the second optimization objective is to minimize the total wagon-hours of shunting locomotives on the basis of minimizing the total time of STPW. At the same time, a new algorithm needs to be designed to find as many optimal solutions as possible that meet the first optimization objective.

2 PROBLEM MODELING

2.1 Description of the Problem

The sequence problem of STPW of railway tree-shaped special line can be described as follows:

Within a period, several freight trains have arrived at the station and completed the shunting for break-up of trains, waiting for STPW. In a single STPW, the shunting locomotive starts from the station to the n operation locations. Some operation locations have different priority levels. Operation locations with higher priority levels should have priority access. All operation locations can only be accessed once in a STPW. Find an access path to minimize the total time of STPW. And the total wagon-hours is the minimum on the basis of meeting the minimum total time.

2.2 Conditional Assumptions

This paper makes the following assumptions about this problem:

- (1) One locomotive shall be responsible for STPW.
- (2) The maximum traction capacity of the locomotive is known.
- (3) The number of tracks on each operation location can meet the requirements of the shunting operation.
- (4) The number of wagons sent to each operation location, the number of wagons to be retrieved from each operation location, and the number of wagons to be transferred between operations are known.
- (5) The network topology of the tree-shaped special line in the hub is known.
- (6) The travel time from the station to each operation location and between operation locations is known. The travel time is a key parameter, including the time to align the freight section and the time to collect wagons. It is not only related to the distance but also related to the number of wagons in a batch. To simplify the calculation it is assumed that the round-trip travel time is equal.

2.3 Parameters and Variables

The parameters and variables involved in this paper are as follows:

- (1) x_{ij} , it is a decision variable, indicating whether there is an arc from operation location i to operation location j , "Yes" = 1, "No" = 0.

- (2) q_{ij} , it is a state variable indicating the number of wagons pulled by shunting locomotives from operation location i to operation location j .
- (3) N , collection of operation locations, $N = \{0, 1, 2, 3, \dots, n\}$, where operation location 0 refers to the station.
- (4) t_{ij} , travel time from operation location i to operation location j .
- (5) C , maximum traction capacity of the locomotive.
- (6) P_i , the priority level of operation location i .

2.4 Mathematical Model

Eq. (1) is the objective function 1, which aims to minimize the total time of STPW. Eq. (2) is objective function 2, which is based on $\min F_1$ to solve the minimum total wagon-hours. Eq. (3) constrains that the number of wagons passing between any two operation locations cannot exceed the maximum traction capacity of the locomotive. Eq. (4) is a priority-level constraint. That is, the priority level of operation location j is higher than operation location i . Eq. (5) constrains that each operation location has only one arc to enter. Eq. (6) constrains that each operation location has only one outgoing arc. Eq. (7) constrains that elements in any subset of set N cannot form a sub-loop. Eq. (8) is a decision variable.

$$\min F_1 = \sum_{i=0}^n \sum_{j=0}^n t_{ij} x_{ij} \tag{1}$$

$$\min F_2 = \sum_{i=0}^n \sum_{j=0}^n t_{ij} q_{ij} x_{ij} \tag{2}$$

S. T.

$$q_{ij} \leq C \quad \forall i \in N, j \in N, \text{ and } i \neq j \tag{3}$$

$$p_i < p_j \quad \forall i \in N, j \in N, \text{ and } i \neq j \tag{4}$$

$$\sum_{i=0}^n x_{ij} = 1 \quad \forall j \in N \tag{5}$$

$$\sum_{j=0}^n x_{ij} = 1 \quad \forall i \in N \tag{6}$$

$$\sum_{i \in U} \sum_{j \in U} x_{ij} \leq |U| - 1 \quad \forall U \subseteq N, U \neq \emptyset \tag{7}$$

$$x_{ij} \in \{0, 1\} \quad \forall i \in N, j \in N \tag{8}$$

3 OPTIMIZATION SOLUTION STRATEGY

The optimization model proposed in this paper is to solve $\min F_2$ based on $\min F_1$. This model is a combinatorial optimization model, which is difficult to solve directly. The heuristic algorithm is a good choice. The genetic algorithm was first proposed by Holland of the United States. It is a computational model of the biological evolution process that simulates the natural selection and

