An Iterative Approach for Profit-Oriented Railway Line Planning

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Abstract

With the rapid development of the Chinese high-speed railway network, more and more railway lines are becoming oversaturated, leading to inefficient operations and reducing the service quality. To improve the network's performance, this paper proposes a profit-oriented line planning model for optimizing both the operational costs and passenger travel times. Due to the complexity of the problem, an iterative approach is designed to solve the problem efficiently. Two case studies are implemented to verify the performance of the approach. The results of the case studies show that the proposed approach can improve the profit while balancing the operational cost and the passenger travel time, with reasonable computation times. For the resulting line plan, the optimal passenger routes, including transfers when necessary, are also determined. The proposed iterative approach increases the profit of an initial solution with on average more than 20% for a medium and a large-scale network.

Keywords

High speed railway network, Line planning problem, Iterative approach

1 Introduction

The Chinese high-speed railway (HSR) network has developed rapidly during the past ten years. Currently, the 4 "vertical" and 4 "horizontal" tracks (4V4H) of the HSR network are the backbone to connect the major cities in China. The four vertical high-speed railway lines are Beijing-Harbin (1800 km), Beijing-Shanghai (1318 km), Beijing-Hongkong (2383) and Hangzhou-Shenzhen (1449 km). The four horizontal high-speed railway lines are Qingdao-Taiyuan (940 km), Xuzhou-Lanzhou (1434 km), Chengdu-Shanghai (2066 km) and Kunming-Shanghai (2056 km). The majority of these HSR lines are only used for providing passenger transportation services. At the end of 2017, the length of the total high-speed railway was more than 25 thousand kilometres, which accounts for more than 60% of HSR lines in the world. The amount of passenger volume transported by HSR trains is 56.8% of the total railway passenger demand in China (China National Bureau of Statistics 2018). With the rapid expansion of the current HSR network, the total length of the HSR lines will reach 30 thousand kilometres and cover more than 80% of the cities in China by 2020. Figure 1 shows the 4V4H network and its associated HSR lines.

Comparing to the HSR lines in Europe and Japan, the large-scale HSR lines in China are different according to its actual operation practice. There are a large number of long-distance HSR trains operating per day to serve as many passengers travel demand as possible. However, the average passenger travel distance is usually much shorter than the HSR line distance. For instance, the average travel distance of the two main HSR lines is about 558 km (Beijing-Guangzhou HSR) and 621 km (Beijing-Shanghai HSR), while the distance of the whole HSR lines are 2281km and 1318 km respectively (Fu et al. (2015)). This may lead to the inefficient use of railway resources such as train capacity and HSR line capacity.

Since the Chinese HSR lines were constructed gradually, single lines were firstly designed between selected stations, and then merging and diverging lines were added to the line plan. Therefore, the previous line plan was designed without considering the network as a whole. After the basic 4V4H HSR network is formed, the operation plans should be made on the consideration of passenger demand features based on the whole HSR network. Because of its large-scale size, high transportation demand and network capacity limitations, it is required to develop efficient operation plans to improve the whole network's operational performances. Line planning is one of the crucial planning stages when designing a railway service.

To improve service quality and reduce the operational cost, this paper proposes an iterative approach for optimizing both operational cost and passenger travel time. This paper

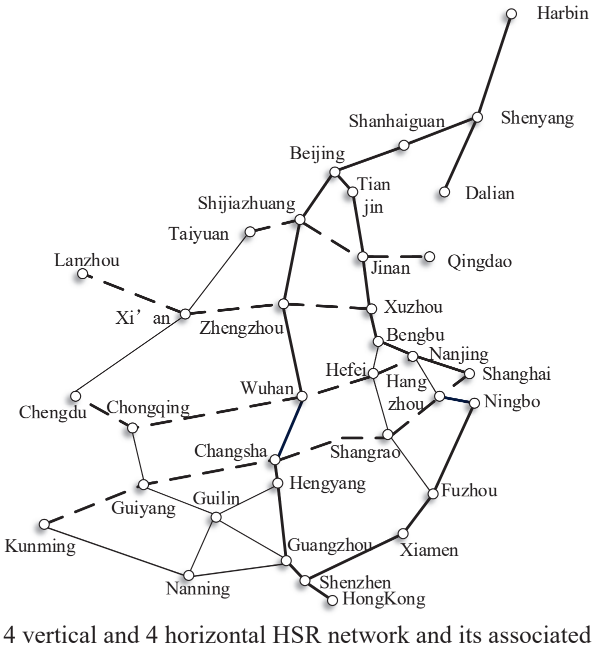

Figure 1. 4 vertical and 4 horizontal HSR network and its associated HSR lines

aims to design a network line plan for the 4V4H HSR network and to determine the frequency of the lines, optimizing operational cost and passenger travel time, while considering transfers when necessary. In order to obtain this, a profit-oriented objective function is introduced. The detailed contributions of this paper are summarized as follows.

(i) A profit-oriented objective is proposed that uses a time value parameter to consider the travel time in the ticket price.

(ii) An iterative algorithm is designed to solve the line planning problem.

(iii) Different local search improvements are considered to generate neighborhood solutions, such as extending a line, reducing a line, inserting a line and removing a line.

(iv) Fast and heuristic evaluation methods are designed to choose the most promising neighborhood solution in order to obtain a better line plan efficiently.

(v) The passenger route choice is optimized by assigning each passenger to its shortest path through the network.

The remainder of this paper is organized as follows. Section 2 gives a brief literature review of the line planning problem. In Section 3, the profit-oriented line planning problem and the proposed mixed integer linear programming model are presented. Section 4 shows an iterative solution approach in detail. Section 5 shows the description and evaluation of the numerical experiments. In Section 6, the major conclusions and further studies are presented.

