Profit-oriented High-speed Railway Network Line Planning with Capacity Limitations

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Abstract: Line planning is the transportation service's fundamental, which directly affects the subsequent operation plans. It is better to focus on the operational profit when considering the market competition for transportation operation plans. This paper aims to maximize the operational profit when optimizing the high-speed railway network line plan by constructing a mixed integer nonlinear programming model. The model integrates line planning and passenger route choice behaviors. An adaptive simulated annealing algorithm with neighborhood search is applied based on a given line pool. A heuristic passenger assignment method is developed to ensure a high level of passenger satisfaction. The proposed model and algorithm are experimentally evaluated. The instance results show that the operational profit and capacity utilization can be significantly improved. Compared with the designed greedy heuristic algorithm, the proposed algorithm performs better in operational profit improvement and has high efficiency.

Keywords: High-speed railway, Line planning, Passenger assignment, Simulated annealing, Neighborhood search.

1. INTRODUCTION

In the competitive transportation market, operational profit derived from operation plans and passenger demand plays a vital role in the present and future development of railway transportation. Line planning is an essential operation plan that primarily focuses on train travel paths, stop station sequences, and train frequencies. Passengers have diverse and personalized transportation service demands. Railway operators must improve transportation services to better meet passenger needs and increase operational profits. However, due to railway capacity limitations, it is impossible to provide direct shortest travel paths between every originating station and destination station (OD pairs). Therefore, it is more realistic to consider capacity limitations when solving line planning.

Railway operators wish to operate as few trains as possible to serve as many passengers as possible. At the same time, passengers expect to reach their destination quickly and easily. To consider the railway operator's perspective and passengers' perspective at the same time, the sum of railway operational cost and passenger generalized travel cost (GTC) (which is widely used to represent passengers' perspective [1-4]) is used as the objective function in previous studies [3-7]. This method only optimizes the line planning from the cost aspect. However, the lowest cost does not ensure higher operational profit. Thus, this paper considers the ticket income at the same time. Instead of using the bilevel model [2, 8-10], which designs the line plan as the upper level and formulates passenger route choices based on the service products as the lower level, this paper constructs a mixed integer nonlinear programming (MINLP) model. The MINLP model presented in this paper uses heuristic passenger assignment to be closer to passenger travel preferences, due to the simplified demand models used in bilevel models. Dynamic pricing is an important consideration in optimizing network line planning, given the trend of ticket prices in the HSR industry. Passenger assignment is a complex process in this context, and this paper focuses on optimizing it under profit-oriented line planning and a certain degree of passenger travel utility. Future work will report on research into optimizing network line planning with dynamic pricing.

The main contributions of this work are as follows:

- A novel optimization model is presented to improve operational profit on the limitation of railway capacity while ensuring a certain level of

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passenger travel satisfaction by converting the passenger GTC into a threshold constraint. It can better describe the selection of lines from the line pool, passenger route choices and their relationships.

- The heuristic passenger assignment based on a particular passenger assignment order is explored to simulate passenger route choice behaviors, which could avoid sacrificing the rights of some passengers to choose the travel routes with the lowest possible travel cost for the pursuit of the lowest overall travel cost.

- The solving method integrates the line pool and neighborhood search method by the constructed adaptive simulated annealing algorithm (ASA), which can generate more reasonable neighborhood solutions.

- Compared with a designed greedy heuristic algorithm, ASA is proved to give higher solution quality and faster convergence speed of the objective function.

The remainder of this paper is structured as follows. In Section 2, the literature review is presented. The problem statement is given in Section 3. Then the profit-oriented HSR network line planning model is established in Section 4. After that, the solution approaches are introduced in Section 5. Section 6 gives several experiments to show the efficiency and effectiveness of the proposed model and algorithm. Finally, the conclusions are summarized in Section 7.

2. LITERATURE REVIEW

Line planning problem (LPP) is the strategic plan of railway transportation operation plan. The LPP aims to determine the line concept [11], which achieves specific optimization objectives based on the railway capacity limitations and passenger demand. According to the different purposes, LPP can be classified into cost-oriented, passenger-oriented and combination.

For cost-oriented LPP, the objective is to minimize the operational cost. Claessens *et al*. [12] developed a cost-oriented LPP model that minimizes the operational costs based on capacity limitation. The model results are lines, line types, routes, frequencies and train lengths. Bussieck *et al*. [13] combined the personnel and rolling stock costs to form operational costs. Before presenting the multi-type cost-oriented LPP model, Goossens *et al*. [14] recalled the single-type cost-oriented LPP model. The differences are that the former considers different types of stations and lines, while only one type of network is involved in the latter. The cost-oriented LPP model may lead to situations where some passengers have very long travel times or have to transfer many times, which is not preferable for passengers.

For passenger-oriented LPP, the models aim to maximize the number of direct passengers, minimize the passengers' total travel time, and/or minimize the number of transfers. The operational costs are considered a budget constraint. Bussieck *et al*. [15] constructed a mixed integer linear programming formulation to maximize the number of direct passengers. Schöbel and Scholl [16] considered maximizing the comfort of the passengers by minimizing the travel time for all passengers, including transfer time. Scholl [17] considered minimizing the passengers' travel time and the number of transfers. If the LPP model only considers passengers' perspective as the objective, it is difficult to optimize the operational cost. More and more researchers focus on combining both cost-oriented and passenger-oriented models.

The LPP can be further classified into the weighted sum of the cost-oriented and passenger-oriented [2, 18, 19] and profit-oriented LPP [20-23]. Since these two objectives conflict with each other, the sum of two weighted coefficients typically equals 1. Zhao *et al*. [2] considered the objective as the weighted sum of operational cost, passenger travel cost (including boarding deviation time, on-board time and transfer time) and a penalty function to relax some constraints. Pfetsch and Borndörfer [18] took the weighted sum of operational cost and passenger travel time as the objective. Yan and Goverde [19] proposed a multi-frequency LPP (MF-LPP) model to minimize the weighted sum of empty-seat-hours, passenger in-vehicle time and the number of lines/stop patterns. The weights in the objective have a significant impact on the final line plan, so the decisions on the weights are essential. Generally, the profit-oriented LPP aims to maximize the operational profit, including ticket income and operational cost. Canca *et al*. [20-21] considered the expected income, fixed operational cost, variable cost, and the building cost of the railway rapid transit network when making a profit-oriented LPP model. Mao *et al*. [22] integrated the LPP with tick*et al*location to construct a profit-oriented objective that used ticket income minus operational cost. However, the model lacks considering passengers' perspectives. Liu *et al*. [23] used the ideal revenue and considered penalties for passengers who have to take extra travel time minus operational cost. The ideal revenue is obtained when each passenger travels along the shortest path in the physical network with a direct connection.

