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A Novel Integrated Model of Train Rescheduling and Station Track Usage Planning Based on Harris Hawks Optimisation Algorithm

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ABSTRACT
Collaborative optimisation of train rescheduling plans and station track usage schemes has emerged as a popular research topic, which can avoid the risk of plan non-fulfilment due to conflicts between the two problems. This paper proposes an integrated model of train rescheduling and the station tracks usage planning, with the total delay time and changes in the station track usage plan as the optimisation objectives. The train tracking intervals, minimum running time in sections of the trains, minimum dwelling time and the track usage restriction, etc., are taken as the constraints of the model. Then, the Harris hawks optimisation algorithm is introduced and applied to find the solution of the model. The comparison of the computing results based on the classical particle swarm optimisation algorithm and the designed algorithm is carried out, and it is found that the total calculation time consumption decreases by 4.12%. The proposed method can provide decision support for daily train dispatching work.

KEYWORDS
train rescheduling; station tracks; usage planning; Harris hawks optimisation.

1. INTRODUCTION

There are two ways to enhance the transportation capacity of the railway system. One is to increase railway lines and improve the topological structure of the railway network. The other is to optimise the transportation organisation plans under the existing railway infrastructure, ensure the railway traffic order, and achieve the capacity improvement [1]. The organisation plans can be divided into four levels: the strategic, the tactical, the operational and the control level [2–4]. The strategic level is to decide the transportation pattern, which means the basic usage relationship between the trains and the railways. For example, whether the high-speed electric multiple units (EMU) can run on the normal-speed railway line should be studied before designing the train line plan. The tactical level is line planning, determining the number of trains, the origins and the destinations of the trains, the stop plan and so on. Certainly, the forecasted passenger flow and the capacity of the railway line should be provided in advance. The operational level includes some detailed organisation work, such as timetable design, train rescheduling, crew scheduling and multiple units scheduling [3]. Timetable and train rescheduling are the basic technical files to guide the operations of the trains, which can be seen as the constraints of crew scheduling and multiple units scheduling [4, 5]. The control level work is divided into two parts. One is the train routing and arrival-departure track assignment, and the other is to design a train traction scheme.

Generally, the transportation plan design of a railway transportation organisation follows the top-down sequence [6]. However, it will bring certain problems. That is, the solution to the upper-level planning problem may not have a corresponding solution to the lower-level problem.

The problem of train rescheduling arises when there is a need to adjust the operational plans and schedules of trains due to unforeseen events or disruptions in the transportation system [7]. This issue is a critical aspect of railway management, as it involves making real-time adjustments to ensure the efficient and safe movement of trains [8, 9]. It has been a hot topic for a long period of time, for a high-quality rescheduled timetable can not only ensure the railway safety [5, 6, 8], but also can improve the railway transportation efficiency [4–6, 9, 10]. Addressing the problem of train rescheduling requires advanced planning, efficient communication systems and the use of sophisticated scheduling algorithms. Modern railway management systems often incorporate real-time data [4], predictive analytics and optimisation techniques to quickly adapt to changing circumstances and ensure the smooth operation of train services. Effective rescheduling not only minimises disruptions but also enhances the overall reliability, safety and efficiency of the railway transportation network [1].

How to generate a highly executable train operation plan? A feasible approach is to formulate a practical plan for the utilisation of station arrival and departure tracks while generating the train schedule, so as to improve the feasibility of the train operation plan. This paper conducts research on this issue.

2. LITERATURE REVIEW

The train rescheduling problem has been a hot topic for a long period of time [1–28]. The departure time domain for passenger trains is a basis for the train rescheduling problem, and a genetic algorithm was proposed based on strategies of conflict detection in order to calculate an optimal arrival and departure time domain for the trains [2]. The key work for rescheduling is to decide the arrival and departure times of the trains at stations, while the novel reinforcement learning approach has been introduced to solve the problem [3]. Sometimes, real-time conflict should be paid attention to, and a fast and effective parallel algorithm is designed [4]. Chen et al. developed a draft passenger train timetable under the constrained capacities of arrival–departure tracks based on node importance [5]. Liao et al. presented a resource-oriented decomposition approach for the train timetabling problem [6]. A parallel algorithm for train rescheduling was also introduced, using a depth-first search strategy that quickly traverses the tree [7]. The train rescheduling problem was formulated as an integer linear programming (ILP) model on a space–time network to minimise the total passenger delay and the number of passengers that could not reach their destination [8]. Reference [9] took the passenger departure time and seat-class preferences into consideration when solving the train rescheduling problem. Reference [10] proposed a demand-driven model to minimise the passenger waiting time [10]. Considering the total travel time and travel cost of passengers, Yin et al. established an approximate dynamic programming model to solve the subway train rescheduling problem [11]. In recent years, scholars have gradually combined the problem of train rescheduling with other railway transportation organisation problems, deriving some integrated transportation organisation optimisation problems.

Some works of literature have conducted integrated research on the train rescheduling problem and passenger flow distribution. Zhu and Goverde designed a mixed integer programming model and redistributed passenger flows while solving the train rescheduling problem, integrating timetable rescheduling and the passenger reassignment problem. The model applied the dispatching measures of re-timing, re-ordering, cancelling, flexible stopping and flexible short-turning trains, handles rolling stock circulations at both short-turning and terminal stations of trains, and takes station capacity into account, and they designed an adapted fix-and-optimise (AFaO) algorithm to solve the model [12]. Hong et al. established a mixed linear programming model to solve the train rescheduling and passenger flow redistribution problem under emergency conditions. A bi-objective function was optimised by a weighted-sum method to maximise the number of disrupted passengers and to minimise the weighted total train delay for all non-cancelled trains at their destinations [13]. Zhan et al. also established an integer linear programming model based on the spatiotemporal network to solve the train rescheduling problem on the basis of considering the passenger redistribution problem, and the alternating direction method of multipliers (ADMM) algorithm was designed [14]. Wang et al. designed a rescheduling model to consider passenger waiting time fairness and train travel time cost, focusing on the timetable rescheduling problem by adopting a stop-skipping strategy during the off-peak period [15].