2 Literature Review

Recently, several studies have addressed the network design or line planning problem (LPP) integrated with traffic assignment or passenger assignment and focusing on the operational cost and passenger preferences (Karbstein (2014); Borndörfer and Karbstein (2012); Friedrich et al. (2017); Nachtigall and Jerosch (2008); Fu et al. (2015); Rosalia (2017); Borndorfer et al. (2007)). In general, the available infrastructure and passenger demand between each origin-destination (OD) pair are considered as given input data of the LPP. The LPP aims to determine the appropriate set of lines, each serving a sequence of stops, together with its associated frequencies, so that the total passenger demand is satisfied directly or with a limited number of transfers.

Past studies typically differ in how they consider the interests of passengers and operator costs. E.g., Friedrich et al. (2017) investigate a cost-oriented line planning model with passenger assignment evaluation. In this case, the line planning solutions focus on the operational cost rather than service quality, such as travel time, transfers and passenger waiting times, which may lead to a reduction of the demand and lower revenues. With this concern, Nachtigall and Jerosch (2008) integrated the cost-oriented objective and customer-oriented objective into a single model by transforming one of them into a constraint. Instead of converting one objective into the constraint, Borndörfer et al. (2007) used a weighted sum of cost-oriented and customer-oriented objectives while the lines are generated dynamically with flexible passenger paths. In addition, Fu et al. (2015) developed a bi-level programming approach to optimize the line planning and passenger assignment sequentially.

Rosalia (2017) developed a model to optimize the operational cost and travel time iteratively on a city road network, which solves the minimum operational cost line plan and then minimizes the travel time based on that line plan

In large-scale networks, transfers are unavoidable because of the infrastructure capacity limitation and the operational costs of operating all direct connections. Moreover, if long-distance trains stop at each intermediate station, the resulting lower speed will have a negative effect on the HSR network capacity and also reduce the attractiveness of the HSR trains. In order to consider transfers, Borndörfer and Karbstein (2012) presented a direct connection approach to integrate line planning and passenger routing optimization by encouraging the direct connection and penalizing the transfers. Furthermore, Karbstein (2014) introduced a new model for integrated line planning and the passenger routing problem by involving a variant of the 2-terminal Steiner connectivity problem as the pricing problem and applying it to handle the transfers in LPP. However, for some passengers it may be beneficial to have transfers rather than spending much more time on a train with a direct connection. Therefore, convenient and time-saving transfers should also be considered. Readers interested in LPP are referred to a review conducted by Schöbel (2012). None of these works are profit-oriented and integrate operator costs and passenger travel time in a single objective by making the revenues dependent on the passenger travel time.

Although more and more researches are focusing on the LPP in recent years, the trade-off between long distance direct connections and transfer services have not been studied greatly. Currently, the passenger flows on the Chinese HSR network have significant characteristics. According to the current timetable, there are 595 stations on the HSR network. While the number of direct connections accounts for around 9% of the total OD pairs according to current line plan (Liu and Li (2018)). Therefore, the majority of the passengers need to take transfers. An explicit decision should be made on which passengers should be able to travel directly and how to facilitate transfers for the remaining passengers.

In this paper, instead of choosing between a cost-oriented and a customer-oriented objective, we propose a profit-oriented line planning model which maximizes the ticket price income minus the operational cost. The ticket price (and thus the operator revenues) are reduced when passengers need a transfer or a detour and have no direct train from origin to destination. Moreover, the operational costs consider fixed and length dependent costs for operating the different lines.

3 Profit-oriented Line Planning

The profit-oriented line planning problem presented in this paper focuses on making a trade-off between a cost-oriented objective related to the number of trains operated to meet all the passenger demand and the customer-oriented objective by minimizing the travel inconvenience. This travel inconvenience is defined here as additional travel time compared to the travel time of having a direct connection along the shortest path in the infrastructure network. The following assumptions are made throughout this paper.

- Assumptions:

  (i) Stopping pattern: Since only major stations are considered as nodes in the network, the stopping pattern of the line plan is an all-stop pattern for the major stations. The passenger demand of small stations can be assigned to the major stations in a pre-calculation phase. After designing the lines, a stopping pattern optimization can be used to determine exactly which (small and large) stations will be served by each line.

(ii) Demand: All demand in the network is served with at most two transfers. In this network of limited size (only considering the major stations) two transfers should be more than enough.

(iii) Passenger route choice: Passengers will always choose the shortest travel time path no matter what the price of the path is. Passengers of the high-speed railway normally pay more attention to the travel time rather than the ticket price.

(iv) Train type: Two train types are considered, a single train-set with 500 seats and a double train set with 1000 seats. For now, there is only one speed of train considered on the network, i.e., the 300-350 km/h high-speed train. Currently, the operation speed on this network is set to 250km/h for some safety reasons. With the development of the high-speed railway in China, there is a tendency to operate higher speed trains in the future. In addition, the train speed is just a parameter in our model, which could easily be changed to 250km/h. Moreover, we do not impose a maximum number of trains for a certain track yet. Including track capacity and trains with different speed on the network is considered as future work.

(v) Line attributes: There is no limitation on the line length considered and lines can start and end in any station.

(vi) Passenger demand is considered symmetrical and therefore each line is assumed to operate in both directions.

- This is considered as input:

(i) Passenger OD matrix: The number of passengers traveling between any two stations is given in the symmetrical OD matrix. The passenger OD matrix represents the daily passenger demand.