genetic mechanism of Darwin's biological evolutionary theory. It is a method of searching for the optimal solution by simulating the natural evolution process [14]. The ant colony algorithm was first proposed by Dorigo. Ant colony algorithm is essentially a probabilistic algorithm used to find the optimal path. This algorithm is a computational model that simulates the process of ants searching for food [15, 16]. In the process of searching the path, the genetic algorithm has a strong global optimization ability but lacks a feedback mechanism. However, the ant colony algorithm has an efficient feedback mechanism, so the two algorithms are fused to make full use of their respective advantages, so as to improve the efficiency of solving. The solution strategy of this paper is divided into three stages: The first stage is to use the improved ant colony algorithm to solve $\min F_1$ and obtain the optimal path set of STPW in this stage. The access time of each path in the set is equal and less than the access time of any path outside the set. For the convenience of the later description, this set is called the one-stage optimal path set (OSOPS). The second stage is to introduce and improve the crossover operation of the genetic algorithm, cross the access order of specific operation locations in each path in OSOPS, and generate new access paths. The new paths that meet the requirements are added to OSOPS to obtain a new optimal path set, which is called the two-stage optimal path set (TSOPS). The third stage is to solve $\min F_2$. Calculate the wagon-hour of each path in TSOPS, where the path with the minimum wagon-hour is the globally optimal path, and the corresponding solution is the optimal solution.

The advantage of the three-stage optimization solution strategy proposed in this article is that through the first and second stages, all paths that meet the first optimization objective can be obtained as much as possible, that is, the set of optimal paths can be obtained. However, the solution methods used in existing literature can only solve for one path that meets the first optimization objective.

3.1 Ant Colony Algorithm and its Improvement Strategy

3.1.1 Heuristic Function

The heuristic function in the traditional ant colony algorithm is the reciprocal of the distance from the current node i to the next node j . The closer the distance between the two nodes, the more likely the ant is to choose the target node. That is, select the shortest path as the next target node. The problem studied in this paper is to solve the minimum total wagon-hours based on the minimum total time. Therefore, the heuristic function in this paper is defined as the reciprocal of the travel time between the current operation location i and the next operation location j . That is, the smaller the travel time between two operation locations, the more likely the ants are to choose the operation location. The heuristic function $\eta_{ij}(t)$ is defined as:

$$\eta_{ij}(t) = \frac{1}{t_{ij}} \tag{9}$$

In Eq. (9), $\eta_{ij}(t)$ represents the heuristic function, and t_{ij} represents the travel time between operation location i and operation location j .

3.1.2 State Transition Rules

The state transition rule of the basic ant colony algorithm defines the probability of ant K moving from operation location i to operation location j , as shown in Eq. (10). In Eq. (10), P_{kij} represents the transfer probability, $\tau_{ij}(t)$ represents the concentration of pheromone on the path between operation location i and operation location j at time t , and $allowed_k$ represents the set of operation locations that the K -th ant ($K = 1, 2, \dots, m$) has not yet accessed. That is, the operation location that ant K can choose next. For $j \notin allowed_k$, it means that the operation location j has been accessed, so the probability of being selected is 0. μ represents an operation location in the set of operation locations ($allowed_k$) that are not currently accessed. α represents the pheromone importance level factor. The higher the value of α , the more likely the ants are to choose the path that other ants walk, and the less random the search will be. β represents the heuristic function importance degree factor. The higher the β value, the easier the ant colony will choose the local shorter path. The higher the value of P_{kij} , the greater the probability of going to operation location j . However, this does not mean that the operation location with the highest probability must be selected. In the actual solution process, the roulette wheel selection will be used to select.

$$p_{ij}^k = \begin{cases} \frac{[\tau_{ij}(t)]^\alpha [\eta_{ij}(t)]^\beta}{\sum_{\mu \in allowed_k} [\tau_{i\mu}(t)]^\alpha [\eta_{i\mu}(t)]^\beta}, & j \in allowed_k \\ 0, & j \notin allowed_k \end{cases} \quad (10)$$

The basic ant colony algorithm selects the next operation location according to the size of the P_{kij} value. In order to improve the diversity of path selection and avoid falling into local optimization, this paper improves the state transition rules of the basic ant colony algorithm by introducing random numbers x , $x \in [0, 1]$ and constants x_0 , $x_0 \in [0, 1]$. When $x \leq x_0$, the ant generates an access path using the roulette wheel selection according to the size of P_{kij} value. When $x > x_0$, an access path is randomly generated to improve the diversity of path selection. The size of x_0 can be set according to actual needs. When we need to generate random access paths with a greater probability, we can set the value of x_0 to a smaller value and vice versa.