With the development of the technology of transportation organisation, a higher-quality organisation scheme is required to be proposed. Researchers have realised that it is necessary to study rescheduling and station track usage planning problems comprehensively. The essence of the problem is to determine the arrival-departure tracks utilisation plan when we do the train rescheduling work. The key is to prevent the failure to assign tracks for the trains after adjusting the train operation schedule.

There are currently two main methods for integrated optimisation of train scheduling and track usage planning problems. One is to establish mathematical models and then design various algorithms to solve the established models. There are mainly three kinds of mathematical models: integer programming models [16–18], mixed integer programming models [19–21] and spatio-temporal network models [22–24]. Ji and Meng designed a priority rule-based heuristic algorithm to generate feasible solutions [16]. Zhou and Teng used efficient train-based Lagrangian relaxation decomposition to solve the problem [17]. Xu et al. proposed a switchable scheduling rule to solve the problem in different train operation scenarios [18]. We also designed an artificial bee colony algorithm to solve the model [1]. Pellegrini et al. provided an instance in which they can represent all the facets of the projection of the convex hull of the problem in the subspace of the binary variables [19]. References [20] and [21] built mixed integer programming models and designed heuristic algorithms that consistently offer high-quality approximate solutions. Zhang et al. modelled the underlying problems using a space–time network on a mesoscopic level and proposed a 0–1 binary integer programming model that can simultaneously modify the timings and routes of trains from different directions [22]. Xu and Dessouky formulated the considered problem as a minimum-cost multi-commodity network flow model with incompatible arc sets and operational constraints [23]. Wang and Li introduced and formulated a space–time model considering three interlocking modes and subsequentially conducted numerical experiments to analyse the optimality differences under each mode [24]. In terms of solution methods, although some scholars directly used commercial solvers such as Gurobi to solve the models based on the fact that the established models were linear models [16], most researchers designed heuristic algorithms to solve the problem based on its high complexity [25]. Sun, Cao and Wu introduced energy consumption as the objective and designed a genetic algorithm for solving [26]. Samà et al. designed a neighbourhood search algorithm to solve this problem [27].

The other method is simulation. That is, to establish a simulation model for the integrated optimisation of train scheduling and routing, taking the trains as the simulation object, and the network formed by the railway section, station tracks and switches as the simulation environment, to realise the simulation of train operation, and finally achieve the purpose of optimising the train operation plan and the usage plan of the arrival and departure tracks [28].

The main purpose of this article is to apply the Harris hawks optimisation algorithm to the solution of the train rescheduling and station track usage planning model, and to find an efficient and feasible solution algorithm for the problem. At present, there is no reported research on the application of the Harris hawks optimisation algorithm to this problem. This is an innovative point of this article and also a difference from other pieces of literature.

The above publications provide valuable references for our current research. This study focuses on the integrated optimisation of the train rescheduling and rerouting problem. The rest of the paper is structured as follows. Section 2 builds the integrated model of the train rescheduling and rerouting problem. Section 3 develops the methodology. Section 4 verifies the validity of the constructed model by a computing case based on the real operation data and discusses the calculation results. Section 6 summarises the content, contributions and future work of this study.

3. METHODOLOGY

3.1 Integrated model of train rescheduling and station track usage planning

Decision variables and parameters

Table 1 – Decision variables of the model

Decision variable	Meaning
a_{ij}	Arrival time of train i at station j
d_{ij}	Departure time of train i at station j
$x_{i,j}^{l}$	Whether train i at station j occupies track l. If yes, it is 1, else it is 0.

The purpose of the model is to determine the inbound and outbound times of the trains at stations and the track assignment plan, which determines which train will occupy which track at a station. The decision variables are the arrival time a_{ij}, the departure time d_{ij} and the occupying sign $x^{l}_{i,j}$. *N* is the number of trains related in the model and *M* is the number of stations. The decision variables are shown in *Table 1*.

The symbols and their meaning in the model are shown in *Table 2.*

Table 2 – Symbols and their meaning in the model

Symbols	Meaning	Symbols	Meaning
N	Number of trains in the model	I_d	The minimum departure interval in the normal situation
M	Number of stations in the model	$t^{\min,\text{dwell}}_{i,j}$	The minimum dwelling time of train *i* at station *k* in the normal situation
Z_1	Total delay time of all trains (optimisation goal)	$t^{\min,\text{run}}_{i,j}$	The minimum running time of train *i* between station *i* and station *j*
Z_2	Penalty for track usage plan change (optimisation goal)	τ_{d-a}	The minimum time between the departure of the preceding train and the arrival of the following train
$a^{0}_{i,k}$	The planned arrival time of train *i* at station *k*	L^{j}	Number of siding tracks in one direction of the station *j*
$d^{0}_{i,k}$	The planned departure time of train *i* from station *k*	ϑ	Parameters for calculating the penalty for the track usage plan change
I_a	The minimum arrival interval in the normal situation	$x^{l,0}_{i,k}$	The track occupancy 0-1 variable in the original operation plan

Optimisation objective of the model

We still take the total delay time as the first optimisation goal in this paper. The total delay time includes the delayed arrival and the departure time of each train at all the stations. Thus, the goal can be described as follows.

$$MinZ_1 = \sum_{i=1}^{N}\sum_{j=1}^{M}[(a_{i,j} - a^{0}_{i,j}) + (d_{i,j} - d^{0}_{i,j})] \tag{1}$$

We hope that the track usage scheme can be kept as consistent as possible with the original plan to maximise the maintenance of the original operation order and state of the trains. So we design an optimisation goal as the penalty for the track usage change.

$$MinZ_2 = \vartheta\sum_{i=1}^{N}\sum_{k=1}^{M}\sum_{l=1}^{L^{k}}\left|x^{l}_{i,k} - x^{l,0}_{i,k}\right| \tag{2}$$

It can ensure that the penalty value is 0 if the usage plan is not changed. It will get a penalty when it is changed, which can be described that $\left|x^{l}_{i,k} - x^{l,0}_{i,k}\right| = 1$, and it will be enlarged by the parameter ϑ. So the optimisation goal should be:

$$Z = Z_1 + Z_2 = \sum_{i=1}^{N}\sum_{j=1}^{M}[(a_{i,j} - a^{0}_{i,j}) + (d_{i,j} - d^{0}_{i,j})] + \vartheta\sum_{i=1}^{N}\sum_{k=1}^{M}\sum_{l=1}^{L^{k}}\left|x^{l}_{i,k} - x^{l,0}_{i,k}\right| \tag{3}$$

Constraints for train rescheduling

There are numerous prerequisite rules in railway operation designed to ensure safety and determined by facilities such as the blocking systems. The most important rule is to determine the relationships between the inbound and outbound times of all the trains, to separate the trains in space. The system constraints are therefore designed as follows.

