sciendo

DOI: 10.2478/rjti-2018-0003

ROMANIAN JOURNAL
OF TRANSPORT INFRASTRUCTURE

OPTIMIZATION OF THE SYNERGIES BETWEEN PREPARATION OF HIGH-SPEED RAILWAY TRAIN RUNNING DIAGRAM AND STATION ROUTE ALLOCATION PLAN

Alhossein Mohamed, PhD Scholar , School of Transportation and Logistics, Southwest Jiaotong University , Chengdu 610031, China, Email: mhmdhosentem@hotmail.com
Peng Qiyuan, Professor, School of Transportation and Logistics, Southwest Jiaotong University Chengdu, China, email: peng@swjtu.edu.cn
Malik Muneeb Abid, Assistant Professor, Department of Civil Engineering, Faculty of Engineering and Technology, International Islamic university, Islamabad, Pakistan. Email: muneeb.abid@iiu.edu.pk , malik.muneeb.abid@hotmail.com

Abstract

Introduction. Station route allocation plan is an important extension of the train running diagram and the both are closely intertwined so the overall research on the synergetic preparation method is more beneficial in improving the preparation quality of the train running diagram and providing better service for passengers. Therefore, the research topic has practical significance.
Methodology. Based on extensive literatures, this paper studies the synergetic preparation method of train running diagram and station route allocation plan in detail and analyses their association for providing a theoretical basis for the synergetic preparation method.
Results. This work introduces the synergetic, analyses the systematic characteristics of the operation organization system of high speed railway and puts forward the optimization strategy of train running diagram and station route allocation plan.
Conclusions. The work provides the solution for the preparation of the train running diagram and station route allocation plan by solving the examples based on the relevant optimization factors, such as train running in districts and train arrangement.

Keywords: High speed railway; train running diagram; station route allocation plan; synergetic

1. INTRODUCTION

In the railway transportation planning system, the train running diagram has an important position. It is a comprehensive guidance plan of train running organization work, which reflects the organization methods of railway transportation management and to a large extent, determines the work of railway transport service quality. The researchers in railway research domain are devoted with a lot of efforts in the research methods of train timetabling problems and accumulating the valuable experience. However, with the advancement of the development process of high speed railway in China, the preparation of the high-speed train running diagram came with a few special new issues, so it is necessary to do further research on the problem of high speed railway train running diagram in China.

Preparing the high-speed train running diagram in China faces two of the more prominent new problems: i) the previous method of preparing the high-speed train running diagram was for the train at each station, running time interval planning doesn't involve using the train’s path information in between stations, which resulted in a train operation plan without any feasible risk of using the station’s path. China has adopted the dominant mode of production scheduling of railway, when there aren't specific paths for trains in the station, management by using the method of dispatching can solve this problem, but in the high-speed railway operation conditions due to the frequent departure and arrival of trains at the stations, that will represent risk of specific paths for trains at the station. Moreover, the realization of high speed railway ‘according to running diagram” has an important significance, which requires modifying the train running diagram when there aren't specific paths for trains in the station; ii) During modification of the previous train running diagram; the researchers didn't consider the information of specific paths for trains in the station, where the train is using the different path inside the station, where the train should occupy the space and time in the previous railway system, so this kind of running diagram can’t satisfy the requirement of producing the high-speed train running diagram refinements. Through the analysis, the common point of these two problems is the use of the train’s station route information, which plays an important role in enhancing the quality of the preparation of the high speed train diagram. The purposes of this paper are:

- To arrange the train in the station according to the defined path for the station route plan,
- To improve the quality of the preparation of train diagram,
- Analysis of the interaction between the running diagram and the station train route planning, preparation of collaborative optimization train diagram and station operation of the train route plan,

- Optimization of the driving system for high speed railway train to occupy the path on the station according to fixed time scheduling,
- To ensure the rationality of the train diagram and finally realize the efficient allocation of resources of the railway system.

The paper is organized as follows: section 2 presents the literature review of studied research about train running diagram and station paths plan and synergetic the preparation method of train running diagram and station paths plan. Section 3 is studying the basic model for synergetic preparation of the train running diagram and the station route allocation plan**.** Section 4 discusses the optimization model based on the macroscopic networked structure, the train running diagram meets train operation needs of the train operation scheme, and its number of operation train is larger than that which is specified in the train operation scheme. Section 5 presents a prototype system for the synergetic preparation of the train running diagram and station route allocation plan of high-speed railway by using a Multi-Agent technology and based on above theoretical framework and model-based algorithm. Section 6 the calculation and analysis of the data.

2. STUDY ON STATUS QUO OF SYNERGIES BETWEEN THE PREPARATION METHOD OF TRAIN RUNNING DIAGRAM AND STATION PATHS PLAN

Researchers have conducted a lot of researches on the train running diagram and Station Paths Plan and have obtained fruitful theoretical achievements. However, the studies on the synergetic theories of both are comparatively scarce. The paper analyses the main research achievements, which include the following aspects.

2.1 Train running diagram

The studies on the preparation of the train running diagram in other nations are mainly based on the traditional mathematical optimization method represented by operational research, in which the optimized objective functions for the problems are typically set as the multi-objective functions with the shortest total running time or the minimum delay time of trains or the equivalent. Moreover, the problems may be solved with a discrete time axis, integer programming and other methods. The solution to the problems mainly focuses on solving the passing and crossing locations or running sequences of trains. And the solutions fall into accurate algorithm and approximation algorithm based on the accuracy of the results. The accurate algorithm includes both an explicit enumeration method and a branch-bound algorithm with definite integral; while the approximation algorithm includes branch-bound algorithm without definite integral, heuristic algorithm and Lagrangian relaxation algorithm.

Researcher Szpigel first proposed the "optimal train running diagram”, established a mixed integer programming model based on job shop scheduling theory for passing and crossing locations and obtained the optimal locations in the train running diagram with the branch-bound algorithm [1]. Frank believed that the passing and crossing locations and related running sequences were the key issues for preparing the running diagram, so he analysed and researched the attributes of passing and crossing locations and solved the preparation problem with the mixed integer programming method [2]. In addition, Petersen, Taylor and Rivier et al. also held such views, conducted in-depth studies on passing and crossing locations and obtained the solutions [3-7].

However, Jovanovie, Carey, Higgins and Zhou et al. believed that the running sequence of trains in each section was crucial to the preparation of the train running diagram, so they set the running sequence of trains at each station as a group of integer variables, expressed the arrival and departure time of trains related to the running sequence with a group of continuous variables and established the integer optimized model through relevant constraints on train running diagram, so that they successfully converted the train running diagram problem into the integer programming problem[8-12].

Besides, a periodic operation organization method was widely used in many western European countries as well as Japan. The periodicity meant that the types, quantities and running sequences of the trains in a same section within each cycle are almost the same, forming a relatively fixed running mode. In this context, by applying the solutions to “periodic event scheduling problem (PESP)” proposed by Serafini [21], Odijk has established a solving model for train running diagram with a periodic time window and solved the periodic train running diagram problem with the cutting plane method [22-23]. Goverde, Lindner and Liebchen et al. have also studied the periodic train running diagram problem [24-30].

In China, the railway has been exposed to a mixed flow of passenger and freight in a long term, so the preparation background for train running diagram is significantly different from that in other nations. In the study on the existing railways, it is more practical and significant to obtain the efficient solution rather than the optimal solution. Therefore, researchers in China have done many researches on specific and actual application problems, with typical application algorithms including hierarchical overlay, time-space rolling, timing-cycle iterative and network hierarchy parallel computing algorithms. For example, the “hierarchical local rolling optimization algorithm” proposed by Zhou Leishan was mainly to use the discrete event dynamic system to establish the transition equation for train running state and Zhou proposed a double-layer representation method for railway network and a representation method for train time sequence. For the train running diagram with multiple running routes in railway network, the network hierarchy parallel computing algorithm was used for solving the running diagram problem by arranging the points in a unified way and based on priority hierarchy. On this basis, the finite time domain local rolling optimization algorithm was used for adjusting and optimizing the running diagram according to the adjustment demands for receiving-departure time, receiving-departure track application and locomotive application [31]; Pen Qiyuan tried to use a local rolling progressive optimization method to solve the running diagram problem [32-35]. Then he improved said method and proposed a new “space-time local rolling optimization algorithm”. According to the new method, a multi-objective optimization model is established based on the objectives of the shortest total running time, the minimum linkage time at stations and the minimum total quantity of locomotives, and the problem of train running diagram is solved through iteratively solving the local train running diagram problem with applicable time-space local rolling strategy [36]. Shi Feng designed a “timing-cycle iterative optimization method” to solve the earliest running conflict rules by decomposing time domains and setting them on each time phase. According to the rules, the time cycle solution was performed to finally obtain the optimal solution of running diagram [37-40]. Sun Yan analyzed the combined characteristics of the running diagram and proposed a mathematical modeling and solution method with many theories such as stochastic programming, network planning and combination optimization [41-44].