Passenger route choice behaviors considered in line planning are simplified as given route choices that are not affected by the line plan [24] or the shortest path without considering the train capacity limitation [25]. The works of literature do not consider the time order of passenger ticket purchases. Literature [26] shows that long-distance passengers tend to buy tickets more in advance. The primary work of this paper is to combine the passenger assignment with profit-oriented line planning and consider the passenger travel utility threshold. This paper is an extension of the existing method used in the literature [27, 28]. In addition, this paper integrates optimization of passenger route choices, stopping patterns and frequency settings to generate the line plan.

With the continuous improvement of the HSR network, the competition between different transportation modes is getting fiercer. It is time to focus on the operational profit of LPP which takes passenger preferences into account such as long-distance passengers tend to buy tickets more in advance. This paper conformed to the requirement and proposed a profit-oriented LPP with a high level of passenger satisfaction.

3. PROBLEM STATEMENT

This study focuses on the integrated of network line planning with passenger route choice. Figure **1** illustrates an HSR network cobsisting of six stations and five sections. The line plan includes four lines with distinct operating zones and stopping patterns. The corresponding frequencies of the lines are 1, 1, 2 and 2.

The operation zones present the origin, destination and the sections the train covered. Passengers can achieve their travel if the train stops at their origin and destination station. The stopping pattern affects passengers' travel time and distribution on a train. For example, since the travel distance between station A and station C on line 2 and line 3 are the same, if passengers from station A to station C board the train on Line 2, those passengers have to spend more travel time than board the train of Line 3 at the same train speed. Because train of Line 3 operates directly from station A to station C without an additional stop at station B. Passengers' route choice behaviors led to the distribution of passengers on different trains. The train frequency, operation zone and stopping pattern determine the transportation capacity that should meet passenger demand. All the above elements influence railway operational cost, ticket income and passenger generalized travel cost.

The cost-oriented objective may only keep Line 3 and Line 4 to operate the least number of trains. The objective of this paper is to identify a network line plan that can maximize operational profit and enhance passenger travel satisfaction by considering generalized passenger travel costs. This approach takes into account the passenger's perspective and aims to minimize inconvenience by increasing the number of lines if necessary.

4. THE PROFIT-ORIENTED HSR NETWORK LINE PLANNING MODEL

Passenger assignment plays an essential role in line planning. The passenger route choice behaviors can be depicted based on the train service network (TSN) [23]. Then the results of passenger assignment, which gives the distribution of passengers on trains, can be used to evaluate and optimize the line plan.

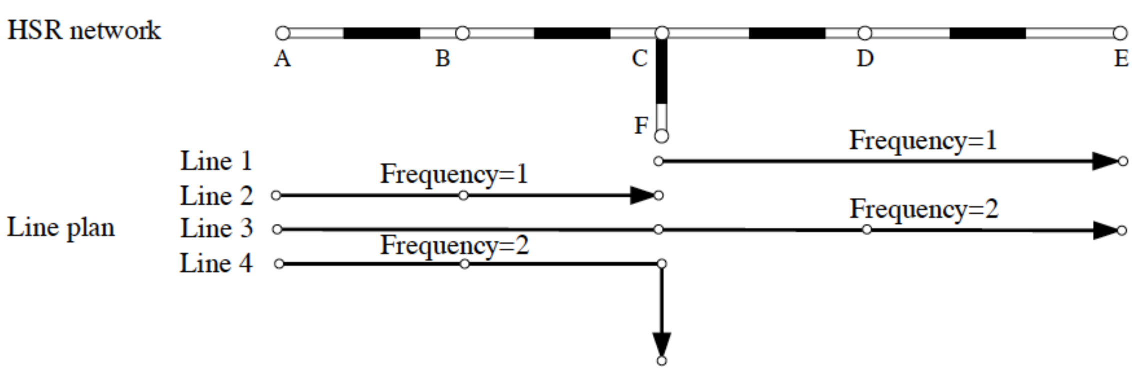

Figure 1: Example of network line plan based on a given HSR network.

Mixed Integer Nonlinear Programming Model

Assumptions

The model is constructed under the following assumptions:

1. Passenger route choice behaviors: Passengers always choose the travel route with the lowest generalized travel cost. If it is not available, passengers will search for other travel routes which are next-to-shortest paths about the generalized travel cost.

2. Train fleet configuration: Trains have the same fleet configuration. This paper focuses on the passenger assignment under the optimization of profit-oriented network line planning. In addition, the model adds long-distance passenger assignment priority and passenger travel utility threshold. The variable fleet configuration is considered for further research.

3. The maximum number of transfers: Passengers need at most one transfer to reach their destination.

4. Train operation: The train operation direction is defined as the sequence of stop stations from the origin to the destination, and vice versa. All trains operate symmetrically. The bi-direction trains have the same frequency.

Variables and Notations

An undirected graph is defined as $G=(S,E)$ constructed according to HSR network typology. The node set is defined as $S=\{1,2,...,n\}$ representing the stations in the HSR network and the arc set is defined as $E=\{e,e\in S\times S\}$ referring to the sections between two stations. The notations and variables used in the model are shown in Table **1**.

Table 1: The Notations and Variables used in the Model

Notations	Definitions
Indices	
i,j,s	Index of stations, $i,j,s\in S$
e	Index of sections, $e\in E$
h	Index of trains in the line plan, $h\in H$
a	Index of arcs in the TSN, $a\in A$
r	Index of feasible travel route of passengers based on the TSN, $r\in R$
d	Index of OD pairs, $d\in D$
Sets	
S	Set of stations
E	Set of arcs
$Q_{i,j}$	Set of passenger demand between station i and j
D	Set of passenger OD pairs
H	Set of trains in line plan
H_e	Set of trains passing through the section e
H_i	Set of trains stopping at the station i
$\lvert S_h\rvert$	The number of stops belongs to the train h
A	Set of arcs in TSN
$A_h^{'}$	Set of riding arcs belonging to the train h
R	Set of feasible travel routes r based on the TSN
$R_{i,j}$	Set of feasible travel routes r between the station i and j based on the TSN
$R_{i,j,h}^{'}$	Set of feasible travel routes r which serve as a direct train between the station i and j based on the TSN
$R_{i,j,h}^{''}$	Set of feasible travel routes r which have to make a transfer between the station i and j based on the TSN
TT	Set of passenger travel times of feasible travel routes
P	Set of ticket prices of feasible travel routes, the ticket price between the station i and j is $P_{i,j}$
Parameters	
C^G	Fixed cost per train
C^V	Variable cost per train per kilometer
C^S	Variable cost per train per stop
Cap_h	Capacity per train
Cap_i	Capacity of station i
Cap_e	Capacity of section e
$\lvert D\rvert$	The number of OD pairs
d_h	The operation distance of the train h
ρ	Average travel time value of passenger
β	The weight coefficient of travel time in the GTC function
C_r	The GTC value of feasible travel route r
ψ	The threshold value of total passenger GTC