3.1.3 Strategies for Pheromone Updating

Ant colony algorithm usually adopts $\tau_{ij}(t)$ used to express the concentration of pheromone on path ij at time t . The pheromone on each path will volatilize, but if ants pass by, the concentration of pheromone will increase accordingly. See Eq. (11) for the updating equation of pheromone concentration.

$$\tau_{ij}(t+1) = (1 - \rho)\tau_{ij}(t) + \Delta\tau_{ij} \quad (11)$$

In Eq. (11), ρ is pheromone volatilization factors, $\rho \in [0, 1]$; $\Delta\tau_{ij}$ represents the total number of pheromones

left by all ants passing through path ij in an iteration. See Eq. (12):

$$\Delta\tau_{ij} = \sum_{k=1}^m \Delta\tau_{ij}^k \quad (12)$$

In Eq. (12), $\Delta\tau_{ij}^k$ represents the number of pheromones left by the K th ant on path ij . There are three different models for calculating $\Delta\tau_{ij}^k$: the ant-cycle system, ant-quantity system, and ant-density system [15]. Ant-cycle system is selected in this paper. See Eq. (13):

$$\Delta\tau_{ij}^k = \begin{cases} \frac{Q}{L_k}, & \text{the } K\text{-th ant once passed the path from} \\ & \text{operation location } i \text{ to } j. \\ 0, & \text{otherwise} \end{cases} \quad (13)$$

3.2 Improved Strategy of Crossover Operation of Genetic Algorithm

This paper introduces and improves the crossover operation of the genetic algorithm to expand the diversity of paths. Through the crossing of coding fragments, the diversity of coding can be expanded, and better individuals can be generated. Considering the characteristics of the TSP problem, the crossover operation in this paper can only be carried out between an individual's own coding fragments. The general genetic algorithm is to randomly select the coding segments to cross, and this paper makes some improvements based on the characteristics of STPW: only specific coding segments can cross. For the convenience of description, the tree-shaped special line is drawn into a tree, called the special line tree, as shown in Fig. 1. In Fig. 1, S_0 represents the station, and S_1 to S_{10} represents the operation location. P refers to the switch, and the number of the switch is 1 to 9.

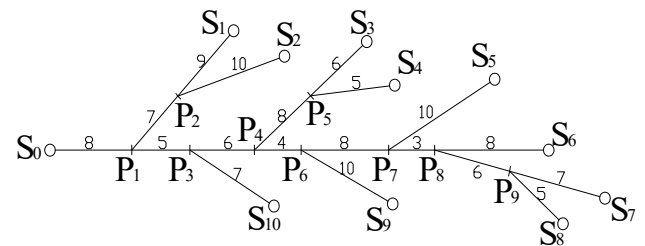


Figure 1 Special line tree

In Fig. 1, the line segments leading to two or more operation locations are called common branches, such as P_1P_2 , P_1P_3 , P_3P_4 , etc. The line segments leading to only one operation location are called branches, such as P_2S_1 , P_2S_2 , P_5S_3 , P_3S_{10} , etc. According to the characteristics of STPW: without special requirements, the branches connected with the same common branch should be accessed continuously, and the access order of the two branches can be interchanged without increasing the travel time. Some common branches in Fig. 1 only connect two operation locations. For the convenience of description, the common branch that only connects two operation locations is called the minimum common branch. In Fig. 1, P_1P_2 , P_4P_5 and P_8P_9 are the minimum common branch. P_1P_2