2.2 Station Paths Plan

The Station Paths Plan mainly relates to the station route allocation and application of receiving-departure tracks in a station. Various researchers in other nations have studied the allocation of receiving-departure tracks in depth, among them were Carey, Cardillo, Zwaneveld et al. [31-34] They considered the running process of a train in a station as three independent stages, viz. the train arrives at a station, the train occupies the receiving-departure track, and the train departs from the station. The operation process of each station shall be considered specifically. The work in the three stages forms part of station operation plan, however, only partial work is specific for trains, that is, arrangement on receiving-departure tracks for trains in the station. Zwaneveld [34] introduced the achievement on the application methods of receiving-departure tracks in major stations in the Netherlands during his days. Carey [31] proposed a method for determining the station route for a train under the premise of flexible arriving and departure time, where the occupancy of any receiving-departure track means the allocated station route for the train. Then the conflicts and corresponding weight loss that may be generated during the allocation of receiving-departure track were discussed on such basis, and a related heuristic algorithm was designed to solve the problem of station route allocation for trains. Carey's method was justified to be practicable through the practical tests on the railways in Leeds. Other scholars had studied the application of receiving-departure tracks with coloring theory of graph. Among them, Cardillo put forward that, supposing the receiving-departure time of a train was fixed in a station, and the selection of route was only relevant to station allocation, the incompatible receiving-departure tracks could thus be identified, and a list of incompatible receiving-departure tracks for trains could be generated. The elements in the list are denoted by (j, a, k, b), which means that train j cannot occupy station a, meanwhile train k cannot occupy station b. Then a graph coloring theory model with incremental constraint can be set up, and heuristic algorithm can be designed to solve such a problem. Based on the same hypothesis, Billionnet [33] proposed to describe the station route allocation for the trains through graph coloring theory, and he developed a corresponding integer linear programming model to solve the problem.

In China, the study on station route allocation mainly focuses on the optimization of application of station receiving-departure tracks and is performed generally on the basis of technical stations (e.g. section station and marshaling station) in the operation stage of existing railway. For instance, Qing Xuejiang[35]considered comprehensively the feasibility of satisfying the demands of receiving-departure tracks, advantages of technical operation, shunting, marshaling and unmarshaling of trains, as well as reduction on cross-operations of trains, the convenience of passengers, etc., and thereby developed a chromosome model for the application of receiving-departure tracks and solved the application of receiving-departure tracks in section stations by using a genetic searching algorithm based on natural selection. Li Wenquan [35] proposed a sequencing model for the receiving-departure tracks in marshaling stations and considered the problem of receiving-departure tracks in marshaling stations as an NP-complete problem. Lv Hongxia and Wang Zhengbin obtained the optimal solutions to the application of receiving-departure tracks in technical stations by using branch-bound algorithm and genetic algorithm respectively [36, 38]. In addition, Cui Bingmou [39] also performed an analysis on station route allocation, he developed a mathematical model for route scheduling in marshaling stations and solved the problem with genetic algorithm with the optimization objective of the minimum total delay time of train operation in the stations. Liu Lan analyzed the optimal occupation model for turnouts at station throat and corresponding solutions and realized the optimal allocation of carrying capacity at station throats by searching the shortest possible running routes [40].

2.3 Synergetic preparation method of train running diagram and station paths plan

Since train running diagram and Station Paths Plan are closely linked, the study on the two has inevitably been a topic of concern for various researchers.
The entire process of passenger service of a train is made up of the running process in sections and stations. Therefore, the preparation of train running diagram has to include the Station Paths Plan. Carey [41] proposed a preparation method for train running diagram based on the allocation of station tracks (platforms). His study focused on the selection of receiving-departure tracks in the station and the optimization of station layout. He has successfully applied the method to a small-scale practical project model which was consisted of 10 nodes, 28 tracks and 28 trains. Later, Carey extended the method for solving the preparation of train running diagram for one-way track to the preparation of train running diagram for two-way track. In 2007, he proposed a heuristic algorithm for solving the preparation problem of train running diagram and included the constraints of the application of receiving-departure tracks in the station during the preparation process [42]. In the algorithm, he assumed that the running time of a train between two stations was fixed and handled the running conflicts of trains with a set of rules; he then reduced the number of integer variables in the model by defining the running route of a train at a time, and thereby obtained the preparation result of the train running diagram at last. Besides, the mixed integer programming model for train running diagram proposed by Jovanovic [43] also included the allocation of receiving-departure tracks for trains in the station.

Some researchers in China also considered the effects of route arrangement for trains in a station on preparation results of the train running diagram. For example, Zhou Leishan proposed a discrete event model integrating the train running diagram and receiving-departure track utilization in a station as well as an arrangement on receiving-departure routes and applied such model in computer automatic preparation system of train running diagram for network route [44]. Peng Qiyuan considered factors associated with receiving-departure track utilization in the station and arrangement on receiving-departure routes in the model and algorithm research of train running diagram based on network [45].

To make full use of the high-speed railway resources, various production resources shall be comprehensively arranged. Therefore, it is necessary to consider the route arrangement of trains in the station during the diagram preparation and optimize the arrangements based on the train routes to properly adjust the receiving-departure time in the train running diagram. For this purpose, some researchers conducted related studies. For example, in the study on synergetic optimization method for station operating plan for PDL, Chen Jianxin proposed to synergistically consider the restrictions on departure time domain and proposed corresponding adjustment suggestions on train running diagram [46]. After solving the Station Paths Plan in busy period with heuristic algorithm, Carey discussed the feasibility of inserting the Station Paths Plan as the independent or key component into the train running diagram preparation, to effectively avoid possible route crossing in receiving-departure track utilization plan in the busy operation period and make the most of station lines such as dedicated lines, multi-purpose lines and alternate lines [31].

Besides, some researchers considered the integrated preparation method for train running diagram and the Station Paths Plan from the development demand for integrated preparation of train operation plane. For example, Mao Baohua reviewed the integrated preparation method of the train operation plan in China, proposed a development idea based on data integration and developed an integrated preparation system on which the preparation of the train running diagram and the Station Paths Plan can be integrated[47]; considering the preparation factors such as different occupation time of train resources and priority weight for selection of train routes resulted from physical conditions of routes (such as curves and turnouts) in many actual operation organization, Yusin Lee proposed an heuristic algorithm for solving routes and train running diagrams to solve the integrated preparation of running diagram and Station Paths Plan[48]. Miao Jianrui proposed an optimization method for feeding back and adjusting the train running diagram based on the preparation results of Station Paths Plan [49].

2.4 Presumptions and Symbols

This paper is intended to expound that due to the tight connection between the train running diagram and the station paths plan; synergetic optimization preparation can obtain more reasonable results than preparing the two separately. Since this chapter mainly deals with the operability and reliability of the synergetic optimization preparation of train running diagram and station paths plan, during the modeling of synergetic optimization, we assumed that the EMU resources within the operation system of high-speed railway are sufficient and EMU service plan could be realized without changing the train running time determined in the running diagram. This assumption weakens the influence of EMU resource constraints on train running diagram and station paths plan. In addition, the high-speed railway has doubled the line number. Regardless of EMU connection plan, the synergetic optimization methods for train running diagram and station paths plan for both lines are the same, thus the analysis below will focus on the down line.

Table 1. The used variables in the modeling of synergetic optimization

G	Railway network, G = (V, E), where V= section, E = station.
station	Station set, e.g. station j represents Station j.
section	Section set. section (j, j') represents the connection section (j, j') between Station j and Station j'.
N train	Number of trains.
train	Train set. Train k represents Train k, and wk represents the weight of train k.
N_S^k	Number of stations occupied by train k successively.
S^k	Set sequence of stations that train k passes in the district, $\{S_j^k\} = S_1^k, S_2^k, S_3^k, \dots, S_{N_S^k}^k . S_1^k = \text{first}\{S^k\}$is the departure station of train k, and $S_{N_S^k}^k = \text{last}\{S^k\}$ is the arrival station of train k. And$I_{S_j^k} = 1$ represents train k dwelling in Station j while $I_{S_j^k} = 0$ represents no dwelling in Station j.
a_j^k	Arrival time of train k in Station j.
d_j^k	Departure time of train k in Station j.
$\text{pre}_d(k,j)$	Preceding train of train k departed from Station j.
$\text{pre}_a(k,j)$	Preceding train of train k arrived at Station j.
$\text{next}_d(k,j)$	Next train of train k departed from Station j.
$\text{next}_a(k,j)$	Next train of train k arrived at Station j.
$I_{S_j^k}$	Dwelling sign, where$I_{S_j^k} = 1$ represents train k dwelling in Station j as per the