(ii) HSR network topology: The available stations (nodes) and tracks (links) are fixed and the distance of each link between two stations is known.

Variables and Notations

In this study, we use the following variables and notations. The physical network topology is considered as the undirected graph $N = (V, E)$. The node set $V = \{1,2,3,\dots,n\}$ represents the stations and the edge set $E = \{e, e \epsilon V \times V\}$ represents the connections of two stations in the network. Before solving the LPP, we introduce the train service network (TSN). In order to take transfer times into account and to calculate the approximate travel time, the TSN is constructed to depict the itineraries of passengers (Fu et al. (2015)). This is also called the Change & Go network in Schöbel and Scholl (2006).

D a set that represents the passenger demand of all the OD pairs.

Inc	the operational income.
Cos	the operational cost.
L_{cur}	the current line plan.
C^{Fix}	the fixed cost for operating a line with frequency one.
C^{Var}	the variable cost per line per kilometre.
d_{v_i,v_j}	the number of passengers want to travel from station v_i to station v_j.
$T^{P}_{v_i,v_j}$	the length of the shortest travel time of each OD pair $(v_i, v_j)$with respect to the physical network independent of the line plan.
T_v	the time value (the ticket price per unit of time) to convert the passenger travel time into the ticket price by multiplying with the riding time and dwelling time.
$StaInc$	the ideal income, if each passenger would have a direct train on his/her shortest path: i.e., $\sum_{v_i,v_j\in V} T^{P}_{v_i,v_j} * T_v * d_{v_i,v_j}$.
$T^{S}_{v_i,v_j}$	the length of the shortest travel time path of each OD pair (v_i, v_j) on the TSN.
T^{Pen}_{v}	the penalty time value: a fixed value for each transfer on a path and per unit of time for the detours.
k_l	the length of line l (in kilometres).
f_l	the frequency of line l.

Objective

Instead of using the weighted sum of a cost-oriented and a customer-oriented objective, this model uses a profit-oriented objective which considers the operational cost and the passenger total travel time represented by the operational income. The operational cost is composed of a fixed cost per line per train and a variable cost depending on the length of the line. By introducing the time value, the passenger travel time can be converted into operational income. Thus, the operational income can be formulated as the passenger total travel time multiplied with the time value and minus the transfer and detour penalties. The goal is to maximize the profit.

$$\max\ Z = Inc - Cos. \tag{1}$$

$$Inc = StaInc - \sum_{v_i,v_j\in V} (T^{S}_{v_i,v_j} - T^{P}_{v_i,v_j}) * T^{Pen}_{v} * d_{v_i,v_j} \tag{2}$$

$$Cos = \sum_{l\in L_{cur}} (C^{Fix} + C^{Var} * k_l) * f_l. \tag{3}$$

Equation (2) gives the specific composition of the operational income. The left side of the minus is the ideal income calculated by the ideal shortest travel time of the direct connection of each OD pair. The right side of the minus is the penalty fee for transfers and detours by using the results of the comparison of actual travel time and the ideal travel time multiply with the penalty time value and the associated passenger demand. The ticket prices reduction is determined in such a way that it (partly) compensates the discomfort or lost time of having to travel longer (than the ideal shortest path). This also implies that passengers will never prefer to travel even longer because it would be cheaper. The operational cost is presented as equation (3), which is related to the number of lines and associated frequencies.

Constraints

The constraints used in the iterative algorithm are mainly about satisfying passenger demand and capacity limitations of the trains: All passenger OD pairs should be served with at most two transfers. Moreover, for each arc of the network, the summed capacity of all the lines (each with a certain frequency and vehicle type) on that arc should be sufficient to meet the passenger demand on that arc.

The solution is represented by a set of lines, each associated with a certain frequency and a vehicle type. A line consists of a sequence of nodes.

4 An Iterative Approach

The TSN is constructed based on the given line plan. A small example is introduced to illustrate the construction of TSN. In Figure 2, the topology of the physical railway tracks and the line plan are given. According to the line plan, a TSN is built as shown in Figure 3. In the TSN, the passenger routes of different OD pairs can be seen as the combinations of several types of arcs with the associated nodes. For example, the dotted line depicts the passenger from station B to station D take the sequence of boarding arc, riding arc, dwelling arc, riding arc, transfer arc, riding arc and alighting arc to reach their destination.

This paper presents an iterative framework for solving the network LPP in two stages. With the idea of minimizing the operational cost and saving the passenger travel time, an initial line plan is generated with a constructive heuristic in the first stage. Then the initial