The difference between a front train's arriving time and a back train's arriving time at the same stations must be longer than the technical intervals, which produces the constraint.

$$\left|a_{i+1,j} - a_{i,j}\right| \geq I_a,\ i = 1,2,...,N-1; j = 1,2,...,M \tag{4}$$

Likewise, the difference between a backwards train's departing time and a forward train's departing time from the same stations must be longer than the technical intervals. The constraint can be described as:

$$\left|d_{i+1,j} - d_{i,j}\right| \geq I_d,\ i = 1,2,...,N-1;\ j = 1,2,...,M \tag{5}$$

The operation rule must satisfy the departure-arrival interval and the arrival-departure interval. Setting τ_{d-a} to be the minimum time interval between a forward train departure from a station and a backwards train arrival at the same station, then the constraints are defined in *Equation 3*.

$$a_{i+1,k} - d_{i,k} > \tau_{d-a},\ i = 1,2,...,N-1;\ j = 1,2,...,M \tag{6}$$

Similarly, setting τ_{a-d} to be the minimum time interval between a forward train arrival at a station and a backwards train departure from the same station, then the constraints are defined in *Equation 4*.

$$d_{i+1,k} - a_{i,k} > \tau_{a-d,} i = 1,2,...,N-1;\ j = 1,2,...,M \tag{7}$$

The running time of each train according to the rescheduled timetable must be longer than the minimum running time, which can be formulated as follows.

$$a_{i,j+1} - d_{i,j} \geq t_{i,j}^{\min,\text{run}},\ i = 1,2,...,N,\ j = 1,2,...,M \tag{8}$$

where $t_{i,j}^{\min,\text{run}}$ is the minimum time of train i on the section between station j and j'.

Again, the dwelling time of each train must be longer than the minimum dwelling time, which produces the constraint below.

$$d_{i,j} - a_{i,j} \geq t_{i,j}^{\min,\text{dwell}},\ i = 1,2,...,N,\ k = 1,2,...,M \tag{9}$$

where $t_{i,j}^{\min,\text{dwell}}$ is the minimum dwelling time of train i at station j.

The passenger trains must not leave the stations before the time planned on the timetable, which is made available to the public, so there is a constraint as follows.

$$d_{i,j} - d_{i,j}^0 \geq 0,\ i = 1,2,...,N,\ k = 1,2,...,M \tag{10}$$

3.2 Harris hawks optimisation algorithm

Harris hawks optimisation

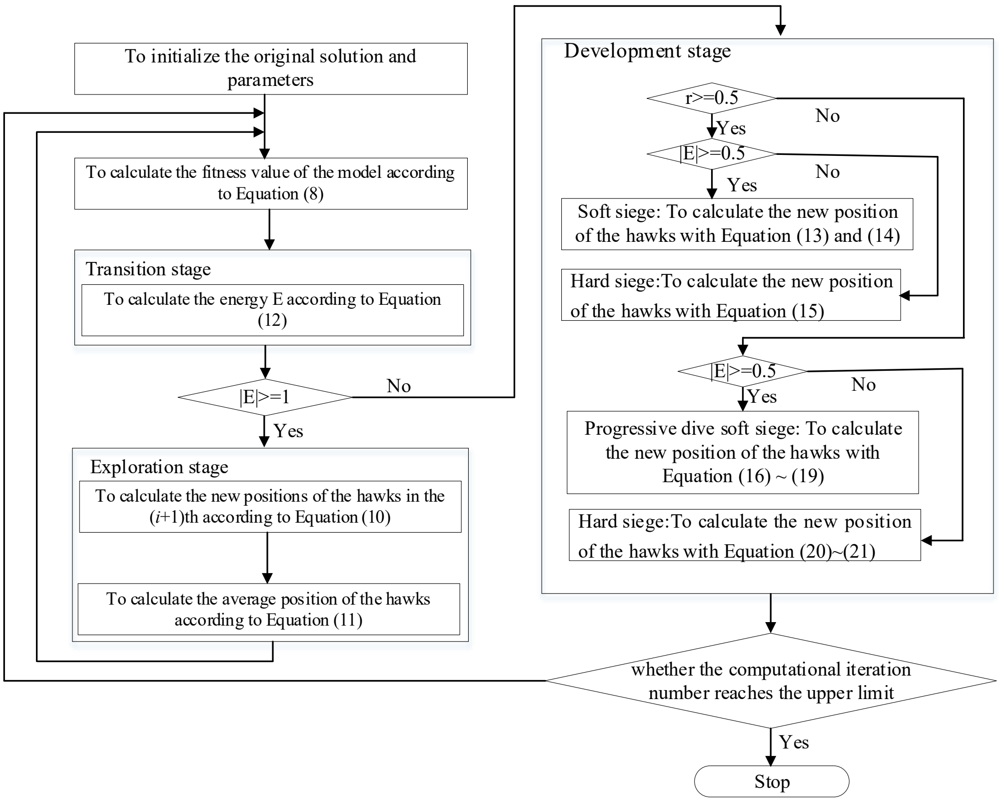

Figure 1 – Flowcharts of the HHO algorithm

The Harris hawks optimisation (HHO) is a novel population-based, nature-inspired optimisation paradigm [29]. The main inspiration for HHO comes from the cooperative behaviour and chasing manner of Harris's hawks in nature, which is termed the *sudden strike*. In this intelligent strategy, several hawks cooperate to pounce on the prey from different directions and try to catch it successfully. The Harris hawks can reveal various chasing patterns based on the dynamicity of the scene and the escape mode of the prey. The optimisation algorithm is developed by mathematically modelling this dynamic pattern and behaviour. The HHO algorithm is a popular population-based gradient-free optimisation algorithm. The algorithm is composed of three stages.

1) Exploration stage;
2) The transition from the exploration stage to the development stage;
3) Development stage.

The whole calculation process is shown in *Figure 1*.