	operation schemes while $I_{S_j^k} = 0$ represents train k passing Station j as per the operation schemes
p_i^v	Pure running time, i.e. the fixed running time (passing running time) of train of speed class v in Section i.
pq^v	Additional departing time, i.e. the additional departing time of train of speed class v.
pt^v	Additional dwelling time, i.e. the additional dwelling time of train of speed class v.
dw_i^v	Minimum station dwelling time, i.e. the minimum station dwelling time of train of speed class v in Station i.
$I_i^{(v,w)}$	Train interval in section, i.e. the interval between train of speed class v and train of speed class w in Section i.
$I_{ii}^{(v,w)}$	Train interval in station. According to the different passing forms of trains in the station, Train interval in station is classified into the following types: departure-departure interval ($I_{dd}^{(v,w)}$), arrival-arrival interval ($I_{aa}^{(v,w)}$), passing-passing interval ($I_{tt}^{(v,w)}$), arrival-passing interval ($I_{at}^{(v,w)}$), passing-departure interval ($I_{td}^{(v,w)}$), departure-passing interval ($I_{dt}^{(v,w)}$) and passing-arrival interval ($I_{ta}^{(v,w)}$).
N_j^{train}	Number of trains in operation in Station j.
RI_j	The receiving route set RI in Station j, and N_{RI_j} represents the number of elements in RI.
RO_j	The departure route set RO in Station j, and N_{RO_j} represents the number of elements in RO.
R_j	The route set R in Station j. $R = RI \cup RO$. N_{R_j}represents the number of elements in R_j. (j, r)represents route r in Station j, $r \in R$. P(r) is the mapping function of connecting receiving-departure track of route r. P(r)=p means that p is the connecting receiving-departure track of r. $T((j,r)^k)$ is the function of route occupation time, representing the time span during which $train_k$ occupies route r in Station j. $\overline{T((j,r)^k)}$ represents the occupation starting time while$\underline{T((j,r)^k)}$ represents the occupation ending time.
P_j	The receiving-departure track set in Station j, and N_{P_j} represents the number of elements in P_j. (j, p) represents receiving-departure track p in Station j, p∈P. $T((j,p)^k)$ is the function of receiving-departure track occupation time, representing the time span during which $train_k$ occupies receiving-departure track p in Station j. $\overline{T((j,p)^k)}$ represents the occupation starting time while $\underline{T((j,p)^k)}$ represents the occupation ending time.
$\rho_{(j,r)}^k$	The weight of $train_k$ occupying route r in Station j.

$X^{k}_{(j,r/p)}$	A dummy variable. If $train_k$ occupies route r or receiving-departure track p in station j, $X^{k}_{(j,r/p)} = 1$, or $X^{k}_{(j,r/p)} = 0$.
$Tmax^{k}_{j}$	The maximum permissible time span from $train_k$ entering the dividing point at one end of station j to $train_k$ leaving the dividing point at another end. Its value is limited by a^{k}_{j}, d^{k}_{j} of the train and has a determined value when a^{k}_{j}, d^{k}_{j} are determined.
F	Conflict route set. Route conflict will occur when putting both r and r' into operation simultaneously. That is, route r or conflict route (r, r') is put into operation for two trains at the same time, expressed by $X^{k'}_{r} = 1 \wedge X^{k}_{r} = 1$ or $X^{k'}_{r'} = 1 \wedge X^{k}_{r} = 1$.
TW	Maintenance gap. TW_{start} is the starting time of maintenance gap, while TW_{end} is the ending time.

3. BASIC MODEL FOR SYNERGETIC PREPARATION OF TRAIN RUNNING DIAGRAM AND STATION ROUTE ALLOCATION PLAN

In existing research on optimization preparation method for train running diagram, before preparing the running diagram, there is usually an anticipated departure time for a train in a departure station, i.e. there is a departure location in train path. Given the departure location within the default running diagram, the train running diagram is thus optimized, and the train running diagram is also obtained with certain optimization objectives. Here the total deviation of the train path in the train running diagram from the departure location is an important factor in evaluating preparation quality of the running diagram, or other, and optimization objective for running diagram problems.

The determination of departure location of a train path is usually called the initial location of train running diagram, which is related to optimization factors such as the total number of trains drawn in the running diagram, the train operation frequency, the estimated travel time of trains in the district and the connection time distribution of locomotives or EMU. Literatures [50] and [51] have analyzed the solution to the initial location of train running diagram of a single line. Literature [52] studied the initial location of the train running diagram of the Beijing-Shanghai Passenger Dedicated Line. According to the above researches, it is obvious that initial location problem is rather hard to solve. Solving initial problems of running diagram is to build a basic frame and solve the optimization of running diagram based on the basic frame, to reduce the degree of difficulties in determining train locations in the diagram, and the optimization result may help realize the optimization objective of initial location of train running diagram.

The obtained anticipated departure time of a train in departure station is only a rough value, because potential train conflict has not been considered in detail during the initial location stage of trains, instead, the departure time was adjusted during optimization of the running diagram to make the train running diagram feasible [11]. The equilibrium of train operation frequency is regarded as the optimization objective of initial location problem in the literature, and it is anticipated that a feasible train running diagram with excellent equilibrium may be acquired after the optimization of the running diagram. However, since the running diagram is optimized according to the conflicts between trains, trains in the diagram may depart either earlier or later than the anticipated time, the final train running diagram is usually against the anticipation of initial location in train running diagram. In Figure 1, according to the equilibrium of train operations, the initial location of trains in a departure station is set as the filled dots, the points of departure time after optimization of running diagram as hollow dots. It can be seen from the figure that despite minor deviation of the actual departure time of each train from the location determined by the initial location, the operation equilibrium of the train group changes significantly, that is, the optimized train running diagram fails to meet the anticipated operation equilibrium of the initial location optimization. This is because the researchers attempted to respectively deal with different optimization objectives of the running diagram in different stages of the running diagram preparation but ignored the strong coupling effects among the elements in the problem, leading to failure in realization of anticipated optimization objectives. The problem may be solved as follows: During the initial preparation stage, provide a feasible train running plan (train paths) under necessary constraints for running diagram problems while ignoring any optimization objective, and regard it as an initial solution to optimization problem of train running diagram; at the optimization stage, include optimization factors and adjust the train paths provided in basic feasible solution for the optimization solution. In basic feasible solution, the more train paths for train optimization adjustment provided, the larger space for optimization adjustment of train paths, and the better preparation quality of final train running diagram will be. Based on that, in the initial stage of train running diagram, the "full timetable" train running diagram is provided as the basic solution to optimization problem here.

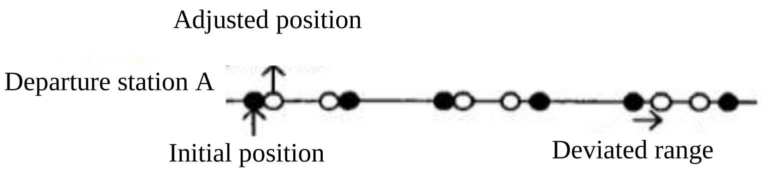

Figure 1. Initial Location of Train Running Diagram

The “Full timetable” train running diagram refers to the running diagram in which feasible train paths of the maximum quantity are drawn with the minimum interval. “Full timetable” train running diagram can be used as the basic solution to the optimization problem of the train running diagram. During the optimization, the operation train paths are determined according to the demand of the passenger flow, while the train paths not needed for operation are reserved, which not only increases the stability of train running diagram but also achieves flexible adjustment of train paths, thus optimizing the preparation result of train running diagram. Given this, a solution model of “full timetable” train running diagram was established in this chapter, where the number of train paths drawn in the running diagram was taken as the optimization objective, and only basic necessary constraints were set in the model.

Here is the basic model for synergetic preparation of train running diagram and station paths plan:

$$\max Z_1 = a.N_{train} + N \quad (1)$$

$$\min Z_2 = \sum_{k=1}^{a.N_{train}+N} \left(a^k_{s^k_{N^k_s}} - d^k_{s^k_1}\right) \quad (2)$$

st.