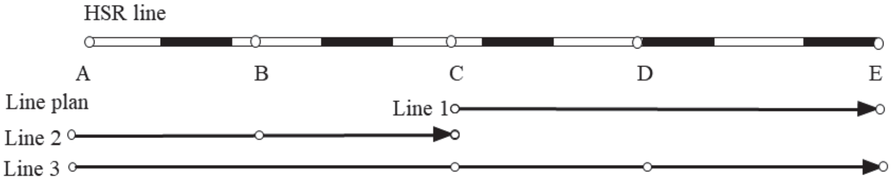

Figure 2: An example of railway topology and given line plan

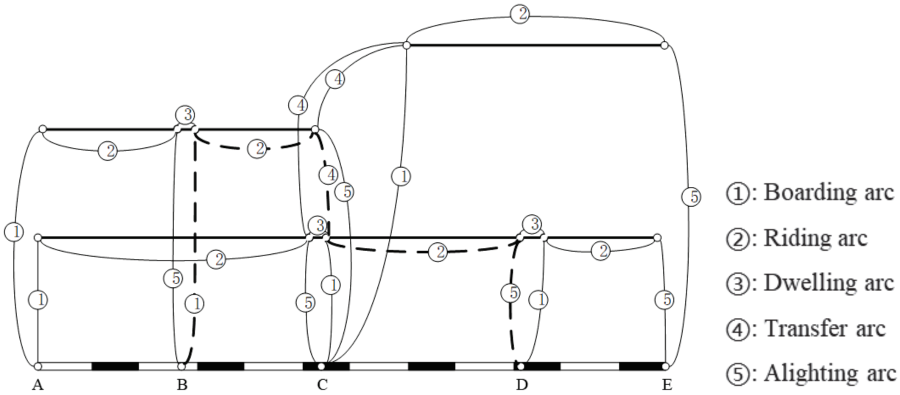

Figure 3: A train service network (TSN) constructed based on the information in Figure 2

line plan is given as the input for the second stage, where an iterative approach is performed to optimize the initial line plan. Each iteration of the second stage starts with the results of the passenger assignment process and determining the most appropriate frequency and vehicle size for each line. Then, some indicators are calculated to evaluate the current line plan and to determine the modifications required to determine a new and better line plan. The second stage is repeated until the algorithm reaches the stopping criterion. The different steps of the approach are now explained one by one in more detail.

Initial Line Plan Generation

The basic idea of the initial line plan generation is to select those lines that serve directly as much passenger demand as possible. First, a line pool $L^P_{v_i,v_j}$ is constructed containing the shortest path between every OD pair in the physical HSR network. Then, one by one, from that pool those lines are selected that serve the most passengers directly, not only from the starting towards the ending station of the line, but also from and towards all stations in between on that line. As in many research papers on railway line planning (Goerigk, Schmidt (2017), Yang et al (2016)), we assume that passengers travel according to their shortest path.

During this evaluation, only OD pairs that are not served yet directly by previous lines are considered. The selection of lines ends as soon as all nodes are covered. After that, the passenger assignment process is performed to check whether the transfer constraint (at most two transfers for each passenger) is satisfied. If not, the passenger OD pairs that break the transfer constraints are selected to be served directly and the corresponding lines from the line pool are added to the initial line plan. The outline of the process described above is shown in Algorithm 1.

Algorithm 1: Heuristic algorithm for calculating the initial line plan

```
Calculate the shortest path set $S$ of each OD $(v_i, v_j) \epsilon D$ w.r.t track lengths
**for** path $l^P_{v_i,v_j} \epsilon L^P_{v_i,v_j}$ **do**
  **for** $(v_i, v_j) \epsilon D$ **do**
    - assign direct passengers on $l^P_{v_i,v_j}$
  **end for**
  - calculate the number of direct passengers assigned on the path $l^P_{v_i,v_j}$
**end for**
**repeat**
  - select the path $l^P_{v_i,v_j}$ with the most direct passengers into the initial line plan
**until** all the nodes in the network are covered.
Checking the transfer constraint. The set of initial line plan $L^0$ is obtained
```

Passenger Assignment and Frequency Setting

We assume that the passengers look for the shortest path in travel time among all the possible paths between their origin and destination in the TSN. Firstly, the TSN of the initial line plan is constructed. The shortest paths are found using a modified Floyd algorithm (Floyd (1962)), which takes into account the transfer constraint by counting the number of transfers of the possible shortest paths and choose those paths with less than two transfers. Due to the TSN used, possible transfers are also considered when determining the shortest path. The line plan generally contains (partially) overlapping lines, for some OD pairs, there may exist several paths with the same shortest travel time. As the consequence, the passenger route choice during the passenger assignment process is assigned randomly based on these paths.

In order to determine the frequency of each line, the number of passengers assigned to each part (link between two consecutive stations) of a line is considered. The part with the highest number of passengers determines the frequency and vehicle size assigned to the line. After calculating the frequencies of lines, the cost of operating all the lines can be obtained.

Line Plan Evaluation and Modification

In order to improve the line plan, four modification methods are considered, namely, reducing a line (*Reduction*), extending a line (*Extension*), removing a line (*Removal*) and inserting a line (*Insertion*). Each type of modification leads to a neighbourhood of possible line plans. The Reduction neighbourhood of a current solution contains all line plans where one terminal node of one line is removed. The Extension neighbourhood contains all line plans where one node, adjacent to the terminal node in the physical network, is added to one of the lines. When it comes to Insertion, all lines corresponding to OD-pairs without a direct connection in the current line plan, are considered. For Removal, the neighbourhood contains all line plans where a line of the current line plan is removed. In each neighbourhood, only feasible line plans are considered.

The detailed evaluation and modification process of the line plan is illustrated in Figure 4 and is now explained. Given the results of passenger assignment, two evaluation calculations are applied on the current line plan considering Reduction and Extension a line. Here we consider all neighbourhood solutions implicitly by heuristically evaluating how promising the neighbourhood solutions are.