In the algorithm flowchart shown in *Figure 1*, *E* is the escape energy of the prey that is used to determine the exploration and exploitation phases of the algorithm. *r* is a random number, which is used to determine the way in which eagles are besieged in the algorithm.

Pseudo-code of HHO algorithm

Inputs: The population size N and maximum number of iterations T

Outputs: The location of the rabbit and its fitness value

Initialise the random population $X_i (i=1,2,...,N)$

while (the stopping condition is not met) **do**

  Calculate the fitness values of hawks

  Set X_{rabbit} as the location of the rabbit (best location)

  for (each hawk (X_i)) **do**

  Update the initial energy E_0 and jump strength J

  $// \; E_0 = 2rand() - 1, J = 2(1 - rand())$

  Update the E using *Equation 14*

  if ($|E| \geq 1$) **then**

   Update the location vector using *Equation 12*//Exploration stage

  if ($|E| < 1$)) **then**

   if ($r \geq 0.5$ and $|E| \geq 0.5$) **then**

    Update the location vector using *Equation 15* and *Equation 16*// Soft siege

   else if ($r \geq 0.5$ and $|E| < 0.5$) **then**

    Update the location vector using *Equation 17*//Hard siege

   else if ($r < 0.5$ and $|E| \geq 0.5$) **then**

    Update the location vector using *Equations 18 – 21*

    //Progressive dive soft siege

  else if ($r < 0.5$ and $|E| < 0.5$) **then**

   Update the location vector using *Equations 22 – 24*

   //Progressive rapid dive hard siege

Return X_{rabbit}

Harris hawks optimisation for the train rescheduling problem

The HHO algorithm for the train rescheduling problem is as follows.

Step 1: To initiate all the original solutions and parameters of the model;

1) To set all of the parameters in *Table 2*;
2) Set the population size and the maximum number of iterations for calculation;
3) To generate the original solution vectors, assigning values to a_{ij}, d_{ij} and $x^l_{i,j}$ (The calculation of the number of the decision variables is shown in Section "Scenario assumption and initial solution coding");

Step 2: To calculate the fitness value of the model according to *Equation 10*;

Step 3: To calculate the Energy E according to *Equation 14*;
Step 4: To judge the value of $|E|$, if $|E| \geq 1$ then go to Step 5, else go to Step 7;
Step 5: To calculate the new positions of the hawks in the (i+1)-th according to *Equation 12*;
Step 6: To calculate the average position of the hawks according to *Equation 13*, go to Step 2;
Step 7: To judge the value of r, if $r \geq 0.05$, go to Step 8; else go to Step 9;
Step 8: To judge the value of $|E|$, if $|E| \geq 0.5$ then calculate the new position of the hawks with *Equations (15) and (16)*; else hard siege: to calculate the new position of the hawks with *Equation 17*; go to Step 10;
Step 9: To judge the value of $|E|$, if $|E| \geq 0.5$ then calculate the new position of the hawks with *Equation (18) ~ (19)*; else calculate the new position of the hawks with *Equation 22 − Equation 24*; go to Step 10;
Step 10: To judge whether the computational iteration number reaches the upper limit; if yes, stop the calculation, go to Step 11; else, go to Step 2;
Step 11: To transfer the solution vector to a new rescheduled timetable and a station track usage plan.

4. CASE STUDY

4.1 Basic operation data

Table 3 – Number of tracks of each station

Station	Number of side tracks in the west-going direction	Number of side tracks in the east-going direction
Xianyang West	3	3
Yangling South	2	2
Qishan	2	2
Baoji South	6	6
Dongcha	1	1
Tianshui South	2	2
Qin'an	1	1
Tongwei	1	1
Dingxi North	2	2
Yuzhong	1	1

Table 4 – The minimum running time of all the trains in each section ($t_{i,k}^{\min,\text{run}}$)

Sections	Minimum running time in the section
Lanzhou West-Yuzhong	11'17"
Yuzhong-Dingxi North	11'17"
Dingxi North- Tongwei	18'58"
Tongwei- Qin’an	13'27"
Qin’an- Tianshui South	9'36"
Tianshui South-Dongcha	15'36"
Dongcha-Baoji South	16'5"
Baoji South-Qishan	6'21"
Qishan-Yangling South	7'2"
Yangling South-Xianyang West	10'7"
Xianyang West -Xian North	5'9"

**Note: dd.ee stands for dd minutes and ee seconds.*

In order to verify the correctness of the model and the high efficiency of the algorithm, we used the data of the real train operation diagram for experimental analysis. The data from 6:00 to 12:00 of the Lanzhou West to Xi'an North east-going train operation diagram are selected as the experimental data, as shown in *Figure 2*. There are 27 trains involved, except that D2736, G3178 and D2732 are all originating from Lanzhou West.

This section includes Xianyang West, Yangling South, Qishan, Baoji South, Dongcha, Tianshui South, Qin'an, Tongwei, Dingxi North and Yushu station. The number of side tracks in each station is shown in *Table 3*.

As we know, if a train does not stop at a station, it must use the main track. Otherwise, it must use the siding track. In *Figure 2*, a short horizontal line is used to indicate the start time, end time and duration of each train occupying the corresponding track. For trains that pass through the station without stopping, they will inevitably occupy the main track, so there is no special indication given in the figure. The minimum running time of all the trains in each section is listed in *Table 4*.