$$a^k_{s^k_{j+1}} - d^k_{s^k_j} \geq p^k_{(s^k_j, s^k_{j+1})} + I_{s^k_{s^k_j}} pq^k + I_{s^k_{s^k_{j+1}}} pt^k \quad (3)$$

$$a^k_{s^k_j} - d^k_{s^k_j} \geq I_{s^k_{s^k_j}} pw^k_{s^k_j} \quad (4)$$

$$\min\left(d^{pre_d(k,s^k_j)}_{s^k_j} - d^k_{s^k_j}, a^{pre_d(k,s^k_j)}_{s^k_{j+1}} - a^k_{s^k_{j+1}}\right) \geq I^{(k,pre_d(k,s^k_j))}_{(s^k_j, s^k_{j+1})} \quad (5)$$

$$d^{pre_d(k,s^k_j)}_{s^k_j} - d^k_{s^k_j} \geq \left(I_{s^{pre_d(k,j)}_{s^k_j}} * I_{s^k_{s^k_j}}\right) * I^{(pre_d(k,j),k)}_{dd} \quad (6)$$

$$a^{pre_a(k,j)}_{s^k_j} - a^k_{s^k_j} \geq \left(I_{s^{pre_a(k,j)}_{s^k_j}} * I_{s^k_{s^k_j}}\right) * I^{(pre_a(k,j),k)}_{aa} \quad (7)$$

$$d_{S_j^k}^{pre_d(k,j)} - d_{S_j^k}^{k} \geq \left(1 - I_{S_{S_j^k}^{pre_d(k,j)}}\right) * \left(1 - I_{S_{S_j^k}^k}\right) * I_{tt}^{(pre_d(k,j),k)} \quad (8)$$

$$d_{S_j^k}^{pre_d(k,j)} - d_{S_j^k}^{k} \geq \left(1 - I_{S_{S_j^k}^{pre_d(k,j)}}\right) * I_{S_{S_j^k}^k} * I_{td}^{(pre_d(k,j),k)} \quad (9)$$

$$d_{S_j^k}^{pre_d(k,j)} - d_{S_j^k}^{k} \geq I_{S_{S_j^k}^{pre_d(k,j)}} * \left(1 - I_{S_{S_j^k}^k}\right) * I_{td}^{(pre_d(k,j),k)} \quad (10)$$

$$a_{S_j^k}^{pre_a(k,j)} - a_{S_j^k}^{k} \geq \left(1 - I_{S_{S_j^k}^{pre_a(k,j)}}\right) * I_{S_{S_j^k}^k} * I_{ta}^{(pre_a(k,j),k)} \quad (11)$$

$$a_{S_j^k}^{pre_a(k,j)} - a_{S_j^k}^{k} \geq I_{S_{S_j^k}^{pre_a(k,j)}} * \left(1 - I_{S_{S_j^k}^k}\right) * I_{ta}^{(pre_a(k,j),k)} \quad (12)$$

$$pre_d(k, S_j^k) - pre_a(k, S_{j+1}^k) = 0 \quad (13)$$

$$\min(d_{S_j^k}^k) \geq TW_{start} \quad (14)$$

$$\max(a_{S_{N_S^k}^k}^k) \leq TW_{end} \quad (15)$$

$$\forall j \in \{1,2,\ldots,N_s^k\}, \forall k \in \{1,2,\ldots,(a.N_{train} + N)\} \quad (16)$$

Notes: Objective function (1) refers to the number of train paths drawn in the running diagram, i.e. the number of trains provided with a running plan; a represents the multiple of planned path types in the operation scheme, and N is a natural number. Objective function (2) refers to the total travel time of trains in the diagram. Constraint (3) means that trains meet the requirements of running time in a section; Constraint (4): minimum dwelling interval is satisfied; Constraint (5): train interval in section is satisfied; Constraints (6-12): train interval in station is satisfied; Constraint (13): overtaking prohibition in section, i.e. the preceding train of a train departed form a station must be the preceding train of the train arrived at the next station; Constraints (14) and (15) refer to the maintenance gap constraint. Constraint (16) refers to the value range of variables. If the variable margin value is insignificant, the constraint will be valid by default, e.g. in Constraint (5.3), if$j = N_S^k, S_{j+1}^k$ is insignificant, then Constraint (3) will be valid by default.

$a_j^k, d_j^k$are independent variables in the objective functions while the function values Z_1 and Z_2 are dependent variables that depend ona_j^k, d_j^k. $a_j^k, d_j^k$are the arrival and departure time of a train in a station, with R, the real number field of the timeline in running diagram as its value range. In practical operation, the arrival and departure time of trains are usually released on basis of minute for passengers' convenience, thus during the preparation of running diagram, the timeline may be discretized into dependent time points by minute. The timeline in a 24-hour train running diagram will start from 00:00 represented by 0, while end at 24:00 represented by 1440, then$a_j^k, d_j^k \in [0,1440]$ and $a_j^k, d_j^k \in Z$

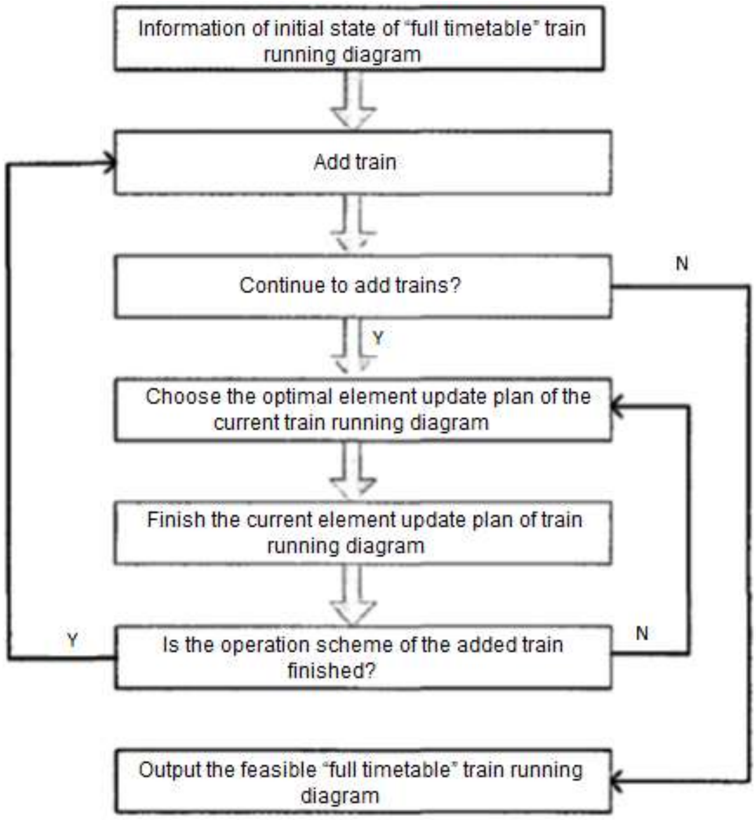

Figure 2. Flow Chart of Solution to "Full Timetable" Train Running Diagram

Algorithm steps

Step 1: Initialize the problem of "full timetable" train running diagram and determine the sequence of added trains. As it is shown in figure 2.

Step 2: Let the current added train be Train k in sequence and calculate the initial position of Train k as ith position of timeline of train running diagram. Then let the total occupation time of train in current train running diagram be TOT, and let the total number of planned operation trains in the current train running diagram be N_{train}.

Step 3: Update the solution element of train running diagram started from the discrete event $D_j^k(tk_j), (j = 1)$ generated from the add operation of Train k in initial position of the train running diagram and finish the arrangement of the train running plan of $D_j^k(tk_j)$ on Train k.

Step3.1: Judge whether the position j of the current Train k is at the last position of train operation scheme. If so, update the solution to the "full timetable" train running diagram, $N_{train} = N_{train} + 1$, $ToT = ToT + \Delta(ToT)$, $k = k + 1$, then go to Step 2, otherwise go to Step 3.2.
Step3.2: Instantiation of $D_j^k(tk_j)$ on "full timetable" train running diagram causes relevant train running conflict. Choose the optimal conflict solving scheme of train running diagram under the current state (if any), record the variation of total occupation time $\Delta(ToT)$ of train in the train running diagram induced by the scheme and update of corresponding solution elements. If $j = j + 1$, then backtrack to Step 3.1. If "full timetable" train running diagram has no conflict solving scheme of train running under the current state, then go to Step 4.
Step4:The initial value of ∂ is 0. Judge whether the current ∂ is less than the constant n. If $\partial < n$, then choose the next neighborhood ($\partial = \partial + 1$) of the initial position i for Train k, and the initial position of Train k in the train running diagram is $i = i + 1$. Then backtrack to step 2 and continue to add Train k. If $\partial \geq n$, then $m = m + 1$, m denotes the number of trains failing to be added, enter Step 5.
Step5:The initial value of m is 0, judge whether m is less than M. M denotes the total number of trains that cannot be added. If $m < M$, then $k = k + 1$, backtrack to step.2 and add the next train; if $m \geq M$, then end the algorithm and output the results.