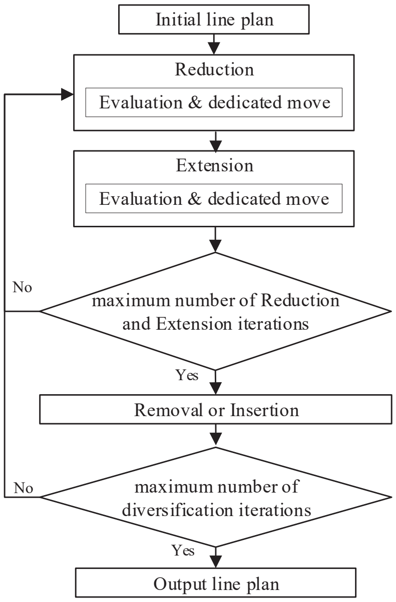

Figure 4: The iterative approach framework for line planning optimization

When considering Reduction, the load factors of terminal edges of each line are calculated as the evaluation indicator of the current line plan. The load factor is the actual passenger volume on the edge of a line divided by the frequency of the corresponding line. Then the terminal edge with the lowest load factor is selected to be reduced. After Reduction, Extension is considered by comparing the number of indirect passengers that can be transported directly through the extended edges. The available extended edge that can provide the most additional direct connections for passengers is selected. After each modification, the passengers need to be assigned to the TSN in order to evaluate the total profit (ticket sales income minus line operating costs). Only solutions that actually improve the profit are accepted and implemented. Reduction and Extension are executed until a predetermined number of iterations. This number is discussed later in Section 5. It was necessary to predetermine such a number because continuing until a local optimum is reached turns out too time consuming. It is well-known that the passenger assignment process, unavoidable when evaluating the profit of a new line plan, is computationally very expensive.

In order to diversify the algorithm, two disturbances are implemented as well: Removal and Insertion. One of both is selected randomly and the line to remove or insert is also selected randomly. The solution of the disturbance is accepted whether the solution is better or worse than the current solution. The number of diversification iterations is also fixed beforehand as a stopping criterion for the algorithm.

The previous process is presented in Algorithm 2. The correlated notations are as follows.

Z_{cur}	the profit of the current line plan.
Z_{nei}	the profit of the neighbourhood solution based on the current line plan.
L_{nei}	the selected neighbourhood line plan.
E_{red}	the neighbourhood solution set of reducing a line.
E_{ext}	the neighbourhood solution set of extending a line.
E_{rem}	the neighbourhood solution set of removing a line.
E_{ins}	the neighbourhood solution set of inserting a line.
A_{undir}	the set of OD pairs with passengers requiring at least one transfer.
TSN_{cur}	the train service network based on the current line plan.
TSN_{nei}	the train service network based on the neighbourhood solution of the current line plan.

Algorithm 2: Iterative evaluation and modification of line plan

```
1:  Repeat
2:    Repeat
3:      Reduction method
4:        Select the $e_{red}$ with the lowest load factor in $E_{red}$
5:        Modify the $L_{cur}$ and $TSN_{cur}$ to obtain $L_{nei}$ and $TSN_{nei}$
6:        if network connectivity check = true do
7:          Calculate passenger assignment and the profit of $L_{nei}$
8:          if $Z_{nei} > Z_{cur}$ do
9:            - $L_{cur} \leftarrow L_{nei}, TSN_{cur} \leftarrow TSN_{nei}, Z_{cur} \leftarrow Z_{nei}$
10:           - update $E_{red}$ and $E_{ext}$
11:         else do
12:           - $L_{nei} \leftarrow L_{cur}, TSN_{nei} \leftarrow TSN_{cur}, Z_{nei} \leftarrow Z_{cur}$
13:           - delete this $e_{red}$ from set $E_{red}$
14:       else do
15:         - roll back to $L_{cur}$ and $TSN_{cur}$
16:     Extension method
17:       Select $e_{ext}$ with the highest number of increased passengers in $E_{ext}$
18:       Modify the $L_{cur}$ and $TSN_{cur}$ to obtain $L_{nei}$ and $TSN_{nei}$
19:       Calculate passenger assignment and the profit of $L_{nei}$
20:       if $Z_{nei} > Z_{cur}$ do
21:         - $L_{cur} \leftarrow L_{nei}, TSN_{cur} \leftarrow TSN_{nei}, Z_{cur} \leftarrow Z_{nei}$
22:         - update $E_{ext}$ and $E_{red}$
23:       else do
24:         - $L_{nei} \leftarrow L_{cur}, TSN_{nei} \leftarrow TSN_{cur}, Z_{nei} \leftarrow Z_{cur}$
25:         - delete this $e_{ext}$ from set $E_{ext}$
26:   until maximum number of Reduction and Extension iterations
27:   Disturb
28:     Index = random (0,1)
29:     if index = 0 do Removal
30:       - select a line $l_b$ randomly from $L_{cur}$ and remove it
31:       - modify the $TSN_{cur}$as $TSN_{nei}$
32:       if network connectivity check = true do
33:         - calculate passenger assignment and the profit based on $L_{nei}$
34:         - $L_{cur} \leftarrow L_{nei}, TSN_{cur} \leftarrow TSN_{nei}, Z_{cur} \leftarrow Z_{nei}$
35:         - turn to step 2
36:       else do
37:         - $L_{nei} \leftarrow L_{cur}, TSN_{nei} \leftarrow TSN_{cur}, Z_{nei} \leftarrow Z_{cur}$
38:         - turn to step 27 and taboo $l$
39:     else do Insertion
40:       - calculate $A_{undir}$
41:       - randomly select an OD pair from $A_{undir}$. Add its shortest path as line $l$
42:       - modify the $TSN_{cur}$ as $TSN_{nei}$
43:       - calculate passenger assignment and the profit based on $L_{nei}$
44:       - accept the $L_{nei}$ as $L_{cur}$ and $TSN_{cur}$ as $TSN_{nei}$
45:       - turn to step 2
46: until maximum number of diversification iterations
47: Output the line plan and objective profit
```

5 Experimental Results

The experimental results of implementing the above iterative approach are presented in this section. The algorithm is implemented in C# and runs on an Intel i7 2.81GHz with 24GB RAM in the environment of Microsoft Win10. The input contains are the HSR network infrastructure, a fixed passenger OD matrix, link distance and link travel time (based on the single average speed considered). In order to show the performance and effectiveness of the proposed dedicated modification methods, we compare it with random modification methods without heuristic evaluation of the current line plan in order to determine the most promising Reduction and Extension (the random method is listed in Algorithm 3 in Appendix). Three passenger demand scenarios are considered corresponding to two networks, i.e., medium-scale network and 4V4H network, which contain 26 nodes (676 OD pairs) and 35 nodes (1225 OD pairs) respectively. The medium-scale network considers a part of the 4V4H network.