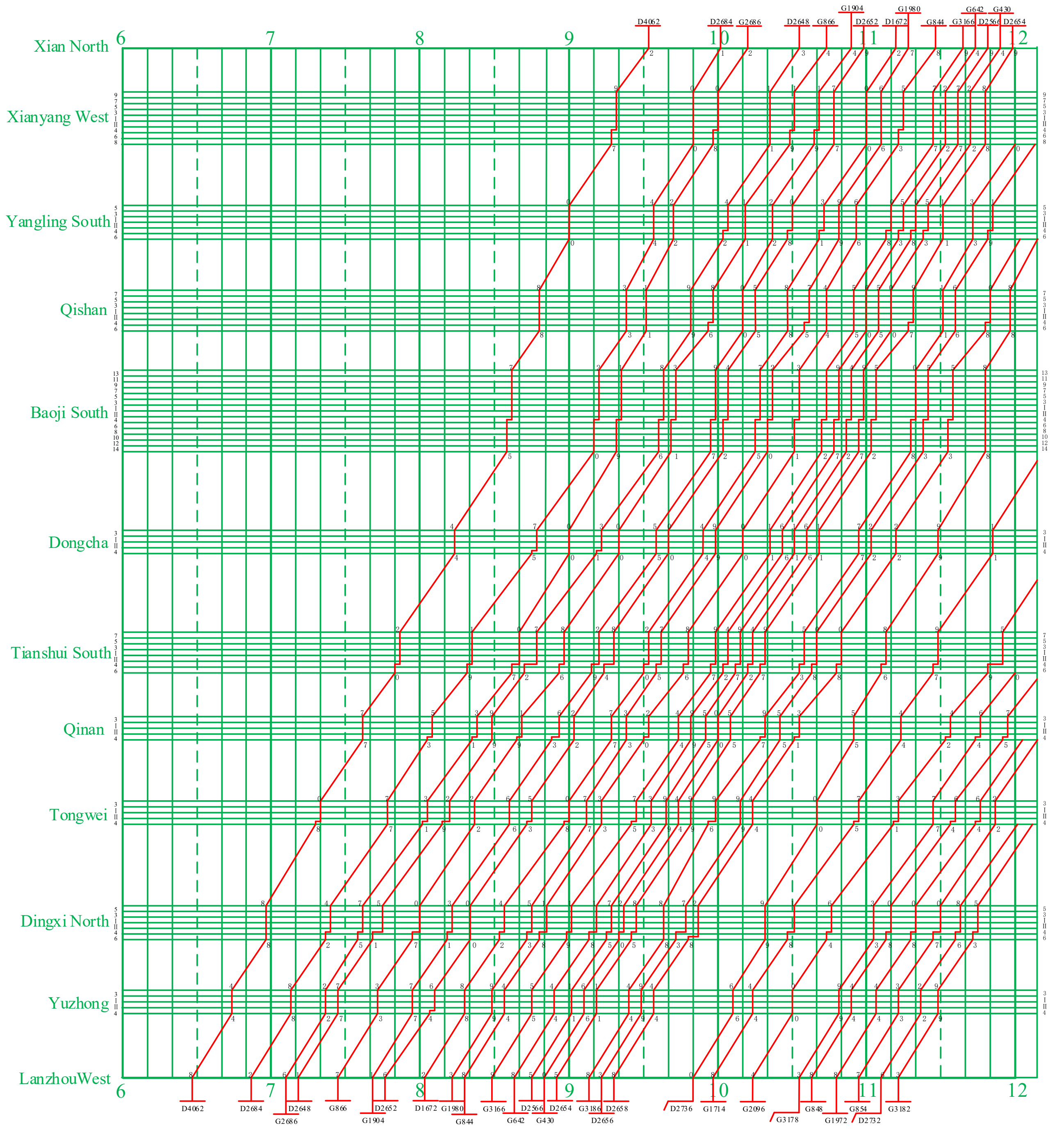

Figure 2 – Original operation chart from 6 to 12 a.m. in the section between Lanzhou West and Xi'an North in the east-going direction

The minimum stop time of the trains at each station is listed in *Table 5*.

Table 5 – The minimal dwelling time of all the trains at each station ($t_{i,k}^{\text{min,dwell}}$)

	D4062	D2684	D2686	D2648	G886	G1904	D2652	D1672	G1980	G844	G3166	G642	D2566	G430
Lanzhou West	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Yuzhong	0	0	0	0	0	0	2	0	0	0	0	0	0	0
Dingxi North	0	2	2	4	3	2	0	2	2	3	2	3	2	2
Tongwei	2	0	2	0	0	0	2	2	0	0	2	0	0	0
Qin'an	0	2	2	0	2	3	0	0	0	2	0	0	0	0
Tianshui South	2	2	3	5	2	3	3	2	2	2	2	2	2	2
Dongcha	0	2	0	2	0	0	0	0	0	0	0	0	0	0
Baoji South	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Qishan	0	0	0	0	2	0	0	0	2	0	0	0	0	0
Yangling South	0	0	0	2	0	0	2	2	0	0	2	2	2	2
Xianyang West	2	0	2	0	2	2	0	0	0	2	0	0	0	0
Xian North	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	D2654	**G3186**	**D2656**	**D2658**	**D2736**	**G1714**	**G2096**	**G3178**	**G848**	**G1972**	**G854**	**D2732**	**G3182**	
Lanzhou West	-	-	-	-	-	-	-	-	-	-	-	-	-	
Yuzhong	0	0	0	0	0	0	0	0	0	0	0	0	0	
Dingxi North	2	0	4	4	0	2	2	2	2	2	3	2	2	
Tongwei	0	3	0	0	0	2	2	0	2	2	0	0	0	
Qin'an	0	2	0	2	0	0	2	2	2	0	2	0	2	
Tianshui South	2	2	2	2	2	2	6	3	3	3	3	4	3	
Dongcha	0	0	0	0	0	0	0	0	0	0	0	0	0	
Baoji South	2	2	2	2	0	2	3	3	2	2	2	2	3	
Qishan	2	0	0	2	0	0	0	0	0	2	0	0	2	
Yangling South	0	0	2	0	0	2	2	2	2	2	2	2	0	
Xianyang West	0	2	0	0	0	0	2	0	0	0	0	0	2	
Xian North	-	-	-	-	-	-	-	-	-	-	-	-	-	

4.2 Scenario assumption and initial solution coding

We set the scenario as follows. G2686 departs late from Lanzhou West by 20 minutes. G1904 departs late from Qin'an by 20 minutes. D1672 departs late from Lanzhou West by 21 minutes. D2654 departs late from Lanzhou West by 20 minutes. D2658 departs late from Lanzhou West by 27 minutes. D2736 departs late from Lanzhou West by 30 minutes. If we do nothing to eliminate the influence of these delays, the total delay time will be 2,876 minutes.