connects S_1 and S_2 , P_4P_5 connects S_3 and S_4 , and P_8P_9 connects S_7 and S_8 . Therefore, changing the access order of S_1 and S_2 , S_3 and S_4 , and S_7 and S_8 will not increase the travel time. The cross strategy of this paper is: for each access path in OSOPS, select one or more minimum common branches multiple times and randomly, exchange the access order of its operation location, generate a new access path, and then judge whether the new access path exists in OSOPS. If it exists, the set will not be updated. If it does not exist, the new path will be added to the set. That is, only two operation locations on the same minimum common branch can cross each other. For example, an access path in the OSOPS obtained in the first stage: $S_0 \rightarrow S_1 \rightarrow S_2 \rightarrow S_3 \rightarrow S_4 \rightarrow S_5 \rightarrow S_6 \rightarrow S_7 \rightarrow S_8 \rightarrow S_9 \rightarrow S_{10} \rightarrow S_0$. This path is called the original path. The original path is a gene with 12 fragments, as shown in Fig. 2. In a crossing process, it is assumed that P_1P_2 and P_8P_9 are selected randomly. Therefore, gene segment S_1 needs to cross with gene segment S_2 , and gene segment S_7 needs to cross with gene segment S_8 . Finally, get the new access path: $S_0 \rightarrow S_2 \rightarrow S_1 \rightarrow S_3 \rightarrow S_4 \rightarrow S_5 \rightarrow S_6 \rightarrow S_8 \rightarrow S_7 \rightarrow S_9 \rightarrow S_{10} \rightarrow S_0$, and check whether it exists in OSOPS. If it exists, do not update the set. Otherwise, add the new path to OSOPS.

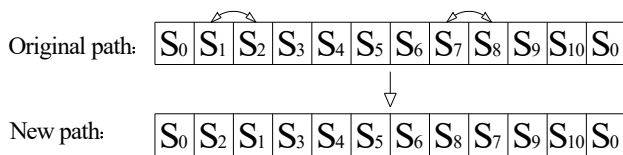


Figure 2 Cross schematic diagram

4 EXAMPLE ANALYSIS

4.1 Example Description

A railway station is connected to ten operation locations, and its layout is shown in Fig. 1. At the same time, the travel time between the station, switch and operation location is also shown in Fig. 1. The travel time includes the time to align the freight section and the time to collect wagon. The unit is minutes. Now it is necessary to send a batch of wagons to each operation location for loading and unloading operations. Due to the limited number of locomotives, the station only provides one shunting locomotive to complete this STPW. All operation locations can only be accessed once. It is necessary to find an access path to minimize the total time of STPW, and the total wagon-hours are the minimum on the basis of meeting the minimum total time.

Table 1 Shunting quantity of each operation location

	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}
SC	-1	-2	-4	0	-2	-2	-2	-3	0	-3
QC	+2	+1	0	+4	+2	+1	0	+1	+3	+2
DC	0	0	$2 - S_5$	0	0	0	0	0	0	0

The number of wagons of STPW is shown in Tab. 1. In Tab. 1, SC represents the number of wagons sent from the station to the operation location. QC represents the number of wagons retrieved from the operation location. DC represents the number of wagons sent from one operation location to another. There are two wagons in S_3

that need to be sent to S_5 . Therefore, the priority level of S_3 is higher than that of S_5 . The maximum traction capacity of shunting locomotive $C = 50$.

4.2 Determination of Basic Data and Relevant Parameters

4.2.1 Determination of Travel Time

According to the travel time between stations, switches and operation locations in Fig. 1, the travel time between stations and operation locations and between operation locations and operation locations is calculated. See Tab. 2.

Table 2 Calculation table of travel time (unit: minute)

	S_0	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}
S_0	0	24	25	33	32	41	42	47	45	33	20
S_1	24	0	19	41	40	49	50	55	53	41	28
S_2	25	19	0	42	41	50	51	56	54	42	29
S_3	33	41	42	0	11	36	37	42	40	28	27
S_4	32	40	41	11	0	35	36	41	39	27	26
S_5	41	49	50	36	35	0	21	26	24	28	35
S_6	42	50	51	37	36	21	0	21	19	29	36
S_7	47	55	56	42	41	26	21	0	12	34	41
S_8	45	53	54	40	39	24	19	12	0	32	39
S_9	33	41	42	28	27	28	29	34	32	0	27
S_{10}	20	28	29	27	26	35	36	41	39	27	0

4.2.2 Determination of Relevant Parameters

Using the ant colony algorithm to solve the optimal solution requires many parameters, and different values of parameters will have a certain impact on the algorithm. The number of ants m affects the search ability. α and β determine the search direction of the algorithm and affect the search ability of the algorithm. ρ affects the strength of the interaction between individual ants and the global search ability and convergence speed of the algorithm. The experiments of Dorigo et al. show that: $\alpha = 1$, $\beta = 2 \sim 5$ is more appropriate. For the basic ant colony algorithm, setting $\rho = 0.5$ is more appropriate, while for the ant colony system, setting $\rho = 0.1$ is more appropriate [15]. According to the existing research results and the actual situation of this example, the values of the main parameters in this paper are shown in Tab. 3. In Tab. 3, Q represents the total number of pheromones, and $Maxiter$ represents the maximum number of iterations.