The specific passenger demand over the network is hard to obtain due to the confidentiality of the China Railway company. Therefore, the passenger demand used in this research is generated randomly. Additionally, other parameters used in the numerical experiments are shown in Table 1.

Table 1: Parameters setting

Name	**Value**	**Unit**
Train speed	300	km/h
Transfer time penalty	30	min
Stopping time	3	min
Ticket rate	0.5	CNY/km
Time value	2.5	CNY/ person, min
Penalty time value	0.55	CNY/min
Fixed cost of different train types	15000/10500	CNY/train
Variable cost of different train types	150/105	CNY/km
Train capacity of different train types	1000/500	seats/train

We assume that there are two types of train capacities, namely the doubled train and the single train, corresponding to different fixed cost and variable cost. The cost values of the single train are 0.7 times of the doubled train. The time value of Table 1 is computed as ticket rate multiply train speed, i.e., 0.5 * 300 / 60 = 2.5 CNY per person per minute. We assume that the average income of citizen is 33 CNY/hour. Thus, the penalty time value is 33/60=0.55 CNY/min. A small example is given in Figure 5 to show how these parameters work in the profit calculation. The example line plan is shown in Figure 6.

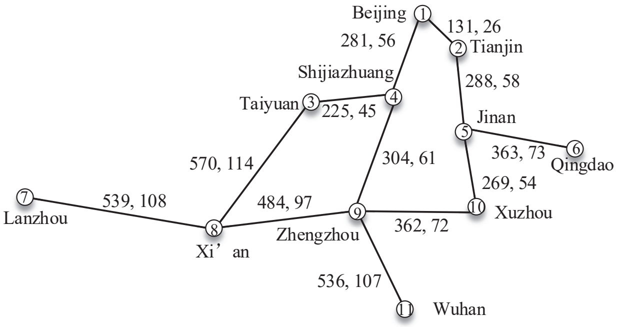

Figure 5. Small example for presenting the profit calculation

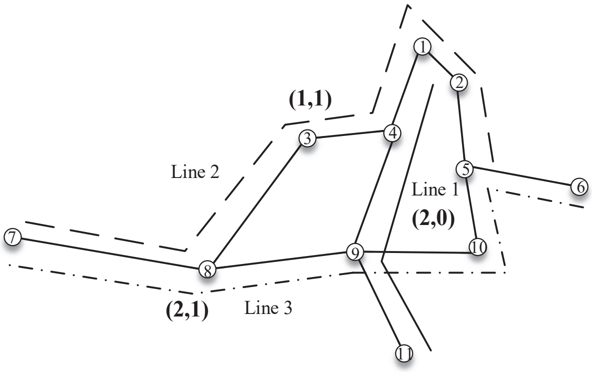

Figure 6. Example line plan of small network

In Figure 5, the first number besides every link indicates the distance between two nodes and the second number gives the corresponding travel time (since all trains have the same speed). In Figure 6, the first number between the brackets is the number of doubled trains (large size) on that line and the second number is the number of single trains. The operational cost of line 1 is 15000+150*(281+304+536)) * 2=366,330. After computing the operational cost of line 2 and line 3, the total operational cost equals to 1,767,855.

The operational income is calculated as the ideal income minus the penalty caused by transfers and detours. We assume here that the passenger demand of each OD pair is 100. The ideal income is the price that all the passenger OD pairs would pay when they are served by direct connections on their shortest paths. For instance, the ideal income of passengers from node 1 to node 5 equals the shortest travel time multiplied with the time value and the passenger demand between node 1 and node 5, i.e., (26+3+58) * 2.5 * 100 = 21,750. According to the ideal income calculation method of node 1 to 5, the total ideal income of all the passenger OD pairs is obtained as 2,435,250. When computing the penalty fee of transfers or detours, the penalty time is calculated as the actual travel time minus the shortest travel time with respect to the physical network. For example, the penalty fee (actually a reduction in the ticket price) for passengers between node 3 and node 9, requiring a transfer in node 4, equals the penalty time multiplied with the penalty time value and the passenger demand of that OD pair: i.e., ((45+30+61) - (45+3+61)) * 0.55 * 100 = 1,485. The total penalty fee of those who have transfers and detours is 102,245. The final operational income of all the passenger is 2,333,005.

Medium-scale Network Study

A medium-scale example is driven from the Chinese 4V4H HSR network (Figure 1) with 26 nodes and 676 OD pairs. The topology of the network can be seen in Figure 7.

For this experiment, we applied the approach presented in Section 4 and tested 3 different passenger demand scenarios. After testing several combinations of different number of Reduction and Extension iterations and diversification iterations on a small network, we concluded that the number of diversification iterations should be much higher than the number of Reduction and Extension iterations in order to obtain a high-quality solution efficiently. Therefore, for now, the number of Reduction and Extension iterations is set to 10 and the number of diversification iterations is set to 50.