We can see that not all trains can reach Xi'an North Station in the time range we study. Therefore, it is necessary to first calculate the number of decision variables in the initial solution. D4062, D2684, G2686, D2648, G886, G1904, D2652, D1672, G1980, G844, G3166, G642, D2566, G430 and D2654 can reach Xi'an North Station, so the number of the decision variables, which are the departure and arrival time of the trains at the stations, is $15\times2\times11=330$, since there are 12 stations, while there is only the departure time Lanzhou West and there is only the arrival time at Xi'an North. By the same calculation method, G3186 and D2656 need $2\times2\times10=40$ variables. G2658 and D2736 need $2\times2\times9=36$ variables. G1714 needs $1\times2\times6.5=13$ variables. G2096 and G3178 need $2\times2\times5.5=22$ variables. G848 needs $1\times2\times4.5=9$ variables. G1972 and G854 need $2\times2\times4=16$ variables. G2732 and G3182 need $2\times2\times3=12$ variables. Therefore, $330+40+36+13+22+9+16+12=478$ variables are needed to describe the arrival and departure times of all the related trains at the stations. In addition, we design 235 0-1 variables to describe the track usage plan. As shown in *Table 6*, we first count the number of trains stopping at the station.

Then we check how many sidetracks are available in each station. If there is only one choice in a station, it is not necessary to design a variable. If there are x choices in a station and there are y trains which stop at this station, the number of variables to describe the track usage plan in a station is x*y. The main purpose of *Table 6* is to illustrate how many 0-1 variables there are in the model and how the quantity of these 0-1 variables is calculated. The 0-1 variables are used to represent whether a train stops at a station or not. Therefore, we first need to know how many trains stop at the station. The first column lists the number of trains that stop at the corresponding stations. Secondly, when a train stops at a certain station, there may be several siding lines available for selection. So the second column of the table gives the number of available siding lines at the corresponding stations. Finally, by multiplying the values in the first column and the second column, we calculate the values in the third column, that is, the total number of 0-1 variables describing the train stopping situations at the stations.

Then we sum up the variables of each station to get the total number of 0-1 variables. It is 235. The parameter of penalty is set to be 10.

Table 6 – Number of 0-1 variables to describe the track usage plan

Station	Number of trains stopping at the station	Number of sidetracks available	Number of 0-1 variables
Lanzhou West	-	-	-
Yuzhong	1	1	1
Dingxi North	23	2	46
Tongwei	10	1	10
Qin’an	10	1	10
Tianshui South	21	2	42
Dongcha	2	1	2
Baoji South	18	6	108
Qishan	4	2	8
Yangling South	8	2	16
Xianyang West	5	3	15
Xian North	-	-	-

We took *Formula (3)* as the fitness function. The coding method is as follows. We take the difference between the arrival (or departure) time and 6:00 and get the number of minutes between 6:00 and the arrival (or departure) time, which is taken as a component of the solution vector. So there are 478 components in this solution vector. Then the initialisation of the original solution is to generate a vector which has 478 components and meets the railway traffic rules.

The hardware conditions for this data experiment are: CPU i5-7500, 8GB memory with a frequency of 2,133MHz. The software used is Matlab2018a. Set the population size to be 40 and set the upper limit of the number of iterations to be 300.

4.3 Calculation results and analysis

As can be seen from *Figure 3*, the fitness function value tends to be stable when the iterative calculation is carried out about 100 times with the Harris hawks optimisation algorithm. Its fitness function value is reduced from 2,886 to 1,348.4, and the total delay time is reduced from 2,876 minutes to 1,338.4 minutes.

In order to analyse the computational efficiency of the Harris hawks algorithm, we also used the basic particle swarm optimisation algorithm for calculation. We can also get the optimal solution with the particle swarm optimisation algorithm. The number of iterations is about 120 when the fitness function value reaches a stable state with the particle swarm optimisation algorithm. Therefore, in terms of the number of iterations, the number of iterative calculations required by the Harris hawks algorithm is less than that of the particle swarm optimisation algorithm.

From the perspective of total calculation time, the Harris hawks algorithm cost 1,251.8 seconds when it carried out iterations of calculation to get the optimal solution, and the average time for each iterative calculation is 12.52 seconds. The particle swarm optimisation algorithm cost 1,305.6 seconds when getting the optimal solution, and the average time for each iterative calculation is 10.88 seconds. It can be seen that in each iterative calculation, the Harris hawks algorithm consumes more time than the particle swarm optimisation algorithm. However, since the Harris hawks algorithm achieves more improvement in each iteration, the total number of iterations required is smaller and the total consumption time is less. The total time consumed by the Harris hawks algorithm is reduced by 53.8 seconds compared to the particle swarm optimisation algorithm, with a reduction of 4.12%.

We can see that the trains resumed a good operation order after rescheduling work in *Figure 4* and *Table 7*. *Table 7* is the rescheduled timetable from 6 to 12 a.m. in the section between Lanzhou West and Xi'an North in the east-going direction. In the table, the italicised times indicate the adjusted arrival and departure times of trains at stations as compared with the original timetable. If the arrival and departure times of a train at a station are the same, it means that the train does not stop at that station. The times in regular font indicate the times that have not been changed as compared with the original timetable. G2686 resumed running according to the planned operation chart at Qishan. G1904 and D1672 resumed the status at Xianyang West. D2654 and D2658 resumed the status at Baoji South. D2763 reduced some of the delay time after a period of rescheduling. However, it has not resumed running according to the planned schedule until 12 o’clock, which is the boundary of the research range.

Some other trains were delayed under the influence of the originally delayed trains, which meant that train delay propagation occurred. In order to enable D2686 to overtake it smoothly, D2648 gave way at Tianshui South and was delayed to depart from Tianshui South Station at 8:55. It resumed running according to the planned schedule at Dongcha. Affected by G2686, G886 was 4 minutes late when departing from Lanzhou West. However, the transmitted delay time was eliminated at Yuzhong due to the relatively short delay time. D2652 was disturbed during its operation from Qishan to Yangling South. In order to avoid a tracking interval conflict with the following train G1904 when arriving at Yangling South, it arrived at Yangling South 5 minutes earlier. After giving way to G1904, it departed from Yangling South with a delay and resumed running according to the planned schedule at Xianyang West. Similarly, G1980 arrived at Qishan 2 minutes earlier to avoid a conflict with the following D1672. The track used was changed from Track 4 to Track 6. It departed from Qishan with a 6-minute delay and resumed running according to the planned schedule at Xianyang West. The same situation occurred with G844, G3186 and G2096. This method was also used on them for rescheduling. D2656 departed from Lanzhou West with a 5-minute delay and resumed running according to the planned schedule at Tianshui South.