4. OPTIMIZATION MODEL

A feasible train running diagram can be obtained with the basic model for synergetic preparation of the train running diagram and station paths plan (the solution to "full timetable" train running diagram). Based on the macroscopic networked structure, the train running diagram meets train operation needs of the train operation scheme, and its number of operation train is larger than that specified in train operation scheme. On such basis, further optimization of solution to basic model and reasonable arrangement of station route for trains are necessary for synergetic optimization of train running diagram and station paths plan. The model for synergetic optimization of train running diagram and station paths plan is given below according to the needs above:

$$\min Z_3 = \sum_{k=1}^{N_{train}} (a^k_{S^k_{N^k_S}} - d^k_{S^k_1}) \quad (17)$$

$$\max Z_4 = O_0(a_j^k - d_j^k) \quad (18)$$

St.

$$a^k_{s^k_{j+1}} - d^k_{s^k_j} \geq p^k_{(s^k_j, s^k_{j+1})} + I_{s^k_{s^k_j}} pq^k + I_{s^k_{s^k_{j+1}}} pt^k \quad (19)$$

$$d^k_{s^k_j} - a^k_{s^k_j} \geq I_{s^k_{s^k_j}} dw^k_{s^k_j} \quad (20)$$

$$\min(d^{pre_d(k,s^k_j)}_{s^k_j} - d^k_{s^k_j}, a^{pre_d(k,s^k_j)}_{s^k_{j+1}} - a^k_{s^k_{j+1}}) \geq I^{(k,pre_d(k,s^k_j))}_{(s^k_j, s^k_{j+1})} \quad (21)$$

$$d^{pre_d(k,j)}_{s^k_j} - d^k_{s^k_j} \geq \left(I_{s^{pre_d(k,j)}_{s^k_j}} * I_{s^k_{s^k_j}} \right) * I^{(pre_d(k,j),k)}_{dd} \quad (22)$$

$$a^{pre_a(k,j)}_{s^k_j} - a^k_{s^k_j} \geq \left(I_{s^{pre_a(k,j)}_{s^k_j}} * I_{s^k_{s^k_j}} \right) * I^{(pre_a(k,j),k)}_{aa} \quad (23)$$

$$d^{pre_d(k,j)}_{s^k_j} - d^k_{s^k_j} \geq \left(1 - I_{s^{pre_d(k,j)}_{s^k_j}} \right) * \left(1 - I_{s^k_{s^k_j}} \right) * I^{(pre_d(k,j),k)}_{tt} \quad (24)$$

$$d^{pre_d(k,j)}_{s^k_j} - d^k_{s^k_j} \geq \left(1 - I_{s^{pre_d(k,j)}_{s^k_j}} \right) * \left(1 - I_{s^k_{s^k_j}} \right) * I^{(pre_d(k,j),k)}_{td} \quad (25)$$

$$d^{pre_d(k,j)}_{s^k_j} - d^k_{s^k_j} \geq I_{s^{pre_d(k,j)}_{s^k_j}} * \left(1 - I_{s^k_{s^k_j}} \right) * I^{(pre_d(k,j),k)}_{dt} \quad (26)$$

$$a^{pre_a(k,j)}_{s^k_j} - a^k_{s^k_j} \geq \left(1 - I_{s^{pre_a(k,j)}_{s^k_j}} \right) * I_{s^k_{s^k_j}} * I^{(pre_a(k,j),k)}_{ta} \quad (27)$$

$$a^{pre_a(k,j)}_{s^k_j} - a^k_{s^k_j} \geq I_{s^{pre_a(k,j)}_{s^k_j}} * \left(1 - I_{s^k_{s^k_j}} \right) * I^{(pre_a(k,j),k)}_{ta} \quad (28)$$

$$pre_d(k, S^k_j) - pre_a(k, S^k_{j+1}) = 0 \quad (29)$$

$$\min(d^k_{s^k_j}) \geq TW_{start} \quad (30)$$

$$\max\left(a^k_{s^k_{N^k_s}} \right) \leq TW_{end} \quad (31)$$

$$\sum_{r=1}^{N_{P_j}} x^k_{(j,p)} = 1, p \in P_j \quad (32)$$

$$\sum_{r=1}^{N_{RI_j}} x^k_{(j,r)} = 1, r \in RI_j, P(r) = p \quad (33)$$

$$\sum_{r=1}^{N_{RO_j}} x^k_{(j,r)} = 1, r \in RO_j, P(r) = p \quad (34)$$

$$\sum_{r=1}^{N_{R_j}} x^k_{(j,r)} * T((j,r)^k) + \sum_{p=1}^{N_{P_j}} x^k_{(j,p)} * T((j,p)^k) \leq Tmax^k_j \quad (35)$$

$$\sum_{r=1}^{N_{R_j}} x^k_{(j,r)} * T((j,r)^k) + \sum_{p=1}^{N_{P_j}} x^k_{(j,p)} * T((j,p)^k) \geq \sum_{r=1}^{N_{R_j}} x^k_{(j,r)} * pr^k_r + \sum_{p=1}^{N_{P_j}} x^k_{(j,p)} * pr^k_p \quad (36)$$

$$\underline{T((j,p)^{k`})} - \overline{T((j,p)^k)} \geq I_p \quad (37)$$

$$T\left((\mathrm{j},\mathrm{p})^{k`}\right)-\overline{T\left((j,p)^{k}\right)}\geq I_{(r,r`)},r`\in F(r) \qquad (38)$$

$$\overline{\sum_{S^{k}=j}S^{k}}=N_{j}^{trian} \qquad (39)$$

$$\forall k\in\{1,2,\ldots,N^{train}\},\forall j\in E \qquad (40)$$

Notes: Objective function (17) refers to the minimum total travel time of train in train running diagram. Objective function (18) is the optimization evaluation index function of the train running diagram. Constraints (19-31) are the train running safety conditions in districts. Constraint (32) indicates that the train occupies only one receiving–departure track when passing the station. Constraints (33) and (34) mean that the train occupies only one receiving route or departure route when travelling in a station and the receiving-departure track connected with the route is the only receiving-departure track occupied in the station. Constraint (35) indicates that the travel time of train in the station is no more than the maximum travel time of planned operation train of the operation scheme, Constraint (36) represents that the travel time of train in the station is no less than the sum of the travel time of the train in station route, Constraint (37) specifies that various trains occupying the same receiving-departure line shall meet the minimum interval time in the route, Constraint (38) indicates that various trains occupying the same route or conflict route shall meet the minimum interval time in the route. Constraint (39) represents that the total number of routes arranged in the station equals to that of dwelling trains in the station, and Constraint (40) represents the valuation range of variable. In the optimization model, the number of planned operation trains equals that specified in train operation scheme $\mathrm{N}^{\mathrm{train}}$.

5. CONSTRUCTION OF PROTOTYPE SYSTEM

A prototype system for synergetic the preparation of the train running diagram and station route allocation plan of high-speed railway by using Multi-Agent technology and based on above theoretical framework and model-based algorithm. In the prototype system, each agent takes charge of one module. These agents can be classified into the following types by function:

(1) STA Agent: Stores the solution algorithms for the train running plan and solves STA problems.

(2) RTA Agent: Stores searching algorithms for station route and searches reasonable station route for each train running plan. This agent can be distributed in multiple computer terminals and search routes in multiple stations simultaneously.

(3) Synergetic Agent: Manages the information transfer between synergetic control strategies of the prototype system and agents, assigns solving tasks to STA agent and RTA agent, obtains solutions, calculates the synergetic control parameters and controls the optimization process.

(4) Data Management Agent: Stores and manages the data of the prototype system, including the date related to networked structure, scale of train operation, train operation scheme, as well as solutions.

STA agent and RTA agent have their own solving methods and can communicate with other agents through synergetic agent. Therefore, the synergetic optimization of train flow in networked structure can be realized through loose coupling. Multi-Agent technology is a proven technology and will not be described here in detail.

Prototype system is a system developed by Visual Studio 2010 based on C# language. Figure 3 depicts the train running diagram prepared automatically by the prototype system.

6. CALCULATION RESULTS AND ANALYSIS

1. Line data: Shanghai-Nanjing Intercity Railway consists of 22 stations, covering an operating distance of 301km with the max. train speed of 300km/h. The railway starts from Nanjing and ends at Shanghai Railway Station or Shanghai Hongqiao Railway Station, with Xianlin Station, Baohuashan Station, Zhenjiang Statin, Dantu Station, Danyang Station, Changzhou Station, Qishuyan Station, Huishan Station, Wuxi Station, Wuxi New District Station, Suzhou New District Station, Suzhou Intercity Station, Suzhou Industrial Park Station, Yangchenghu Station, Kunshan South Station, Huaqiao Station, Anting North Station, Nanxiang North Station, Shanghai West Station, etc. located in between. See Figure 3.

