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Study on Optimization of Railway Passenger Train Sets Assignment

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Abstract: The passenger train sets is the carrier of railway passenger transport production and reasonable use of the passenger train sets is one of the key goals of railway transportation plan. In order to improve the operation efficiency of passenger train sets, optimization model of railway passenger train sets assignment have been built to minimize the non-production staying time of passenger train sets at passenger station based on established train diagram and established configuration of train sets system. On that basis, considering that the parameters of simulated Annealing Algorithm (SA) directly affect the efficiency and precision of solving, SA parameters is optimized based on nested partitions, then improved simulated annealing algorithm (ISA) is designed to solve this model. Finally, a case study has been carried out taking Zhengzhou railway station of china as an example in order to testify validity of this model and its algorithm by using calculating and comparing analysis and further solved practical problems is analyzed. The results show that the number of passenger train sets required and carriage staying time at passenger station are reduced and this model and its algorithm can be used to optimize railway passenger train sets assignment to improve efficiency of railway passenger train sets assignment.

Key words: Passenger train, passenger train sets, train diagram, simulated annealing algorithm, nested partitions

INTRODUCTION

The train sets of china are used with fixed train numbers and running routes. However, this operation mode delays the void time in station. The departments of railway management have paid attention to this problem and relevant scholars have done much study in this area. Numbers of train sets have been studied (Nie *et al*., 2001). Operation of train sets has been studied (Liu *et al*., 2004). Operation efficiency of train sets has been studied (Zhao and Tommi, 2004). Motor train set assignment under fixed operating lines has been studied (Geng *et al*., 2006. Chen *et al*., 2006). Rational departure time and train following time have been studied (Xie *et al*., 2006; Chen and Wang, 2007). These studies can be used for reference during plan of train working diagram. But train set operation with given train working diagram is hard for scholars. Hence, under precondition of fixed ownership of train sets, void staying time of train set will be reduced by consecutive-use of train set. Considering synergy among train sets assignment, arrival and departure lines and shunting locomotives, model of train set assignment was established to improve operating efficiency by train sets assigned with short-distance routes again after completion of original tasks.

ESTABLISHMENT OF OPTIMIZATION MODEL

Problem statement: Suppose that O is set of origin stations of long-distance passenger trains that arrive in station k. V is set of final arrival stations of short-distance passenger trains whose origin station is k. I is set of long-distance passenger trains whose origin station is k. J is set of short-distance passenger trains whose origin station is k. Train set m (m = 1,2,..., M) is assigned with train number i. Passenger train i runs between station o (o∈O) and k. Train set n (n = 1,2,..., N) is assigned with train No. J', J'.J' and J'' run between station v (v∈V) and k. Standard time of i arriving at station k is $t_{i'}^{a}$. Standard departure time of i″ departing from station k is $t_{i''}^{d}$. Standard time of J' arriving at station k is $t_{i''}^{a}$. Standard departure time of J'' departing from station k is $t_{i'}^{d}$. Operation task of i', i″ and J', J″ are needed two train sets. When train set m is assigned with J', J″. Train set m arrives at station k assigned with train number i'. Then, after serving work, train set m is assigned with train number J' which departs from $t_{j'}^{d}$. When m arrives at v station, after several technical work, train set m is assigned with train number J″ and arrives station k at $t_{j'}^{a}$. Then, train set m is assigned with train number i' which departs from station k at $t_{i'}^{d}$. Hence, it can reduce one train set in the same task which means m can take the place of n to complete its task.

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where, $l_{i'i''}$ denotes the time interval between arrival train i' and departure train i" with the same train set:

$$l_{i'i''} = \begin{cases} t_{i''}^{d} - t_{i'}^{a} & t_{i''}^{d} - t_{i'}^{a} > 0 \\ t_{i''}^{d} - t_{i'}^{a} + 1440 & t_{i''}^{d} - t_{i'}^{a} < 0 \end{cases}$$

where, $l_{j'i''}$ is the time interval between departure train j' from station k and departure train i" from station k:

$$l_{j'i''} = \begin{cases} t_{i''}^{d} - t_{j'}^{a} & t_{i''}^{d} - t_{j'}^{a} > 0 \\ t_{i''}^{d} - t_{j'}^{a} + 1440 & t_{i''}^{d} - t_{j'}^{a} < 0 \end{cases}$$