It is easy to see that only G1980 changed from Track 4 to Track 6 at Qishan. For all other track usage schemes, they are consistent with the original scheme. It is because we design the track usage penalty as one of the optimisation objectives.

Table 7 – The rescheduled timetable from 6 to 12 a.m. in the section between Lanzhou West and Xi'an North in the east-going direction

	G2686		**D2648**		**G866**		**G1904**		**D2652**		**D1672**		**G1980**	
	Arrive	**Depart**	**Arrive**	**Depart**	**Arrive**	**Depart**	**Arrive**	**Depart**	**Arrive**	**Depart**	**Arrive**	**Depart**	**Arrive**	**Depart**
Lanzhou West	——	*7:26:00*	——	7:11	——	7:27	——	7:41	——	7:46	——	*8:23:00*	——	8:13
Yuzhong	*7:37:17*	*7:37:17*	7:27	7:27	7:43	7:43	7:57	7:57	8:04	8:06	*8:39:00*	*8:39:00*	8:29	8:29
Dingxi North	*7:48:34*	*7:50:34*	7:41	7:45	7:57	8:00	8:11	8:13	8:20	8:20	*8:53:00*	*8:56:00*	8:43	8:45
Tongwei	*8:14:00*	*8:17:00*	8:09	8:12	8:22	8:22	8:36	8:36	8:43	8:45	*9:08:00*	*9:20:00*	9:07	9:07
Qin'an	*8:34:00*	*8:36:00*	8:29	8:29	8:39	8:41	8:53	*9:16:00*	9:02	9:02	*9:33:00*	*9:33:00*	9:23	9:23
Tianshui South	*8:47:00*	*8:50:00*	8:42	*8:55:00*	8:56	*9:00:00*	*9:25:36*	*9:28:36*	9:15	9:18	*9:42:36*	*9:44:36*	9:35	9:37
Dongcha	*9:05:36*	*9:05:36*	9:11	9:13	9:20	9:20	*9:45:00*	*9:45:00*	9:40	9:40	*10:04:00*	*10:04:00*	9:59	9:59
Baoji South	*9:21:41*	*9:23:41*	9:36	9:38	9:41	9:43	*10:07:00*	*10:09:00*	10:02	10:04	*10:25:00*	*10:27:00*	10:20	10:22
Qishan	*9:31*	*9:31*	9:49	9:49	9:56	9:58	*10:20:00*	*10:20:00*	10:15	10:15	*10:38:00*	*10:38:00*	*10:33:00*	*10:43:00*
Yangling South	*9:42*	*9:42*	10:02	10:04	10:11	10:11	*10:27:02*	*10:27:02*	*10:22:02*	*10:32:02*	*10:45:02*	*10:47:02*	*10:52:02*	*10:52:02*
Xianyang West	9:58	10:00	10:21	10:21	10:29	10:31	10:39	10:41	10:41	10:47	11:00	11:00	11:06	11:06
Xian North	10:12	10:20	10:33	——	10:44	10:50	10:54	11:00	10:59	——	11:12	11:18	11:17	11:21

	G844		**D2654**		**G3186**		**D2656**		**D2658**		**D2736**		**G2096**	
	Arrive	**Depart**	**Arrive**	**Depart**	**Arrive**	**Depart**	**Arrive**	**Depart**	**Arrive**	**Depart**	**Arrive**	**Depart**	**Arrive**	**Depart**
Lanzhou West	——	8:18	——	*9:15:00*	——	9:08	——	*9:20:00*	——	*9:45:00*	9:42	*10:20:00*	——	10:14
Yuzhong	8:34	8:34	*9:29:00*	*9:29:00*	9:24	9:24	*9:34:00*	*9:34:00*	*9:56:17*	*9:56:17*	*10:35:00*	*10:35:00*	10:30	10:30
Dingxi North	8:48	8:51	*9:43:00*	*9:45:00*	9:38	9:38	*9:48:00*	*9:52:00*	*10:07:34*	*10:11:34*	*10:46:17*	*10:46:17*	*10:41:17*	*10:51:17*
Tongwei	9:13	9:13	*10:04:00*	*10:04:00*	9:56	9:59	*10:10:58*	*10:10:58*	*10:30:32*	*10:30:32*	*11:05:15*	*11:05:15*	11:11	11:13
Qin'an	*9:28:00*	*9:38:00*	*10:17:27*	*10:17:27*	*10:12:27*	*10:22:27*	*10:27:27*	*10:27:27*	*10:43:59*	*10:45:59*	*11:19:00*	*11:19:00*	11:32	11:34
Tianshui South	*9:47:36*	*9:49:36*	*10:27:03*	*10:29:03*	10:33	10:35	10:38	10:40	*10:55:35*	*10:57:35*	*11:32:00*	*11:34:00*	11:49	11:55
Dongcha	10:10	10:10	*10:44:39*	*10:44:39*	10:57	10:57	11:02	11:02	*11:13:11*	*11:13:11*	*11:56:00*	*11:56:00*	-	-
Baoji South	10:31	10:33	11:02	11:04	11:18	11:20	11:23	11:25	11:33	11:35	11:48	11:48	-	-
Qishan	10:44	*10:48:00*	11:17	11:19	11:31	11:31	11:36	11:36	11:48	11:50	11:58	11:58	-	-
Yangling South	*10:57:02*	*10:57:02*	11:31	11:31	11:43	11:43	11:49	11:51	-	-	-	-	-	-
Xianyang West	11:13	11:15	11:48	11:48	-	-	-	-	-	-	-	-	-	-
Xian North	11:28	11:36	11:59	-	-	-	-	-	-	-	-	-	-	-

Note: The time in italics is the time after rescheduling. aa.bbcc stands for bb minutes cc seconds at aa o'clock.