$\theta_{r,a}$	The relationship between passenger travel route and arcs in the TSN, *i.e.*, if the passenger travel route r contains the arc a, $\theta_{r,a}$=1, otherwise, $\theta_{r,a}$=0
M	A very large value
Variables	
y_h	0-1variable, if train h operates, y_h=1, otherwise, y_h=0
f_h	The frequency of train h
$x_{i,j}^r$	The number of passengers using the travel route r between station i and j

Mathematical Formulations

The objective and constraints can be seen as equation (1) to Equation (13).

$$\max Z=\sum_{h\in H} y_h\times\sum_{i\in S}\sum_{j\in S}\left[\left(P_{i,j}\times\sum_{r\in R'_{i,j,h}} x_{i,j}^r\right)+\sum_{\substack{s\in S\\ i,j\neq s}}\left(P_{i,s}+P_{s,j}\right)\times\sum_{r\in R''_{i,j,h}} x_{i,j}^r\right] -\sum_{h\in H}\left(C^G+C^V\times d_h+C^S\times\left|S_h\right|\right)\times f_h \tag{1}$$

s.t.

$$\sum_{i\in S}\sum_{j\in S}\sum_{r\in R}\left(x_{i,j}^r\times\theta_{r,a}\right)\le f_h\times Cap_h,\forall a\in A_h^{'},h\in H \tag{2}$$

$$\sum_{h\in H_e} f_h\le Cap_e,\forall e\in E \tag{3}$$

$$\sum_{h\in H_i} f_h\le Cap_i,\forall i\in S \tag{4}$$

$$\sum_{r\in R_{i,j}} x_{i,j}^r=Q_{i,j},\forall i,j\in S \tag{5}$$

$$\sum_{i\in S}\sum_{j\in S}\sum_{r\in R_{i,j}}\left(x_{i,j}^r\times C_r\right)\le\psi \tag{6}$$

$$C_r=\beta\times TT_r\times\rho+\left(1-\beta\right)\times P_{i,j},\forall i,j\in S,r\in R_{i,j} \tag{7}$$

$$y_h\times TT_{0,r}+M\times\left(1-y_h\right)\le TT_r,\forall h\in H,r\in R'_{i,j,h}\cup R''_{i,j,h} \tag{8}$$

$$f_h\le M\times y_h,\forall h\in H \tag{9}$$

$$x_{i,j}^r\le M\times y_h,\forall i,j\in S,h\in H,r\in R'_{i,j,h}\cup R''_{i,j,h} \tag{10}$$

$$f_h\in\mathbb{N},\forall h\in H \tag{11}$$

$$x_{i,j}^r\in\mathbb{N},\forall i,j\in S,r\in R_{i,j} \tag{12}$$

$$y_h=\left\{0,1\right\},\forall h\in H \tag{13}$$

Equation (1) is the objective function that calculates operational profit using total ticket income minus operational cost. The total ticket income is the sum of direct passengers' ticket income and the transfer passengers' ticket income. Since the transfer passengers have to take different trains and pay the corresponding ticket prices, it is more reasonable to consider the ticket income of direct passengers and transfer passengers separately. The operational cost includes fixed cost and variable cost. Fixed cost includes deprecation of vehicles' fixed assets, vehicle overhauls, crew salary expenditures, etc. Due to the confidentiality of the HSR network in China, some costs, such as rail line maintenance and station service costs, are difficult to obtain. Thus, we use train traveling kilometer cost and train stopping cost (widely considered in literature [4, 6, 29]) to represent variable cost. The train traveling kilometer cost is related to train operation mileage and frequency, while train stopping cost refers to the number of train stops and train frequencies. To avoid assigning passengers to the routes with higher prices from the objective function, the GTC threshold constraint (Equation (6)) requires the selected routes should no more than a GTC threshold. Moreover, by heuristic passenger assignment, passengers are preferentially assigned to the shortest paths with generalized travel cost unless the demand exceeds the capacity limitations.

Equation (2) to (4) are transportation capacity limitation constraints. Equation (2) is the train capacity constraint, which is used to limit the number of train passengers that should be less than or equal to the capacity that the train can provide. Equation (3) is the section capacity constraint, which describes that all trains passing through a particular section should be less than or equal to the section capacity. Equation (4) gives the station capacity constraint to limit the number of trains stopping at a station.

Equation (5) to (7) are the passenger assignment constraints. Equation (5) represents the passenger flow conservation constraint. The number of passengers of a specific OD pair selecting different travel routes should equal the total passenger demand of that OD pair. Equation (6) presents the GTC threshold constraint representing passengers' perspectives. The total GTC of passengers should be less than a given value. This paper assumes that the threshold value is determined by the GTC of all passengers traveling according to the direct shortest route multiplied by an amplification factor, such as 1.2 times. The threshold value can be calibrated for a particular case in further study. Since the objective only contains elements related to railway operation without considering the travel utility of passengers, the GTC threshold representing the travel utility of passengers is introduced into the constraints. Besides, a heuristic passenger assignment approach is adopted to ensure a certain degree of passenger travel satisfaction. Equation (7) is a GTC function. It is assumed that the main factors affecting passengers' route choice behaviors are the travel time and ticket price.

Equation (8) to (10) are constraints that set the relationship between the train operation and travel time of the travel routes, train frequencies and the number of passengers on the train. Here we introduce $TT_{0,r}$ which is the given travel time of the route r. TT_r is the final travel time of the route r which depends on whether the related train h operates or not. Equation (8) indicates that the travel routes related to that train have the corresponding travel time if the train operates. Otherwise, the travel times of the routes are infinite. For the transfer route, if one train is selected while the other is not, Equation 8 makes sure the transfer route travel time $M \le TT_r$ so that the transfer route cannot be selected for transfer passengers. Equation (9) presents that the train frequency is lower than infinite if the train operates. Otherwise, it equals zero. Equation (10) gives that it can be assigned passengers if the train operates. Equation (2) and (10) limit the number of passengers from aspects of train capacity and travel routes. Equation (2) is based on the train capacity to limit the number of passengers using that train. Equation (10) sets the relationship between the travel route, the number of passengers using the related travel route and the train operation. Equation (11) to (13) are variable bounding constraints.