where, $l_{j'j''}$ is the time interval between departure train j' and arrival train j˝ from station k:

$$l_{j'j''} = \begin{cases} t_{j''}^{d} - t_{j'}^{a} & t_{j''}^{d} - t_{j'}^{a} > 0 \\ t_{j''}^{d} - t_{j'}^{a} + 1440 & t_{j''}^{d} - t_{j'}^{a} < 0 \end{cases}$$

where, $l_{i'j'}$ denotes the time interval between arrival train i' and departure train j' from station k:

$$l_{i'j'} = \begin{cases} t_{j'}^{d} - t_{i'}^{a} & t_{j'}^{d} - t_{i'}^{a} > 0 \\ t_{j'}^{d} - t_{i'}^{a} + 1440 & t_{j'}^{d} - t_{i'}^{a} < 0 \end{cases}$$

where, $l_{j''i''}$ denotes the time interval between arrival train j˝ and departure train i˝ from station k:

$$l_{j''i''} = \begin{cases} t_{i''}^{d} - t_{j''}^{a} & t_{i''}^{d} - t_{j''}^{a} > 0 \\ t_{i''}^{d} - t_{j''}^{a} + 1440 & t_{i''}^{d} - t_{j''}^{a} < 0 \end{cases}$$

Analysis of constraints: $t_{j'}^{d}$ which represents departure time of train j' at station k is later than the arrival time of i'. And $t_{j''}^{a}$ which represents arrival time of j˝ at station k is earlier than $t_{j'}^{d}$. $t_{j''}^{a}$ should meet with servicing time T_B and buffer time Δt.

If train set arrivals at station k with train number i' and can be assigned with another train number which can return to the station k in the same day:

$$\begin{cases} t_{i''}^{d} < t_{i'}^{a} \\ t_{j'}^{d} \ge t_{i'}^{a} + T_B + \Delta t \\ t_{i''}^{d} < t_{j''}^{a} \end{cases} \tag{1}$$

If train set arrivals at station k with train number i' and can be assigned with another train number which can return to the station k in the next day:

$$\begin{cases} t_{i''}^{d} < t_{i'}^{a} \\ t_{j'}^{d} \ge t_{i'}^{a} + T_B + \Delta t \\ t_{j''}^{a} + T_B + \Delta t < t_{i''}^{d} \end{cases} \tag{2}$$

If train set arrivals at station k with train number i' and can be assigned with another train number in the next day and train set can return to k before departure time of i˝ in the next day:

$$\begin{cases} t_{i''}^{d} < t_{i'}^{a} \\ t_{j'}^{d} < t_{i''}^{d} \\ l_{j'i''} > T_B + \Delta t \\ t_{j''}^{a} > t_{j'}^{d} \\ t_{j''}^{a} + T_B + \Delta t < t_{j''}^{d} \end{cases} \tag{3}$$

The constraint on consecutive-use of train set which arrives at station k with assigned with train number i' is expressed as follow:

$$\begin{cases} t_{i''}^{d} > t_{i'}^{a} \\ t_{i'}^{a} + T_B + \Delta t < t_{i''}^{d} \\ t_{j'}^{d} < t_{j''}^{a} \\ t_{j''}^{a} + T_B + \Delta t < t_{i''}^{d} \end{cases} \tag{4}$$

The train set should come back before the departure time of train i˝ at station k and the time interval is longer than the total time of servicing time T_B and buffer time Δt to ensure the operation:

$$l_{i'i''} \ge l_{j'j''} + T_B + \Delta t \tag{5}$$

The train set which arrives at station with train number i' can be assigned with only one train number. Define 0-1 variation X_{ij}, where:

$$X_{ij} = \begin{cases} 0 & \text{i is not assigned with j} \\ 1 & \text{i is assigned with j} \end{cases}$$

$$\begin{cases} \sum_{j=1}^{N} X_{ij} = 1 \\ \sum_{i=1}^{M} X_{ij} = 1 \end{cases} \tag{6}$$

where, W_{ij} is matching weight value of following time between two pairs of trains i and j. the bigger the value is, the less possible the realization of consecutive-use is:

$$w_{ij} = \begin{cases} t_{j'}^{d} - t_{i'}^{a} - p_i(t_{i'}^{aw} - t_{i'}^{a}) & t_{j'}^{d} - \max(t_{i'}^{aw}, t_{i'}^{a}) \ge T_B + \Delta t \\ t_{j'}^{d} - t_{i'}^{a} - p_i(t_{i'}^{aw} - t_{i'}^{a}) + 1440 & t_{j'}^{d} - \max(t_{i'}^{aw}, t_{i'}^{a}) \le T_B + \Delta t \end{cases}$$

where, $t_{i'}^{aw}$ is the actual arrival time of train i'. p_i is 0-1 variation:

$$p_i = \begin{cases} 0 & \text{train i' arrived on time} \\ 1 & \text{otherwise} \end{cases}$$