The algorithm is executed during ten runs for each passenger demand scenario. For these ten runs, the maximum profit, average profit, the average percentage of improvement in profit compared to the initial line plan and the average computation time for a single run are selected as the parameters to illustrate the performance of the iterative approach. The results are listed in Table 2.

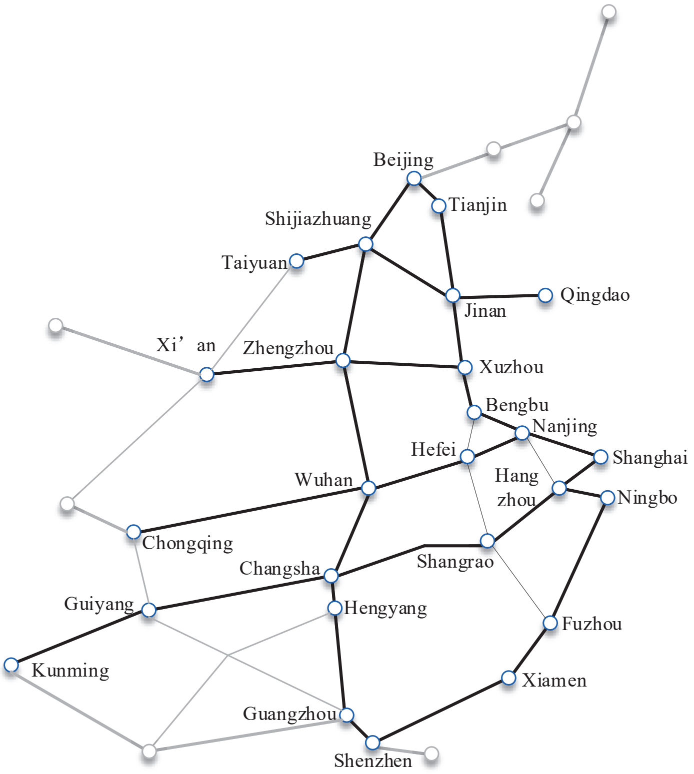

Figure 7: The medium-scale example HSR network (grey links and stations are not considered)

Table 2: Numerical experiment results on medium-scale network

Passenger demand scenarios	Maximum profit (*10^7)	Average profit (*10^7)	Improvement	Average running time
Initial 1	1.91	-	-	14s
Random 1	2.31	2.26	18%	2229s
Dedicated 1	2.34	2.26	18%	2711s
Initial 2	1.69	-	-	6s
Random 2	2.34	2.24	33%	2873s
Dedicated 2	2.33	2.24	33%	3017s
Initial 3	1.80	-	-	3s
Random 3	2.09	2.06	15%	1071s
Dedicated 3	2.10	2.08	16%	1786s

It can be seen from the improvement column that the proposed iterative algorithm of both random modification and dedicated modification performs well in this medium-scale network by increasing the profit from 15% to 33% compared to the initial line plan. The average of the improvements of random modification and dedicated modification are 21.8% and 22.4%. The improvement of the dedicated modification is the same or slightly better than the random modification in all three passenger demand scenarios.

From the aspect of computation time, the dedicated modification needs more time than the random modification because of the extra time for the heuristic line plan evaluation. However, in general, the computation time of both modifications are acceptable. To sum up, the solution approach is effective and efficient, and for the medium-scale network the dedicated and the random modification perform similarly.

Large-scale HSR Network Study

Also the large-scale HSR network (Figure 1) is used to show the efficiency and performance of the proposed algorithm. The running configurations setting is the same as the medium-scale network, however only 5 runs are performed for each scenario. The numerical experiment results are shown in Table 3.

Table 3: Numerical experiment results on large-scale network

Passenger demand scenarios	Maximum profit (*10^7)	Average profit (*10^7)	Improvement	Average running time
Initial 1	4.72	-	-	59s
Random 1	6.03	5.79	23%	11258s
Dedicated 1	6.11	6.04	28%	20694s
Initial 2	5.18	-	-	84s
Random 2	6.21	6.17	19%	6890s
Dedicated 2	6.27	6.24	20%	14805s
Initial 3	4.65	-	-	87s
Random 3	5.58	5.55	19%	7120s
Dedicated 3	5.64	5.57	20%	9586s

Due to the increase in the size of the network and the network connectivity, the network provides more choice for passengers to travel, which makes it much more complicated to solve the LPP and requires more computation time. In addition, the size of the solution neighbourhoods, mostly related to the number of lines considered, has increased significantly.

Also for the large network, both modifications improve the results of the corresponding initial line plan. The random modification and dedicated modification increase the profit with on average 20% and 23%. The results of the dedicated modifications are now clearly better than the random modifications for all three passenger demand scenarios. Obviously, the approach with dedicated modifications requires more computational time.

When looking at all six scenarios, some tendencies can be observed. The operational cost and income of all these scenarios are shown in Table 4. The operational income is an indication of the direct passengers and the operational cost indicates the frequency and number of lines. The M and L in Table 4 represent the medium-scale network and the large-scale network.

From Table 4, we can see that the operational costs of the modified line plans are always significantly lower than that of the initial line plan. However, the majority of the scenarios have a higher number of lines. The reason may that the proposed algorithm tends to reduce the frequencies of the long-distance lines and add short-distance lines on the busiest part instead.