5. SOLUTION APPROACHES

Solution Process

The solution process is divided into two stages, *i.e.*, initial HSR network line plan generation and network line plan optimization.

Firstly, given the input data, the line pool which contains all possible candidate lines is constructed. In this paper, the candidate lines include the origin and destination station of the trains, train routes and train stopping patterns. The train frequencies are determined after passenger assignment. Train routes are calculated by k shortest paths, say $k=3$. The train stopping patterns are enumerated by different combinations of stops at intermediate stations. For example, if the train has s intermediate stations, the stopping patterns can be obtained by enumerating $s, s-1, s-2, ..., 0$ stops combinations. The reasons why we use this stopping pattern are manifold. The stations considered in this paper are large and medium-sized cities with around 95% passenger demand of all the HSR passenger demand [2]. It is reasonable to consider such enumeration stops. The enumeration stops can improve the diversity of transportation services, which fits the tendency of passenger demand. The optimization of the stopping pattern could be set based on certain stopping conditions or according to the station weight when the network scale of the involved stations is large. In practical applications, the generation of train stopping patterns should be set according to the actual situation of different countries.

Secondly, the initial HSR network line plan is constructed based on the line pool and passenger demand. The large passenger demand (which is larger than one train capacity) of different OD pairs is sorted in descending order. Then the lines with the corresponding origin and destination stations are selected as the initial line plan until all the large

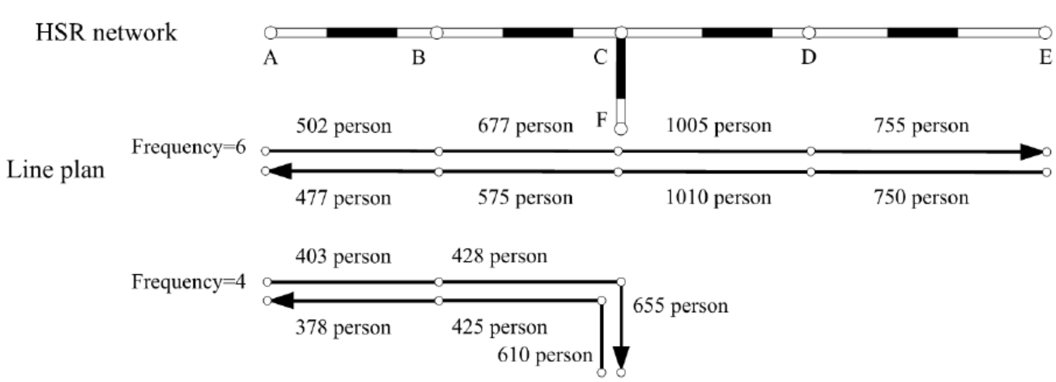

Figure 2: Example of the initial network line plan.

passenger demand OD pairs have direct connections. If lines have a part of common routes or the exact origin or destination stations, these lines can be merged. Then the initial line plan feasibility is checked, *i.e*., all passenger OD pairs have available travel routes with at most one transfer in the TSN based on the initial line plan. If there is an OD pair that does not have travel routes, then select lines from the line pool to make it feasible. Figure **2** is taken as an example to show the initial HSR network line plan generation.

Table 2: The Passenger Demand Based on Figure 1 HSR Network

	A	B	C	D	E	F
A		100	105	100	300	300
B	105		150	50	50	50
C	150	100		100	200	100
D	100	50	105		105	105
E	250	50	250	100		100
F	250	50	105	105	100	

Assuming that each train can carry 200 people, the passenger OD pairs A-E, A-F and C-E in Table **2** meet the requirement for operating trains. Then the OD pairs are sorted by the number of passengers. The train travel routes between those OD pairs are A-B-C-D-E, A-B-C-F, A-B-C and C-D-E. Then line A-B-C and C-D-E can be merged as A-B-C-D-E. After that, we check the selected lines that all the passengers have available travel routes. Line A-B-C-D-E and A-B-C-F frequencies are calculated based on passenger assignment.

After completing the aforementioned process, the initial line plan without train frequencies can be derived. The calculation of train frequencies is done subsequently through a heuristic passenger assignment method. The long distance passengers have priority when they are assigned to trains. Generally, long distance passengers tend to buy tickets in advance to avoid purchase competition closing to the departure date. In addition, it is a benefit for railway operators to ensure the long distance passengers' traveling because they contribute a lot to ticket income.

The passenger assignment rules are based on the shortest travel paths, train capacity limitations and multi-commodity network flow model. When the passenger assignment encounters train capacity constraints, passengers will be allocated to travel along the shortest paths. In cases where multiple shortest paths are available, passengers are assigned based on a multi-commodity network flow model. This approach ensures efficient utilization of resources and fair distribution of passengers among the available paths. Otherwise, the updated shortest paths among the available travel paths are obtained for unsatisfied passengers. Then the passenger assignment process continues. For example, in Figure **1**, for passengers from station A to station C, the available travel routes are Line 2 (A-B-C), Line 3 (A-C) and Line 4 (A-B-C). The travel time of Line 3 is shorter than that of Line 2 and Line 4. In this case, if the ticket price of these lines is the same and the capacities meet passenger demand, the passengers between station A and station C will take Line 3 to accomplish their travel until Line 3 cannot serve any passengers. Then the unsatisfied passengers will choose Line 2 and Line 4 according to the multi-commodity network flow model.

Then it turns to the second stage. The results of the passenger assignment are used to evaluate the line plan according to indicators such as passenger attendance rates, the number of transfer passengers, and the number of boarding and alighting passengers at stations. After that, the neighborhood search of the line plan can be applied to construct new line plans. Then heuristic passenger assignment is used to compute the train frequencies. The whole process continues the second stage until it meets the terminal conditions.

Neighborhood Search

The neighborhood search operators are based on the line pool, such as extending a line, reducing a line, adding a stop, removing a stop, adding a line and removing a line. Each operator can generate a set of neighborhood line plans. Only one neighborhood line plan which is the most likely to improve the network line plan is selected to be applied at a time. The detailed information of operators is introduced as follows.

Extending a line will first calculate the capacity utilization of the extended section of each line, which is good for balancing the usage of section capacities. The section with the lowest capacity utilization is selected to extend. Then the line plan is updated by selecting a line that contains the updated origin, destination and extended station from the line pool. Reducing line computes the train capacity utilization of end sections of each line. The section with the lowest capacity utilization is considered to reduce. The updated lines selected from the line pool should include the updated origin and destination station.

Adding a stop is to add an extra stop of the selected line, which stopping pattern is not all stop patterns. By calculating the train capacities of the non-stopping sections, the extra stop can be added at the lowest train capacity utilization sections. Removing a stop is to remove one stop of the selected line, which is not a non-stopping line. The stop station with the lowest number of boarding and alighting passengers is considered to remove.