φ_{ij} is weight value denotes matching degree among design speed and train sets composition of train i and j. The higher the value is, the less the possibility of consecutive-use is.

Take synergetic of train sets assignment, arrival and departure lines, servicing lines and shunting locomotives into consideration to avoid the situation that station capacity becomes bottleneck.

Suppose that t_{zd} is the standard time of arrival operation for passenger train, t_{sf} is the standard time of departure operation for passenger train, δ_{qe} is the delay time of placing-in operations for any train set e, δ_{qe} is the delay time of taking-out operation for any train set e, t^s_{er} is the standard time of taking-out operation which is from arrival line r (r∈R) to servicing line for any train set e, t^q_{eh} is the standard time of placing-in operation which is from serving line h (h∈H) to arrival line for any train sets e, t_{qe} is the void time of locomotives which is placing-in train set e, t_{se} is the void time of locomotives which is taking-out train set *e*, t^{dq}_{eh} is the time of placing-in train set e,t^{ds}_{er} is the time of taking-out train set e. Then t^{dq}_{eh},t^{ds}_{er} can be expressed, respectively as:

$$t^{ds}_{er} = \sigma + t_{qe}, t^{dq}_{eh} = \sigma + t_{se}$$

$$\sigma = \begin{cases} T & \text{lomotive and train in same location} \\ 0 & \text{otherwise} \end{cases}$$

Define variations ψ_{ir}, ζ_{ih}

$$\psi_{ir} = \begin{cases} 0 & \text{train i arrives at line r} \\ 1 & \text{otherwise} \end{cases}$$

$$\zeta_{eh} = \begin{cases} 0 & \text{train set e not occupy line h} \\ 1 & \text{otherwise} \end{cases}$$

where, t_{eh}^a, t_{eh}^d is time that train sets *e* assigned with train number q arrives at or departs from servicing line h:

$$t^a_{eh} = t^a_q + t_{zd} + t^{ds}_{er} + \delta_{se}, t^d_{eh} = t^d_q - t_{sf} - t^{dq}_{eh} + \delta_{qe}$$

where t^d_{qe} t^a_q represents the arrival time and departure time. Constraints on serving line are expressed as:

$$\begin{cases} \sum_{e=1}^{M+N} \zeta_{eh} \le 1 \\ \sum_{H=1}^{h} \zeta_{eh} = 1 \\ (\zeta_{er} t^a_{eh} - \zeta_{vr} t^a_{vh})(\zeta_{er} t^d_{eh} - \zeta_{vr} t^a_{vh}) > 0, e \ne v \end{cases}$$

Constraints on arrival and departure lines are expressed as:

$$\begin{cases} \sum_{r\in R} \psi_{ir} = 1 \\ \sum_{y\in(I'+J')} \psi_{ir} \le 1 \\ (\psi_{yr} t^a_y - \psi_{ur} t^a_u)(\psi_{yr} t^d_y - \psi_{ur} t^a_u) > 0 \quad y \ne u \end{cases}$$

Objective function: Suppose that the total void staying time at station k is τ. Then the train set assignment schedule with minimum τ is the optimal:

$$\min \tau = \sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij} \cdot X_{ij} \vartheta_{ij} \varphi_{ij}$$

where, t_{ij} is the void staying time between arrival time of train i and departure time of train j.

Solution based on improved simulated annealing algorithm: Suppose that the amount of parameters value of initial temperature, sampling frequency and decreasing temperature rate is P_T, P_L and P_λ. The number of combined parameters is $P_T \times P_L \times P_\lambda$. Referencing for parameter design in response surface methodology where random of parameters and combination of parameters don't take into consideration, parameters of SA algorithm based on nested partitions is applied to solve the problem (Yang *et al*., 2009).