Table 3 Values of main parameters in the ant colony algorithm

m	α	β	ρ	Q	$Maxiter$
300	1	5	0.1	1	300

4.3 Calculated Results

In this paper, the solution is divided into three stages: In the first stage, the improved ant colony algorithm is used to solve $\min F_1$ to obtain OSOPS; in the second stage, TSOPS is solved, and TSOPS is obtained by cross operation of each path in OSOPS; in the third stage, $\min F_2$ is solved to obtain the global optimal access path.

4.3.1 Solve $\min F_1$

In this paper, the improved ant colony algorithm is used to solve $\min F_1$ and obtain OSOPS. The constant x_0 is introduced to adjust the probability of generating random paths by adjusting the size of x_0 . This paper sets x_0 equal to

0.4, 0.6, 0.8 and 1 respectively. When $x_0 = 1$, it is the basic ant colony algorithm. Since the number of paths in the OSOPS is large, we will not list them one by one here, but count the total number of paths to verify whether the improved ant colony algorithm is effective. In order to make the experimental results more objective and accurate, each value of x_0 is tested five consecutive times, and the average value is finally obtained. See Tab. 4 for calculation results.

Table 4 Total number of access paths in OSOPS

	1	2	3	4	5	average value
$x_0 = 0.4$	221	226	224	222	232	225
$x_0 = 0.6$	208	207	209	205	209	207.6
$x_0 = 0.8$	198	192	198	197	198	196.6
$x_0 = 1$	183	177	185	190	183	183.6

It can be seen from Tab. 4 that when $x_0 = 1$, that is, when the basic ant colony algorithm is used, the average value of five consecutive experiments is 183.6, which is the smallest compared with the average value of the total number of optimal paths when x_0 is equal to 0.8, 0.6 and 0.4 respectively, which proves that the improved ant colony algorithm in this paper is effective and can increase the number of optimal paths within a certain range. The access time of each path in OSOPS is 264 minutes. That is, $\min F_1 = 4.4$ hours. In an experiment ($x_0 = 0.4$), the search process of the optimal solution is shown in Fig. 3.

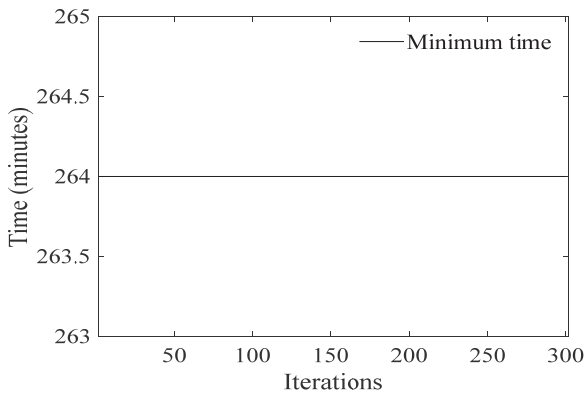


Figure 3 Searching process diagram of the optimal solution

It can be seen from Fig. 3 that in the first iteration, the minimum total time of STPW was found. This is the first stage of the three-stage optimization solution strategy proposed in this article. The purpose of this stage is to solve all paths that meet the first optimization objective as much as possible through an improved ant colony algorithm. From Tab. 4, it can be seen that when $x_0 = 0.4$, each experiment can solve more than 200 paths that meet the first optimization objective. This also proves that when the optimization objective is to minimize the total time, there is more than one optimal path.

4.3.2 Solve TSOPS

Cross according to the cross strategy proposed in this paper. Each path in the OSOPS obtained when x_0 is equal to 0.4, 0.6, 0.8 and 1 is randomly crossed ten times. Each value of x_0 shall be tested continuously five times, and the

average value shall be obtained finally. See Tab. 5 for calculation results.