Adding a line is to add a line selecting from the line pool, which can provide the most direct connections for those who have to transfer based on the current line plan. Removing a line is to remove one line from the current line plan with the lowest average train capacity utilization.

The scope of the lines that neighborhood search operators selected has to be involved in the line pool. Here we take Line 1 in Figure **1** as an example of extending the line's neighborhood search process based on candidate lines in the line pool, see Figure **3**.

For Line 1, the available lines for extending the line based on the line pool are Line 5 to Line 8. Then the neighborhood solution is constructed by Line 2 to Line 4 and randomly selected line from Line 5 to Line 8.

Adaptive Simulated Annealing Algorithm (ASA)

The model in this paper is difficult to solve by exact algorithms. The simulated annealing algorithm has been widely used in line planning [10, 21, 30]. This paper applies the simulated annealing algorithm framework (Canca *et al*. [21]) and the designed neighborhood search operators to solve the proposed model. Based on the elements of simulated annealing [31], the ASA takes the following steps. The framework of ASA can be seen in Figure **4**.

1. Initialization

Constructing the HSR network line pool includes the candidate lines with feasible train routes and stopping patterns.

2. State transition

An adaptive selection mechanism based on the roulette wheel selection method is applied according to different neighborhood search operators' historical effectiveness (scores). Then the objective value of the current HSR network line plan (E_{cur}) and neighborhood network line plan (E_{nei}) are calculated separately. After obtaining the difference of the objective values ΔE ($\Delta E = E_{nei} - E_{cur}$), the Metropolis criterion is used to determine whether to accept the neighborhood solution or not, see Equation (14).

$$\gamma = \begin{cases} 1, \Delta E \geq 0 \\ \exp\left(\Delta E / \tau\right), \Delta E < 0 \end{cases} \tag{14}$$

where γ is the probability of accepting the neighborhood solution and τ is the current temperature of ASA. If there are K neighborhood operators, the ASA assigns a weight ε_k (equals 1 at the beginning of iteration) for each neighborhood operator. The weights are adjusted after a particular iteration (n_{seg}). The selection probability of the m

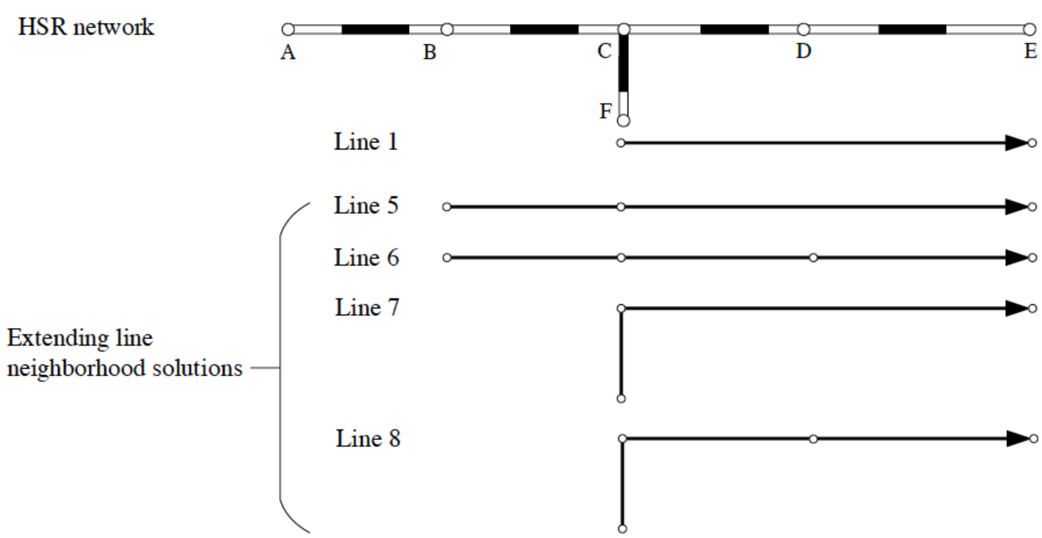

Figure 3: The neighborhood solutions for extending the line of Line 1.