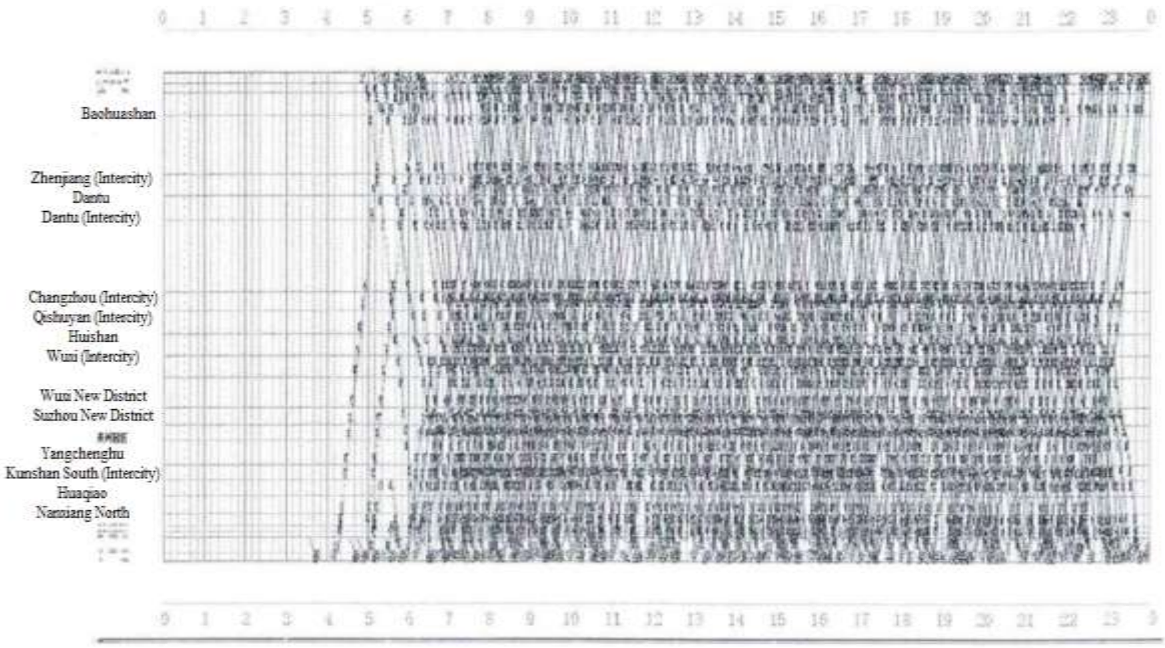

Figure 3. Automatic Preparation of Train Running Diagram by Prototype System

Figure 4. Network Structure of Shanghai-Nanjing Intercity Railway

2. Section scale data: The EMUs of two different riding speeds (200km/h and 300km/h) are operated in Shanghai-Nanjing Intercity Railway, in which the high-speed EMUs (300km/h) are divided into non-through and through EMUs.

3. Operation scheme data: 90 pairs of EMU trains are planned to be operated in Shanghai-Nanjing Intercity Railway to cater to the current traffic demand. In which, 32 pairs, 25 pairs, 1 pair, 2 pairs, 5 pairs and 5 pairs of G series EMUs are planned to be operated in the districts of Nanjing-Shanghai, Nanjing-Anting North Block Station and Xianlin-Anting North Block Station, Changzhou-Shanghai, Wuxi-Shanghai and Suzhou-Shanghai respectively; while 18 pairs and 2 pairs of D series are planned to be operated in the districts of Xianlin-Anting North Block Station and Nanjing-Anting North Block Station respectively. we can see that in Figure 4.
4. Use Visual studio 2017 to program and get the results of running diagram for each experiment.

6.1 Train running diagram

A 24h "full timetable" running diagram was obtained in accordance with the drawing sequence and minimum interval between trains. In this running diagram, 39 pairs, 32 pairs, 1 pair, 2 pairs, 6 pairs and 7 pairs of G series EMUs are planned to be operated in the districts of Nanjing-Shanghai, Nanjing-Anting North Block Station and Xianlin-Anting North Block Station, Changzhou-Shanghai, Wuxi-Shanghai and Suzhou-Shanghai respectively; while 21 pairs and 2 pairs of D series are planned to be operated in the districts of Xianlin-Anting North Block Station and Nanjing-Anting North Block Station respectively, 100 pairs in total. The "full timetable" running diagram in the operation period 8:00-11:00 in down direction is depicted in Figure 5. Then the orderliness of the train flows in the operation periods of 8:00-9:00, 9:00-10:00 and 10:00-11:00 was calculated, and the current local problem was thereby located in the time of 8:00-9:00. This problem involves 7 departure trains, with one extra non-through G train as compared with the operation scheme (between the two dotted lines). Then, the extra train was deleted, and the rest of the trains were optimized locally. Figure 6 shows the optimization result.

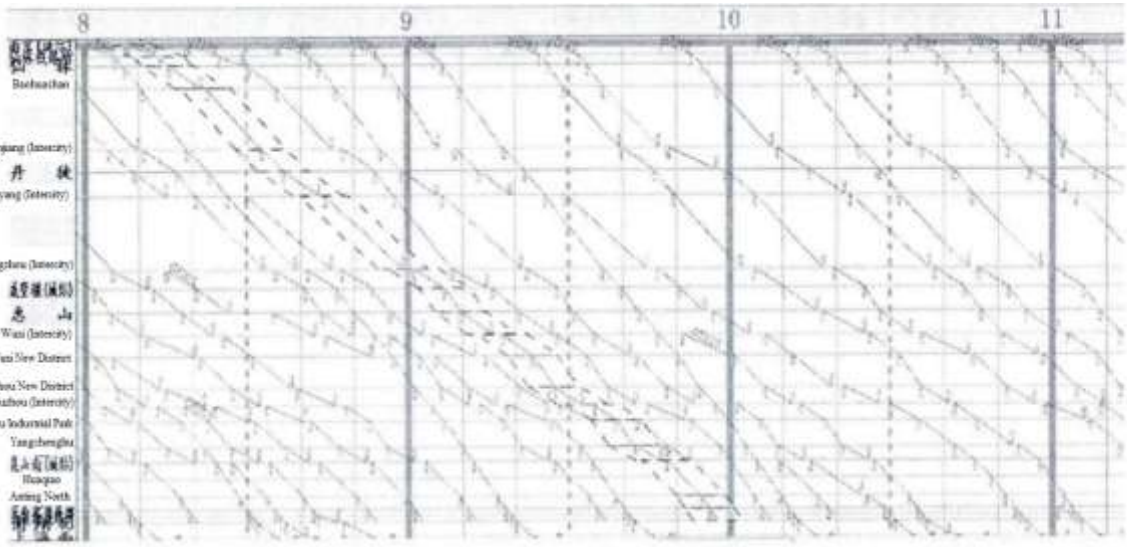

Figure 5. Basic Solution to Running Diagram of the Synergetic Optimization Problem

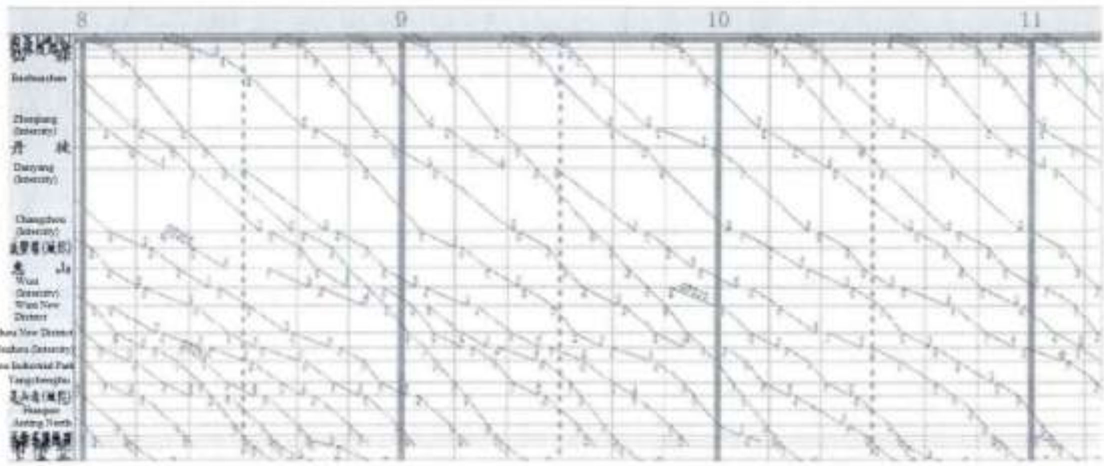

Figure 6. Process of Basic Solution

With the synergetic optimization method provided herein, the optimal solution to train running diagram can be obtained through iteration of local problem. Figure 7 offers part of the optimal solution. This optimal solution has better integrated indices, i.e. shorter total travel time, better orderliness of the train flow composed of all trains in the running diagram.