Table 5 Statistics of the number of paths in TSOPS

	1	2	3	4	5	average value
$x_0 = 0.4$	256	256	256	256	256	256
$x_0 = 0.6$	253	254	256	255	256	254.8
$x_0 = 0.8$	253	248	253	255	255	252.8
$x_0 = 1$	249	246	250	252	245	248.4

From Tab. 5, when $x_0 = 1$, the average number of optimal paths is 248.4, which is 64.8 more than 183.6 in Tab. 4. In addition, when x_0 is equal to 0.4, 0.6 and 0.8 respectively, the average number of optimal paths in Tab. 5 increases by 31, 47.2 and 56.2 respectively compared with Tab. 4, which shows that the improved crossover strategy proposed in this paper is effective and can expand the diversity of optimal paths. For different values of x_0 in Tab. 5, the maximum average value of the number of optimal paths obtained is 256, the minimum is 248.4, and the difference is only 7.6; In Tab. 4, the maximum number is 225, the minimum number is 183.6, and the difference is 41.4. This shows that the improved crossover strategy can effectively reduce the impact of the x_0 value on the results. This is the second stage of the three-stage optimization solution strategy proposed in this article. The purpose of this stage is to solve more paths that meet the first optimization objective through improved crossover strategies.

4.3.3 Solve $\min F_2$

According to the solution results in the second stage, when $x_0 = 0.4$, the number of optimal paths obtained is the maximum. Therefore, based on the TSOPS obtained when $x_0 = 0.4$, calculate the wagon-hour of each access path in the set, where the minimum wagon-hour is the global optimal solution. After calculation, the minimum wagon-hour is 4378 wagon-minutes. That is, $\min F_2 = 72.97$ wagon-hours, and the corresponding global optimal access path is $S_0 \rightarrow S_{10} \rightarrow S_3 \rightarrow S_4 \rightarrow S_5 \rightarrow S_8 \rightarrow S_7 \rightarrow S_6 \rightarrow S_9 \rightarrow S_2 \rightarrow S_1 \rightarrow S_0$. This is the third stage of the three-stage optimization solution strategy proposed in this article. At this stage, the second optimization objective is solved by calculating the wagon-hour consumption of each path in TSOPS.

5 CONCLUSION

This paper studies the sequence optimization of the STPW of the railway tree-shaped special line. Two optimization objectives are put forward: the minimum total time of STPW, and the minimum total wagon-hours of shunting locomotives on the basis of meeting the minimum total time. Two constraints are considered: one is the constraint of the priority level, and the second is the restriction of locomotive traction capacity. Build the problem model and propose a three-stage optimization solution strategy. The strategy first uses the improved ant colony algorithm to solve $\min F_1$ and obtain OSOPS. Then, according to the characteristics of STPW, it is specified that only two operation locations on the same minimum common branch can cross each other. By improving the crossover operation of the genetic algorithm, the number

of optimal paths is increased, and TSOPS is obtained. Then calculate the wagon-hour of each path in TSOPS. The minimum value is $\min F_2$, and the corresponding path is the global optimal access path. Finally, an example is given to verify the proposed optimization strategy. The results show that the improved strategies proposed in this paper are effective and can increase the number of optimal paths within a certain range. The innovation of this paper is as follows: First, two optimization objectives are proposed, and the globally optimal path calculated at last is more in line with the actual requirements. The second is to consider the priority level between operation locations, which is more in line with the principle of first send and first take in an emergency. Thirdly, combining the characteristics of STPW, the ant colony algorithm and the crossover strategy of genetic algorithm are improved. Fourth, the solution method in this paper has a wide range of applications, high computational efficiency, and is easy to use. The deficiency of this study is that the improved crossover strategy only considers the crossover between two operation locations on the same minimum common branch and does not consider the crossover between two branches on the same common branch connecting three or more operation locations. Further research will be carried out in the next step.