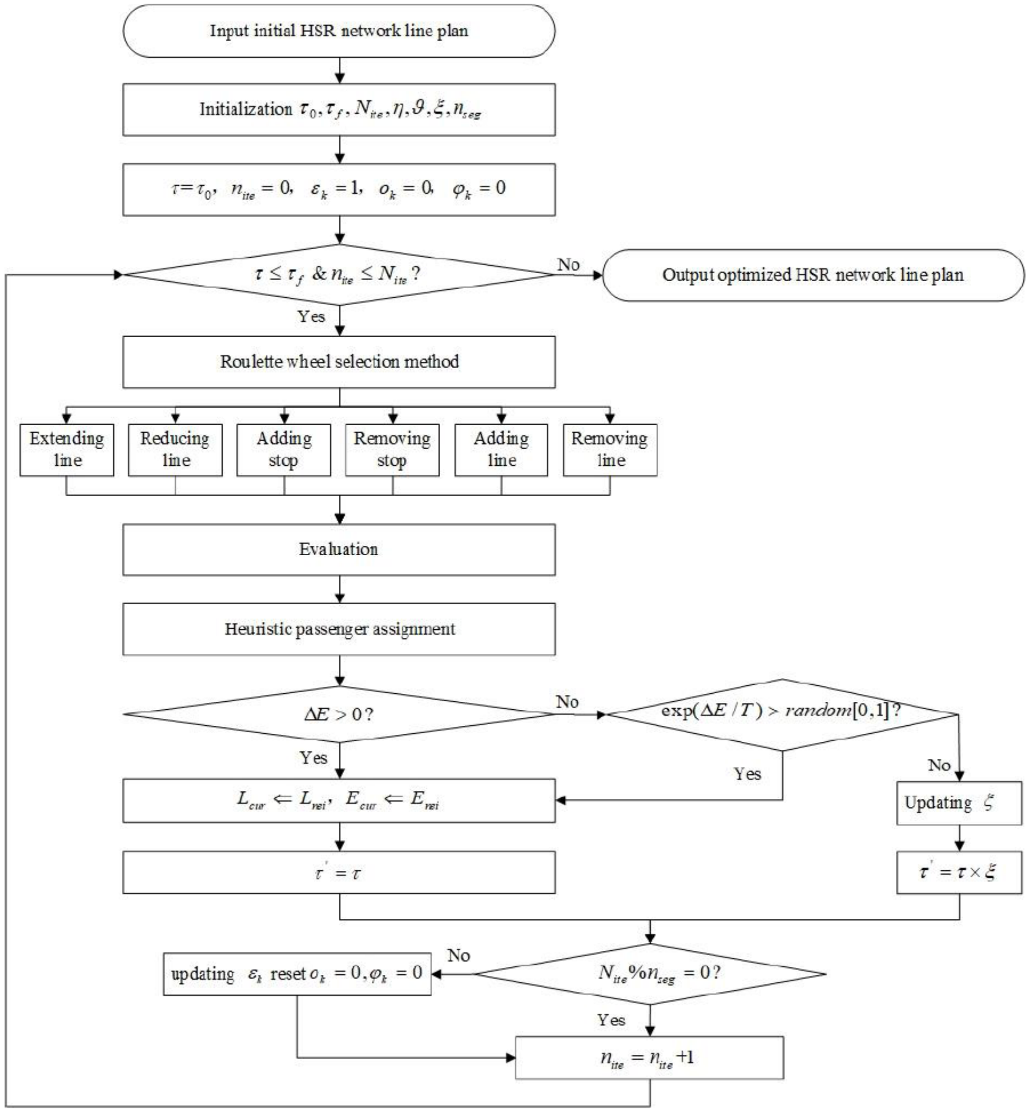

Figure 4: ASA algorithm for solving profit-oriented HSR network LPP.

operator is $\varepsilon_m / \sum_{k=1}^{K} \varepsilon_k$. During the n_{seg} iterations, the score (φ_k)of each operator is updated based on E_{nei} each iteration, see Equation (15).

$$\varphi_k = \begin{cases} \varphi_k + 10, E_{nei} > E_{best} \\ \varphi_k + 5, E_{best} > E_{nei} > E_{cur} \\ \varphi_k + 2, E_{nei} \quad is \quad accpeted \\ \varphi_k + 0, E_{nei} \quad is \quad not \quad accepted \end{cases} \tag{15}$$

The initial scores of neighborhood operators are set to 0. If k the operator's objective value is higher than the historical best objective value, increase the score by 10. If it is lower than the E_{best} but higher than E_{cur}, then increase the score by 5. Otherwise, using the Metropolis criterion to check whether E_{nei} is accepted or not. If it is taken, then it increases the score by 2. If it is not, the score remains unchanged.

At the end of n_{seg} iterations, the weight of each operator is calculated (see Equation (16)) and the score of each operator is reset to 1.

$$\varepsilon_k = \begin{cases} \varepsilon_k, \ o_k = 0 \\ (1 - \vartheta) \times \varepsilon_k + \vartheta \times \varphi_k / o_k, \ o_k \ne 0 \end{cases} \tag{16}$$

where ϑ is the reaction rate between 0 to 1 used to control the degree of depending on the historical results. o_k is the number of selections of the operator. Equation (16) indicates that if the operator is not selected during the n_{seg} iterations, its weight keeps unchanged. Otherwise, the updated weight depends on the current weight and historical results considering the reaction rate.

3. Cooling schedule

Assigning an initial temperature, see Equation (17). At the beginning of the iteration, the initial temperature is set to a very large value. Since the initial temperature does affect the acceptance rate of the solution, which is no better than the current solution, the initial temperature (see Equation (18) [20]) is accepted at 50% when $\Delta E < \eta E_{cur}$, where η is the coefficient.

$$\tau_0 = \Delta E / \mathrm{In}(0.5) \tag{17}$$

$$\xi = \begin{cases} \xi_0, \; n_{ite} < N_{ite} / 4 \\ \left(\tau_f / \tau\right)^{1/(2 \times n_{ite})}, \; n_{ite} < N_{ite} / 3 \\ \left(\tau_f / \tau\right)^{1/(n_{ite}/2)}, \; n_{ite} < N_{ite} / 2 \end{cases} \tag{18}$$

where, ξ_0 is the initial cooling rate, ξ is the updated cooling rate, τ_f is the final temperature, n_{ite} is the number of iterations, N_{ite} is the maximum number of iterations. By equation (18), the cooling rate can be dynamically adjusted. The updated temperature equals to $\tau \times \xi$.

4. Checking termination

This paper employs two termination conditions:

1. The current temperature becomes lower than the final temperature.

2. The number of iterations exceeds the maximum specified number of iterations.

These conditions are utilized to determine when the optimization process should be halted.

After initialization, the roulette wheel method selects a particular neighborhood operator. Based on the corresponding evaluation, a neighborhood line plan that is most likely to improve the HSR network plan is selected. Then carry out the heuristic passenger assignment and calculate the operational profit. Step 2 state transition is applied. Then ε_k and o_k are updated. After that, it is checked whether the current n_{seg} iterations are finished. If it is completed, the selection probabilities of operators are calculated. o_k is reset to 0. The algorithm goes to the next iteration. The algorithm keeps iterating until the termination.

A greedy heuristic algorithm (GHA) is designed to compare with ASA on solution efficiency and effectiveness. The main idea of the GHA is based on a given line pool. First, the network line plan is empty. The candidate lines are selected from the line pool one

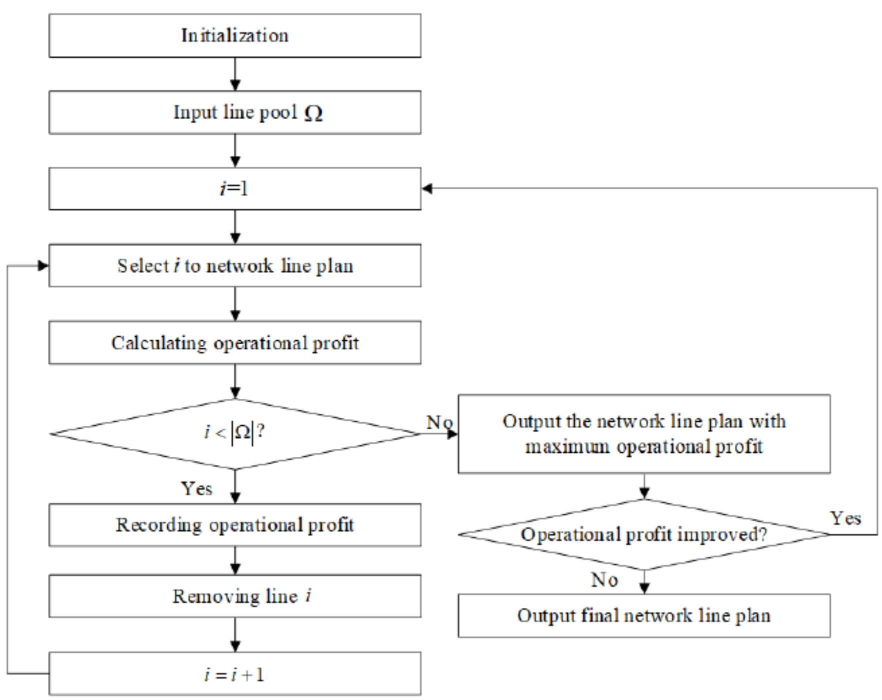

Figure 5: The framework of the GHA.

by one. Then the operational profit is calculated every time after changing the network line plan. The line which increases the operational profit most is retained. The selection goes to the next iteration based on the existing lines in the network line plan. The line selection process ends until the operational profit cannot be further improved. The framework of the GHA is shown in Figure **5**.