Table 4: The maximum results of different scenarios

Passenger demand scenarios	Average profit (*10^7)	Improvement	Average running time
M Initial 1	3.92	2.01	8
M Random 1	3.90	1.59	10
M Dedicated 1	3.91	1.58	11
M Initial 2	3.95	2.26	8
M Random 2	3.94	1.61	11
M Dedicated 2	3.94	1.60	9
M Initial 3	3.74	1.94	7
M Random 3	3.73	1.65	8
M Dedicated 3	3.75	1.65	14
L Initial 1	10.60	5.88	9
L Random 1	10.65	4.62	13
L Dedicated 1	10.62	4.51	16
L Initial 2	10.73	5.55	11
L Random 2	10.66	4.45	10
L Dedicated 2	10.63	4.35	14
L Initial 3	9.90	5.24	11
L Random 3	9.87	4.29	10
L Dedicated 3	9.86	4.22	11

Taking large-scale network with passenger demand scenario 1 as an example, we compare the performance of the proposed approach. The results of its initial line plan and modified line plan are given in Table 5. The average length of the lines is weighted by frequencies.

The number of lines increase while the operational cost decrease when using the dedicated modification. It is because that the average length of the lines is lower in the dedicated optimized line plan. It can be seen that he dedicated modification tends to reduce the line length.

Table 5: The results of large-scale network with passenger demand scenario 1

Line plan	**Initial line plan**	**Random optimized line plan**	**Dedicated optimized line plan**
Maximum profit (*10^7)	4.72	6.03	6.11
Operational cost (*10^7)	5.88	4.62	4.51
Standard income (*10^7)	10.82	10.82	10.82
Actual income (*10^7)	10.60	10.65	10.62
No. lines	9	13	16
Ave length of lines (km)	42695	23083	18227
No. single trains	7	5	7
No. doubled trains	128	114	123

Comparison with Different Objectives

We think there are two ways to compare our model with models from the state of the art with a cost-oriented objective or a customer-oriented objective. In the first method, the profit-oriented objective is modified by removing the cost part or the customer part. The cost-oriented objective can be obtained by ignoring the ticket income (and imposing that all demand should be served by at most two transfers). The customer-oriented objective can be obtained by ignoring the operational cost. In this case, an extra constraint should be considered on the maximum number and length of the lines operated in the line plan. Otherwise, in the end, each OD-pair would be served by its own direct line. The second method is to adjust the parameters or implicit weights associated with the operator cost part and the customer part in our objective. The cost-oriented approach is obtained by increasing the operating costs of the trains while the customer-oriented approach is obtained by increasing the penalty time value.

6 Conclusions

In this paper we tackle the Line Planning Problem (LPP). Instead of using a weighted sum of a cost-oriented objective and a customer-oriented objective, we propose the concept of travel time value in this paper and convert passenger travel time into ticket price and thus operator revenues. This allows to combine the operational cost and the passenger travel time in a single objective. In order to solve this complex problem, this paper presents an iterative approach. In the first stage of optimizing the LPP, an initial line plan is constructed heuristically. Based on the initial line plan, the iterative approach optimizes the line plan by reducing and extending different lines. Then, disturbances to the line plan are considered by removing or inserting an entire line.

We evaluate the performance and efficiency of the algorithms with numerical experiments on a medium and a large scale HSR network in China. Three different passenger scenarios are used. According to the experimental results, the proposed algorithm shows good performance in both examples and it is shown that the operational profit is improved by using the most promising moves calculated during our heuristic evaluation, compared to using random moves. On average, our resulting line plans increases the profit by more than 20% for the medium and large-scale networks. For the large network, the dedicated modifications obtain better results compared to the random modifications. The proposed iterative approach intends to reduce the long-distance line frequencies and add more short-distance lines to make a trade-off between the operational cost and passenger travel time.

The further research will focus on involving different speeds of high-speed trains and increasing the efficiency of the algorithm to reduce the running time consumption. In addition, a variety of parameter sensitivity analyses will be done using a large amount of numerical experiments.

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Appendix

Algorithm 3: Iterative approach of randomly move without evaluations

```
Repeat
  Repeat
    Reduction
      Select a $e_{red}$ randomly from $E_{red}$
      Modify the $L_{cur}$ and $TSN_{cur}$ to obtain $L_{nei}$ and $TSN_{nei}$
      if network connectivity check = true do
        Calculate passenger assignment and the profit of $L_{nei}$
        if $Z_{nei} > Z_{cur}$ do
          - $L_{cur} \leftarrow L_{nei}, TSN_{cur} \leftarrow TSN_{nei}, Z_{cur} \leftarrow Z_{nei}$
          - update $E_{red}$ and $E_{ext}$
        else do
          - $L_{nei} \leftarrow L_{cur}, TSN_{nei} \leftarrow TSN_{cur}, Z_{nei} \leftarrow Z_{cur}$
          - delete this $e_{red}$ from set $E_{red}$
      else do
        - roll back to $L_{cur}$ and $TSN_{cur}$
    Extension method
      Select $e_{ext}$ randomly from $E_{ext}$
      Modify the $L_{cur}$ and $TSN_{cur}$ to obtain $L_{nei}$ and $TSN_{nei}$
      Calculate passenger assignment and the profit of $L_{nei}$
        if $Z_{nei} > Z_{cur}$ do
          - $L_{nei} \leftarrow L_{cur}, TSN_{nei} \leftarrow TSN_{cur}, Z_{nei} \leftarrow Z_{cur}$
          - update $E_{ext}$ and $E_{red}$
      else do
          - $L_{nei} \leftarrow L_{cur}, TSN_{nei} \leftarrow TSN_{cur}, Z_{nei} \leftarrow Z_{cur}$
          - delete this $e_{ext}$ from set $E_{ext}$
  until maximum number of Reduction and Extension iterations
  Disturb (the same as Algorithm 2)
until maximum number of diversification iterations
Output the line plan and objective profit
```

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