6 REFERENCES

- [1] Yuan, Z. Z., Yuan, X. J., Yang, Y. et al. (2023). Greenhouse Gas Emission Analysis and Measurement for Urban Rail Transit: A Review of Research Progress and Prospects. *Digital Transportation and Safety*, 1(1), 37-52. <https://doi.org/10.48130/DTS-2023-0004>
- [2] Guo, C. J. & Lei, D. Y. (2014). Model of Wagons' Placing-In and Taking-Out Problem in a Railway Station and Its Heuristic Algorithm. *Mathematical Problems in Engineering*, 1-8. <https://doi.org/10.1155/2014/493809>
- [3] Li, B., Qu, W. Y., Xuan, H., Xu, C. Q., Wang, X. Y., & Geng, Y. F. (2020). Shunting strategy for placing-in and taking-out wagons on branch-shaped freight operation network with simulation method. *Journal of Advanced Transportation*, (4), 1-25. <https://doi.org/10.1155/2020/3410481>
- [4] Qi, B. (2016). Placing-In and Taking-Out Method for Working Wagons Under the Random Environment. *International Conference on Electrical and Information Technologies for Rail Transportation*, 777-785. https://doi.org/10.1007/978-3-662-49370-0_81
- [5] Guo, C. J., Sun, X. Y., Chen, T. et al (2022). General Optimization Model and Algorithm for Placing-in and Taking-out Wagons in Mixed Freight Operation Sites. *China Railway Science*, 43(3), 164-172. <https://doi.org/10.3969/j.issn.1001-4632.2022.03.18>
- [6] Guo, C. J. (2020). Optimization model and algorithm for the placing-in and taking-out of wagons in railway stations with branch-shaped goods operating sites. *International Journal of Rail Transportation*, (2), 579-594. <https://doi.org/10.1080/23248378.2020.1823254>
- [7] Mu, F., Wang, C. G., & Mu, C. K. (2012). A method for generating solutions of the generic model for taking-out and placing-in wagons in railway station. *China Railway Science*, 33(5), 105-113. <https://doi.org/10.3969/j.issn.1001-4632.2012.05.16>
- [8] Mu, F., Wang, C. G., Zuo, D. J., & Zhang, Z. J. (2010). Model and algorithm for taking out and placing in wagons in shunting operation on radial private lines. *Journal of Southwest Jiaotong University*, 45(1), 104-110. <https://doi.org/10.3969/j.issn.0258-2724.2010.01.018>
- [9] Yang, Y., Tian, N., Wang, Y. P., & Yuan, Z. Z. (2022). A Parallel FP-Growth Mining Algorithm with Load Balancing Constraints for Traffic Crash Data. *International Journal of Computers Communications & Control*, 17(4), 4806. <https://doi.org/10.21203/rs.3.rs-1311180/v1>
- [10] Guo, C. J. (2017). Multi-objective optimization model and algorithm for scheme of placing-in and taking-out of wagons in branch-shaped freight operation sites. *China Railway Science*, 38(1), 138-143. <https://doi.org/10.3969/j.issn.1001-4632.2017.01.19>
- [11] Li, H. J., He, R. C., & Zhu, C. F. (2011). Genetic Algorithm for Railway Placing-In and Taking-Out of Wagons in Actinoid Private Line for Through Wagon Flow. *International Conference on Transportation Engineering*, 446-451. [https://doi.org/10.1061/41184\(419\)74](https://doi.org/10.1061/41184(419)74)
- [12] Li, B., Xu, G. L., & Xuan, H. (2022). Taking-out and Placing-in Shunting of Non-through Wagon Flow with Capacity Limited on Hybrid Siding. *Operations Research and Management Science*, 31(06), 9-16. <https://doi.org/10.12005/orms.2022.0176>
- [13] Yang, Y., Yang, B., Yuan, Z. Z. et al. (2023). Modeling and Comparing Two Modes of Sharing Parking Spots at Residential Area: Real-time and Fixed-time Allocation. *IET Intelligent Transport Systems*. <https://doi.org/10.1049/itr2.12343>
- [14] Holland, J. H. (1992). Genetic algorithms. *Scientific american*, 267(1), 66-73. <https://doi.org/10.1038/scientificamerican0792-66>
- [15] Dorigo, M., Maniezzo, V., & Colomi, A. (1996). Ant system: optimization by a colony of cooperating agents. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, 26(1), 29-41. <https://doi.org/10.1109/3477.484436>
- [16] Dorigo, M., Birattari, M., & Stutzle, T. (2006). Ant colony optimization. *IEEE computational intelligence magazine*, 1(4), 28-39. <https://doi.org/10.1109/MCI.2006.329691>

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