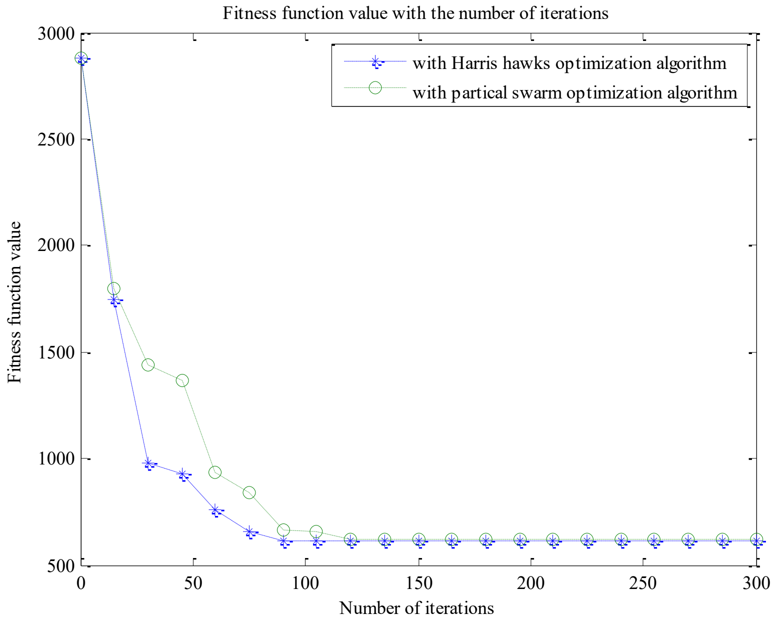

Figure 3 – Graph of fitness function value changes during the iterative calculation process

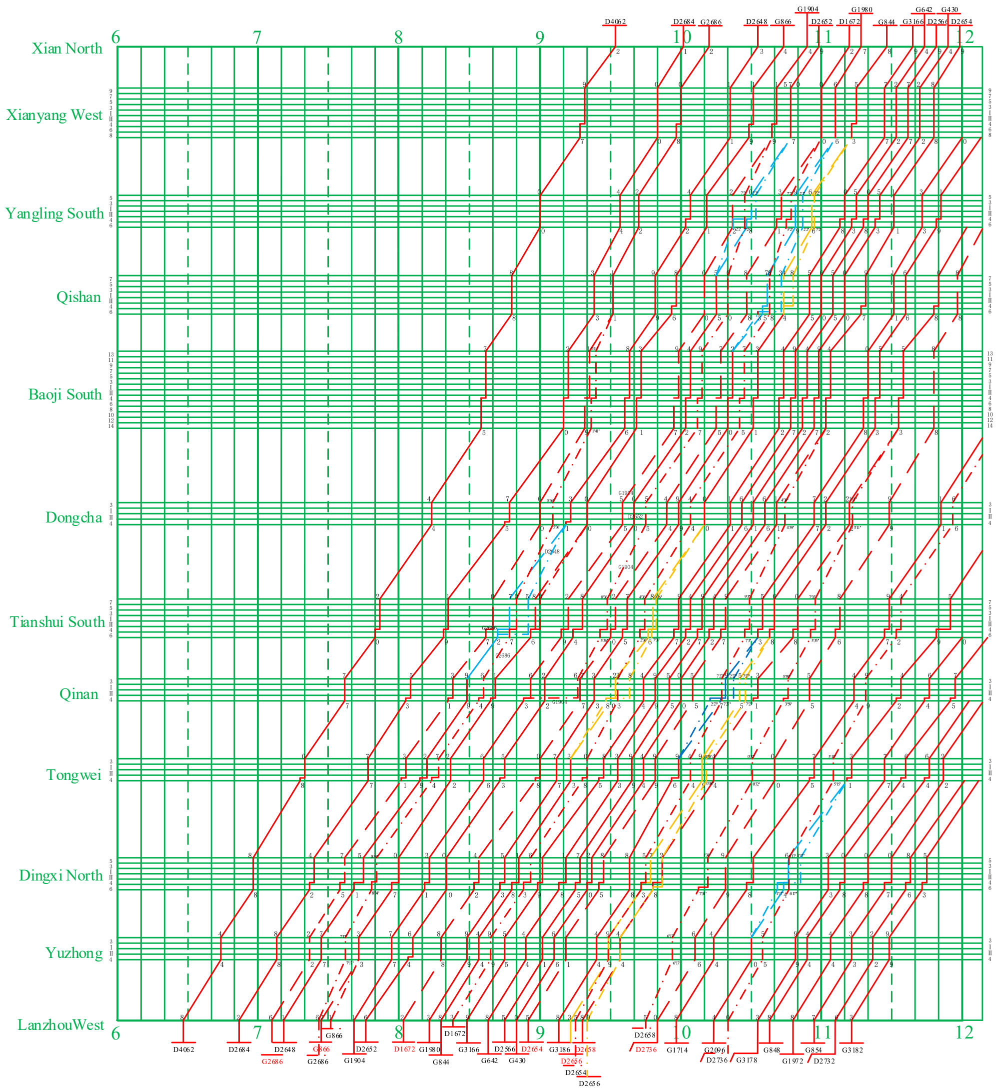

Figure 4 – Rescheduled operation chart from 6 to 12 a.m. in the section between Lanzhou West and Xi'an North in the east-going direction
Note: The dotted line in Figure 4 shows the rescheduled train running lines.

5. CONCLUSION

This paper proposes a novel method to solve the problems of train rescheduling and station track usage planning in an integrated way. The research achievements of this paper can be summarised into the following three points.

1) The integrated model constructed in this paper can describe the train rescheduling and station track usage planning.
2) The model designed meets the requirement of keeping the train operation order and state as much as possible, by adding the track usage plan change as an optimisation goal.
3) The Harris hawks optimisation algorithm is suitable for finding the solution of the model and the efficiency of the algorithm is proved by the data experiment, by comparing the used algorithm and the particle swarm optimisation algorithm. The total calculation time is reduced by 4.12%.

The most significant differences between this paper and other works of literature are as follows:

1) A new integrated design and optimisation model for train operation adjustment and arrival-departure track utilisation is established. Minimising the changes in the train arrival-departure track plan at stations is also set as an optimisation objective of the model, which maximises the executability of the train operation plan.
2) The Harris hawks algorithm is innovatively applied to the solution process of this problem. The effectiveness and high efficiency of this heuristic algorithm in train operation adjustment problems are verified, which has not been achieved in other works.

In the future, we will continue to improve the model by considering more actual conditions and constraints of on-site railway train dispatching work. We will study the efficiency and adaptability of the constantly emerging optimisation algorithms and apply them to the solution of this problem.

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