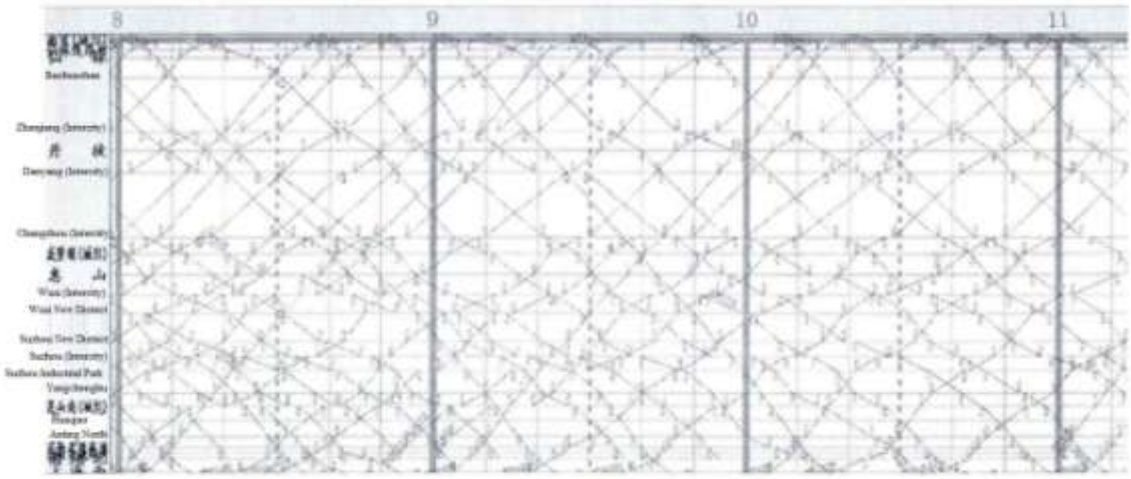

Figure 7. Part of Optimal Solution to Synergetic Optimization Problem

6.2 Station route allocation plan

Figure 8 presents part of the route allocation plan of Nanjing Station optimized with the synergetic method. In the method, the operation time parameter of departure trains is set as 10min, and that of quick turnaround trains is set as 15min. Altogether, 24 trains arrive at or depart from Nanjing Station in time 8:00-11:00, validating the feasibility of station route allocation method. This method produces such results that prevent conflicts in using the station route between trains departing reversely with quick turnaround operation and trains departing forward in Nanjing Station, further justifying the reasonability of the arrival/departure time of trains in the station. In another word, the train running diagram is feasible.

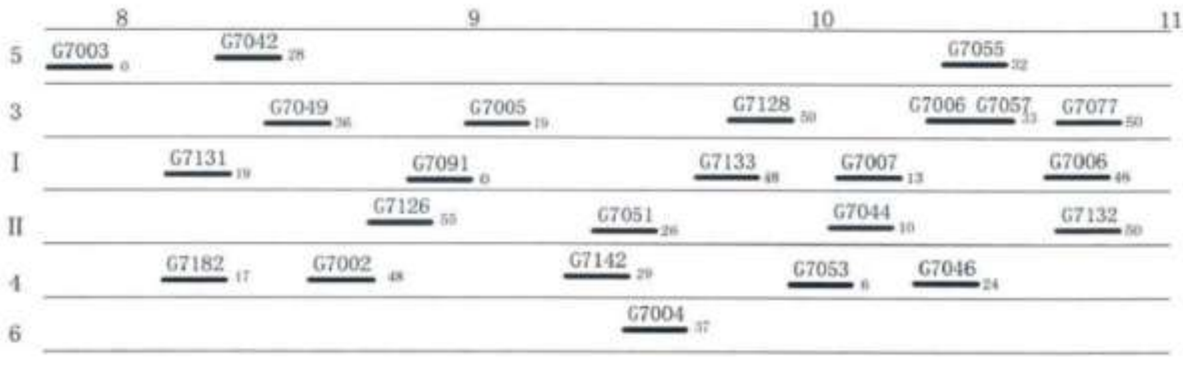

Figure 8. Part of Station path Plan

6.3 Results Analysis

(1) Table 2 presents the comparison results between synergetic optimization method and independent phased solving method. It is found that the synergetic optimization method outperforms the latter. Here, independent phased solving method refers to that the train running diagram and station route allocation plan are solved independently with search algorithm.

Table 2. Comparison of Synergetic Optimization Method and Independent Phased Solving Method

Optimization method	Frequency of solving feedback (times)	Calculation time (s)	No. of effective solutions (times)
Independent phased solving	325	33.2	55
Synergetic optimization	237	40.7	78

(2) In this paper, the synergetic optimization process is controlled through the measures of stability and responsivity of passenger service quality.

Responsivity measurement: the better the equilibrium of trains delivering the same service type, the more the trains connected in other direction, the better the transfer index, and the better the stability. For the scheme in Figure 6, the responsivity of passenger service is 0.895, and for the scheme in Figure 5, the responsivity is 0.615. It indicates that the scheme in Figure 6 can provide more convenient transfer choice for passengers than the scheme in Figure 5. During the synergetic optimization process, the trend of responsivity is depicted in Figure9, where the curve stands for the variation trend of increment rate of responsivity of trains in the running diagram with the calculation iteration of local problems in synergetic algorithm method.

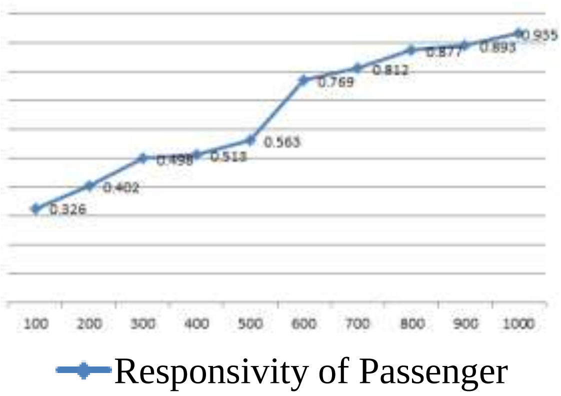

Figure 9. Trend of Responsivity of Passenger Service

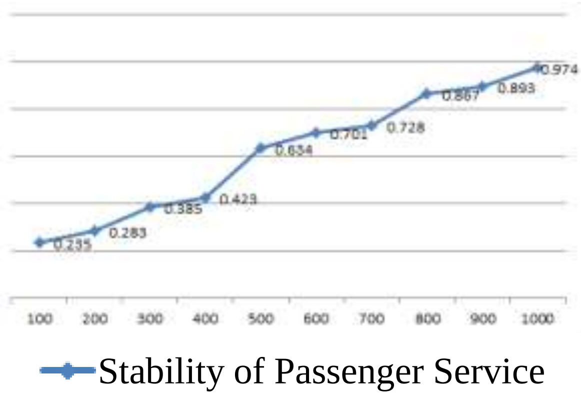

Figure 10. Trend of Stability of Passenger Service

In solving local problems during the preparation of train running diagram, the more the reasonability of buffer time, the higher the probability of shorter path allocated to important trains, the better the stability of passenger service. For the scheme in Figure 6, the stability of passenger service is 0.853, and for the scheme in Figure 5, the stability is 0.746. It indicates that the scheme in Figure 6 outperforms the scheme in Figure 5 in terms of equilibrium of train path allocation and reasonability of buffer time allocation, in which its station paths are allocated in line with setting principles. During the synergetic optimization process, the trend of stability is depicted in Figure 10, where the curve stands for the variation trend of increment rate of stability of trains in the running diagram with the calculation iteration of local problems in synergetic algorithm method.

The different distances of station routes allocated to the trains may save the travel time in the station. In the paper, this saved time was calculated by referring to the determination method of different consumed time in different tracks allocated to the trains as stated in Literature [53]. Literature [53] specifies that the train will take 1min additionally in occupying primary track than secondary track in the station. Since the EMUs of common speed have no priority in choosing the route, after adjustment, the buffer time will increase to provide favorable conditions for high-speed trains. This can be found in D5401 and D5589 in the table below. Conclusively, the adjustment can promote an integrated index of the station route allocation. Therefore, the synergetic preparation method can balance the train running diagram and station route search process, make the station route search more proactive, enable equilibrium and effective utilization of station tracks and shorter total travel time simultaneously, moreover, save running time and increase buffer time between receiving and departure trains through adjustment to station route allocation plan.

7. CONCLUSIONS

A basic model and an optimization model were established for the synergetic optimization of train running diagram and station paths plan to analyze the synergetic optimization problem in layers. The basic model was analyzed first, and a "full timetable" running diagram was obtained by depicting train adding process with discrete dynamic events and by using heuristic algorithm. It establishes the synergetic optimization model for train running diagram and station route allocation plan based on hierarchical optimization concept and the features of high-speed railway train flow and provides the solution ideas for hierarchical optimization. Firstly, "full timetable" train running diagram is prepared in view of maximum utilization of capacity, and thus the local problems are solved using the global adjustment algorithm based on state transition, and models are solved by means of dynamic synergy.