6. EXPERIMENTS

Figure **6** displays an example HSR network that encompasses several large and medium-sized cities. Each link in the network is annotated with the length of the section and the average travel time. The numbers assigned to the links and stations represent the section numbers and station numbers, respectively. The relevant parameters of the HSR network line plan are shown in Table **3** (according to the data used in [32, 33]). The passenger demand which Gravity Model calculates is shown in Table **4**. The section capacities and station capacities are shown in Table **5** and Table **6**. The parameters of ASA are shown in Table **7**. The number of OD pairs involved is 110. There are 519 lines in the line pool. The experiments are programmed in C# and run on an Intel i7 2.60 GHz laptop with 16GM RAM in a Microsoft Win 10 environment.

Table 3: HSR Network Line Planning Parameters

Parameters	Values	Unit
Average transfer time	60	min
Additional time to start	2	min
Additional time to stop	3	min
Average stopping time	3	min
Train fixed operational cost	15000	¥/train
Train variable cost per kilometer	150	¥/train
Train variable cost per stop	100	¥
Train capacity	1000	person/train
Ticket price weight	0.4	—
Travel time weight	0.6	—
GTC threshold amplification factor	1.2	—

Table 4: Passenger Demand of HSR Network

OD	NoP	OD	NoP	OD	NoP	OD	NoP	OD	NoP
0-1	29545	0-2	78720	0-3	10096	0-4	28519	0-5	20423
0-6	4882	0-7	18434	0-8	25745	0-9	18475	0-10	24394
1-0	28796	1-2	12489	1-3	4028	1-4	8067	1-5	6192
1-6	1509	1-7	5835	1-8	10351	1-9	4851	1-10	8063
2-0	81280	2-1	12239	2-3	5463	2-4	17280	2-5	11902
2-6	2426	2-7	9114	2-8	11752	2-9	9914	2-10	11222
3-0	10134	3-1	4159	3-2	5157	3-4	3100	3-5	2580
3-6	843	3-7	3572	3-8	3705	3-9	2136	3-10	4126
4-0	29932	4-1	7784	4-2	17779	4-3	3031	4-5	9008
4-6	1606	4-7	5966	4-8	7877	4-9	9532	4-10	7632
5-0	20772	5-1	6081	5-2	11722	5-3	2659	5-4	9635
5-6	1564	5-7	5530	5-8	6799	5-9	6035	5-10	7145
6-0	4798	6-1	1514	6-2	2422	6-3	832	6-4	1582
6-5	1598	6-7	2874	6-8	2582	6-9	1512	6-10	2480
7-0	17780	7-1	5970	7-2	8957	7-3	3416	7-4	5718
7-5	5512	7-6	2932	7-8	11576	7-9	5719	7-10	9324
8-0	26220	8-1	9955	8-2	12257	8-3	3664	8-4	7903
8-5	6991	8-6	2484	8-7	11365	8-9	9500	8-10	14947
9-0	18506	9-1	4887	9-2	10494	9-3	2122	9-4	9482
9-5	5964	9-6	1474	9-7	5708	9-8	9499	9-10	7107
10-0	24566	10-1	8156	10-2	11706	10-3	4176	10-4	7552
10-5	6965	10-6	2414	10-7	9298	10-8	14653	10-9	7244

Table 5. Section Capacities on HSR Network

Sections	0	1	2	3	4	5	6	7
Capacities	166	173	158	164	158	161	166	144
Sections	8	9	10	11	12	13	14	
Capacities	148	153	166	158	158	161	156	

Table 6: Station Capacities on the HSR Network

Stations	0	1	2	3	4	5	6	7	8	9	10
Capacities	468	446	345	170	395	255	414	510	477	413	287

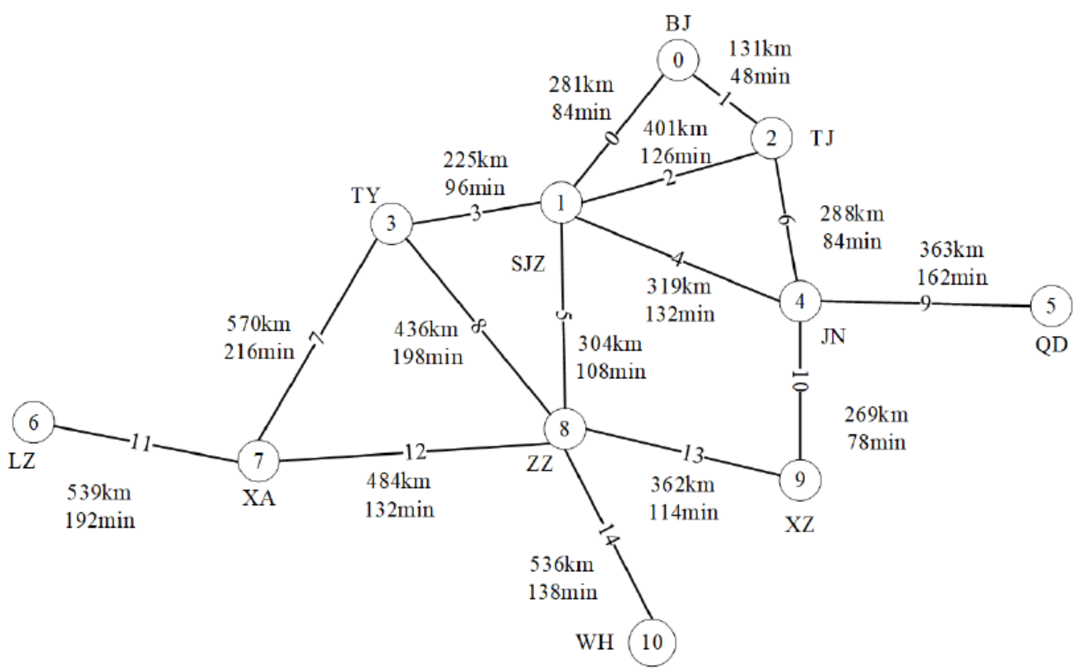

Figure 6: Topology of the example HSR network.

Table 7: Parameters of ASA

Parameters	Values
Maximum number of iterations N_{ite}	1000
Initial cooling rate ξ	0.9
Initial temperature τ_0	10000
Final temperature τ_f	0.001
Weighted response rate ϑ	0.7
The number of iterations per stage n_{seg}	10
Initial temperature setting coefficient η	0.33

Based on the above parameters, the optimized network line plan given by ASA and GHA is shown in Figure **7** and **8**. All trains operate in two directions. The train frequencies besides the lines are trains that operate in one direction.

Comparing Figure **7** and Figure **8**, the network line plan given by GHA is all medium and long distance lines, which can reduce the number of lines but without considering the difference in passenger demand on section level. The network line plan given by ASA can provide more transportation capacities based on short and medium distance lines better to consider the difference in passenger demand on section level. The operational results of the two algorithms are shown in Table **8**. OP, TI, OC, NoT, AveTCU, RT and PI represent the operational profit, ticket income, operational cost, the number of trains, the average train

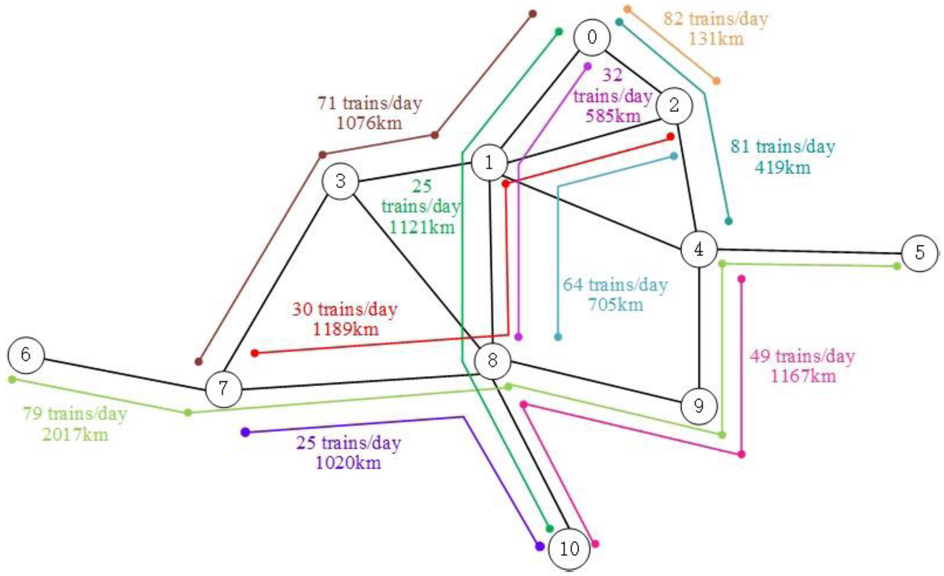

Figure 7: The final network line plan given by ASA.

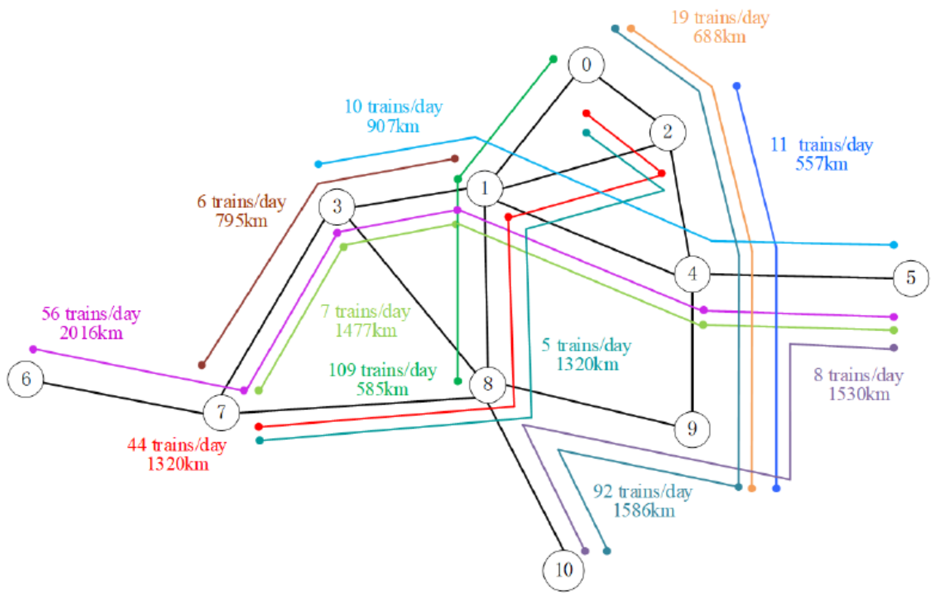

Figure 8: The final network line plan given by GHA.

Table 8: The Network Line Plan Indicators of ASA and a Greedy Heuristic Algorithm

	OP ($\times10^8$)	TI ($\times10^8$)	OC ($\times10^8$)	NoT	AveTCU	RT (min)	PI
GHA	1.974	3.415	1.439	367	91.38%	21.97	—
ASA	2.220	3.855	1.633	538	92.66%	3.50	14.05%

capacity utilization, running time and profit improvement, respectively.

Table **8** shows that ASA's operational profit of the network line plan is 14.05% higher than that of the greedy heuristic algorithm. Although the number of trains operated differently, the operational cost difference is relatively small. The reason is that the greedy heuristic algorithm's network line plan contains fewer lines and most of the lines travel long distance, while the ASA holds the opposite situation. The average train capacity utilization of the network line plan given by ASA is also higher than GHA.

7. CONCLUSIONS

This paper presents a mixed integer nonlinear programming model to determine the HSR network line plan with high operational profit. A heuristic passenger assignment method was used to simulate passenger route choice behaviors based on certain roles, such as long distance passengers' priority, multi-commodity network flow model and the next-to-shortest path method. An ASA was developed to solve the profit-oriented HSR network LPP. The passenger assignment and network line plan were solved in an intertwined way. The ASA was experimentally evaluated by comparing it with the designed GHA. It was illustrated that ASA performs better in increasing the operational profit in a shorter computation time. Therefore, the model and algorithm constructed in this paper show good performance in solving the network line planning. In further work, the stopping pattern could be considered as a decision variable. It would also be interesting to consider different train sizes and speeds. Other possibilities would be integrated line planning with dynamic ticket pricing or the reliability and robustness of the network [34] to optimize the line plan.

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DECLARATION OF INTEREST STATEMENT

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

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