REFERENCES

[1]. Szpigel, B., "*Optimal train scheduling on a single-track railway*" [J]. Operational Research. 1973: 343-352

[2]. Frank, O., *Two-way traffic on a single line of railway* [J]. Operations Research. 1965, (14):801-811

[3]. Petersen, E.R., Taylor, A.J., *Design of a single-track rail line for high speed trains* [J]. Transportation Research Part A. 1987,21(1):47- 57

[4]. Smith, M.E. *Keeping trains on schedule: On-line planning systems for the advanced railroad electronics system (ARES)* [J]. Journal of the Transportation Research Forum. 1990, (31):17-24

[5]. River, R.E., Tzierepoulos, P. *Interactive graphics models for railway operational planning* [J]. The Practice of Transportation Planning. 1985:245-259

[6]. Rivier, R.E., Tzieropoulos, P. *Computer-aided planning of railway networks, lines and stations* [J]. Computers in Railway Management. 1987:3-16

[7]. Chxirchod, A., Emerry, D. *Computer-aided planning for major railway stations* [J]. Computers in Railway Installations, Track and Signaling. 1987:3-19

[8]. Jovanovic, D., Haricer, P.T. T*actical scheduling of rail operations: the SCANI system* [J]. Transportation Science. 1991,25(l):46-64

[9]. Carey, M., Lockwood, D. *A model, algorithms and strategy for train pathing* [J]. Journal of the Operational Research Society. 1995, (46): 988-1005

[10]. Carey, M., Carville, S., *Scheduling and platforming trains at busy complex stations* [J]. Transportation Research Part A. 2003,37(3): 195-224

[11]. Higgins, A., Kozan, E., Ferreira, L. *Optimal scheduling of trains on a single line track* [J]. Transportation Research Part B.1996, 30B (2): 147-161

[12]. Zhou, X. Zhong, M., *Single-track train timetabling with guaranteed optimality: Branch-and-bound algorithms with enhanced lower bounds* [J]. Transportation Research Part B. 2007,41(3):320-341

[13]. Petersen, E.R., Taylor, A.J. Martland, C.D., *An introduction to computer-assisted train dispatch* [J], Journal of Advanced Transportation. 1986, 20(1): 63-72

[14]. Brannlund, U., Lindberg, P.O., Nou, A.,Nilsson, J. E.. *Railway timetabling using Lagrangian relaxation* [J], Transportation Science. 1998,32(4): 358-69

[15]. Nou, A. *Railway timetabling-lagrangian heuristics. Technical report TRITA/MAT-97-OS12* [R].Royal Institute of Technology, Stockholm, Sweden. 1997

[l6]. Caprara. A., Fischetti, M., Toth., *Modeling and solving the train timetabling problem* [J]. Operations Research. 2002,50(5):851-861

[17]. Caprara, A., Monacix P., Guida., P.L..*A lagrangian heuristic algorithm for a real-world train timetabling problem* [J].Discrete Applied Mathematics. 2006,154(5):738-753

[18]. Valentina, V., Caprara, A., Toth,P.. *Scheduling extra freight trains on railway networks* [J]. Transportation Research Part B. 2010,44(2):215-231

[19]. Kraay,D., Harker, P.T.,Chen,B - *Optimal pacing of trains in freight railroads: model formulation and solution* [J]. Operations Research. 1991,39(l):82-99

[20]. Zhou, X., Zhong,M.. *Bi-criteria train scheduling for high-speed passenger railroad planning applications* [J]. European Journal of Operational Research.2005,167(3):752-771

[21]. Serafini, R, Kovich, W.U.. *A mathematical model for periodic event scheduling problems* [J].SIAM Journal on Discrete Mathematics. 1989,2(4):550-581

[22]. Odijk, M.A.. *A constraint generation algorithm for the construction of the construction of periodic railway timeta*ble [J]. Transportation Research Part B. 1996, 30(6):455-464

[23]. Odijk, M,A.. *Railway timetable generation* [D].Ph.D. Dissertation. Delft University of Technology. 1997

[24]. Goverde,R.M.P.. Im*proving punctuality and transfer reliability by railway timetable optimization* [R].In Proceedings of the 5 TRAIL Congress. Delft University Press. 1999

[25]. Lindner,T.. *Train schedule optimization in public rail transport* [D]. Ph.D. Dissertation. University Braunschweig. 2000

[26]. Liebchen,C., Mohring,R.H.. *A case study in periodic timetabling* [J], Electronic Notes in Theoretical Computer Science. 2002,66(6): 1-14

[27]. Liebchen,C..Symmetry for periodic railway timetables [J]. Electronic Notes in Theoretical Computer Science. 2004,92(17):34-51

[28]. Peeters,L.. *Cyclic railway timetable optimization* [D]. Ph.D.Dissertation. Erasmus University Rotterdam. 2003

[29]. Wong,R.C.W., Leung,J.M.Y.. *Timetable synchronization for mass transit railway* [R]. In Proceedings of the 9th International Conference on Computer-Aided Scheduling of Public Transport. San Diego. CA, USA, 2008

[30]. Wong, R.C.W., Yuen, T.W.Y., Fung, K.W., Leung, *Optimizing timetable synchronization for rail mass transit* [J]. Transportation Science. 2008,42(1):57-69

[31]. Carey, M., Carville, S.. *Scheduling and platforming trains at busy complex stations* [J]. Transportation Research Part A. 2003,(3): 194-224

[32]. De Luca Cardillo, D., Mione, N.. *K L-list τ colouring of graphs* [J]. European Journal of Operational Research. 1998,(106): 160-164

[33]. Billionnet, A.. *Using integer programming to solve the train-platforming problem* [J], Transportation Science. 2003,37(2):213-222

[34]. Zwaneveld, P.., Kroon, L.G, Romeijn, H.E., et al. *Routing trains through railway stations: Model formulation and algorithms* [J]. Transportation Science. 1996,30(3): 181-194

[35]. QING Xue-jiang, MA Guo-zhong. *Application of Genetic Algorithm in Receiving-*

Departure Tracks in District Stations [J] Journal of Southwest Jiaotong University. 1998,33(4): 387-393 (in Chinese)

[36]. LI Wen-quan, WANG Wei, CHENG Shi-hui. *Ranking Model and Algorithm for Receiving-Departure Tracks in Marshaling Stations of Railway* [J]. Systems Engineering —Theory & Practice.2000,20(6):75-78 (in Chinese)

[37]. LV Hong-xia, NI Shao-quan, JI Hong-ye. *Supporting System for Dispatching Decision-making Technical Station — Rational Utilization of Receiving-Departure Tracks in Technical Station* [J]. Journal of Southwest Jiaotong University. 2000,35(3):255-258 (in Chinese)

[38]. WANG Zheng-bin, DU Wen. *Adjustment Model and Algorithm for Receiving-Departure Tracks in Technical Station* [J].Journal of Southwest Jiaotong University. 2006,41(2): 202-205 (in Chinese)

[39]. CUI Bing-mou, MA Diao-pei, ZHANG Pu. *Optimization Algorithm for Dispatching of Route in Marshaling Station* [J].China Railway Science. 2007,29(3): HXM04 (in Chinese)

[40] LIU Lan, WANG Nan, DU Wen. *Network Optimization: Models & Algorithms for Carrying Capacity of Station Throat* [J]. Journal of the China Railway Society. 2002,24(6) 1-5 (in Chinese)

[41]. Carey,M.. *Extending a train pathing model from one-way to two-way track* [J], Transportation Research Part B. 1994,28(5):395-400

[42]. Carey, M., Crawford. *Scheduling trains on a networic of busy complex stations* [J].Transportation Research Part B. 2007,41(2): 159-178

[43]. Jovanovic, D., Harker, P.T.. *Tactical scheduling of rail operations: the SCAN I system* [J], Transportation Science. 1991,25(1):46-64

[44]. Zhou Leishan, Hu Siji. *Network Hierarchy Parallel Algorithmof Automatic Train Scheduling* [J]. Journalofthe China Railway Society.1998,20(3):15-21

[45]. PENG Qi-yuan, WANG Pei. *Mathematical Model and Algorithm for Train Diagram in Railway Network* [J].Journal of the China Railway Society.2001，23(1):1-8 (in Chinese)

[46]. CHEN Jian-xin. *Methods for Synergetic Optimization of Station Operation Plan in Passenger Dedicated Line* [M]. Master Dissertation.Beijing Jiaotong University. 2007 (in Chinese)

[47]. MAO Bao-hua, WANG Bao-shan. XU Bin. *Methods for Integrated Preparation of*

Train Operation Plan in Railways in China [J].Journal of Transportation Systems Engineering and Information Technology. 2009,(2):1-7 (in Chinese)

[48]. Yusin Lee, Chuen-Yih Chen. *A heuristic for the train pathing and timetabling problem* [J]. Transportation Research Part B. 2009,43(8-9):837-851

[49] MIAO Jian-rui. *Methods for Preparation of Train Running Diagram in High Speed Railway* [D].Doctor Dissertation.Beijing Jiaotong University. 2010 (in Chinese)

[50] SUN Yan, LI Zhi-zhong, LI Fengliang. *Methods for Optimizing Initial Distribution of Train Running Diagram* [J].Journal of Changsha Railway University. 1997,(4): 80-87 (in Chinese)

[51] LIU Ai-jiang, XU Chang-feng, HE Da-ke. *Paired Model for Initial Distribution of Train Running Diagram based on Genetic Algorithm* [J] Railway Computer Application. 2003,12(1): 13-15 (in Chinese)

[52] MA Jian-jun. *Preparation Theory of Train Running Diagram in Beijing-Shanghai High Speed Railway based on Railway Network* [D]. Doctor Dissertation.Beijing Jiaotong University. 2002 (in Chinese)

[53] Yusin Lee, Chuen-Yih Chen. *A heuristic for the train pathing and timetabling problem* [J]. Transportation Research Part B. 2009,43(8-9):837-851