The solution is P ={P_1, P_2, P_3,.....P_n}. P_i denotes the corresponding train number which is assigned with train number i. P = {$P_i \backslash P_i$, I, i = 1, 2,....n} is Initial solution which means train sets are assigned with their original train number. Decreasing temperature function is $T_{k+1} = T_k \times \lambda$. For any given solution, new solution can be generated by exchanging two different train numbers. If the new solution satisfies constraints, it can be feasible. Repeat above steps and new neighborhood consisting of several solutions can be reached (Yan *et al*., 2010).

Step 1: Data processing. Origin trains are labeled in sequence from zero. One label consists of arrival and departure train number and related time. Convert arrival time and departure time into minutes which means convert 0~24 h into 0~1440 min

Step 2: Set control parameter T_0, λ, finial temperature T_f, the number of iterations in current temperature u and successful iteration frequency is l

Step 3: Read arrival and departure time from files. Set up initial solution S_o, $T_i = T_o$, u = 1

Step 4: Exchange P_i, P_j to generate new solutions S_i define u = u+1

Step 5: If $f_j \ge f_i$, then it turns to step 6, or else,f_i = f_j. Record the current optimal solution, l = l +1.It turns to step 6

Step 6: $\Delta f_{ij} = f_j - f_i$, if $\exp(-\Delta f_{ij}/T_l) > \varepsilon$, ε is the random number in (0,1), $f_j = f_i$, $l = l+1$, or else, it turns to step 7

Step 7: If $u \geq U$ or $l \geq L$, $T_{k+1} = T_k \lambda$, $u = 0$, $l = 0$, it turns to step 8, or else, it turns to step 4

Step 8: If $T_{i+1} \leq T_f$, then end the calculation. Or else, it turns to step 4

EMPIRICAL ANALYSES

To verify the precision of the model in the previous sections, Zhengzhou station of china is chosen to verify the effectiveness of model and algorithm above mentioned. The information of arrival trains and departure trains for Zhengzhou station are shown in Table 1.

As can be seen from Table 1, the number of arrival trains and departure trains for Zhengzhou station are 31 respectively, the total time of staying time at station and operating time for each train is between 258 min and 4870 min and the total time of a considerable part of train more than 2000 min, the total time of part of train or even more than 3000 min. This shows that the passenger train sets assignment of Zhengzhou station is not reasonable and needs to be improved immediately.

According to scale of the model above mentioned, the range of T, L,ë is respectively.

{50,100,300,500,1000,1500,2000,2500,3000,4000}, {100,200,300,500,800,1000l,3000,5000,10000,15000}, {0.2,0.3,0.4,0.50.6,0.7,0.8,0.9,0.95,0.99}.

P_T, P_L and $P_ë$ are 10 which mean the size of solution space is 1000. The total number of evaluation in calculation is 30000. And total calculated amount in iterations is 200. The number of samples is 20. The number of sub-partition in every iteration phase is {2, 2, 2, 5, 5, 5}. Difference in amounts of departure and arrival trains results in difference in results of combination parameters. The rational values of combination parameters T, L,*ë* are 3000,10000,0.98 respectively. Choose the satisfying solution and record the number of satisfying solutions to find out the train set assignment. The optimization result of passenger train sets assignment for Zhengzhou station is shown in Table 2.

The optimization result in Table 2 shows that 6 train sets and 8640 min of void staying time are reduced. Train sets labeled with train number 0 matches with train number 23, namely K332/K329 matches with 4718 and K330/k331 matches with 4717. The operation process of train set labeled with 0 and 23, respectively under condition of consecutive-use is shown as Fig.1.

As can be seen from Fig.1, under condition of not consecutive-use, the void time of the train K332/K329, 4718/4717 is 757 min, 1101 min, respectively, the total void

Table 1: The information of arrival trains and departure trains for Zhengzhou station

Label	Arrival trains	Arrival minutes	Departure trains	Departure minutes	Total time of staying time at station and operating time
0	4717	1040	4718	701	339
1	1303	459	1304	440	1459
2	1487	1239	1488	1207	1472
3	K179	426	K180	1332	1974
4	K870	989	K869	816	3053
5	K746	1106	K745	1078	2908
6	K715/718	879	K716/717	988	4211
7	K744/741	1428	K742/743	788	3475
8	T256	519	T255	962	2437
9	K260	794	K259	1214	2460
10	K928/925	1308	K926/K927	934	3254
11	2276/2277	466	2278/2275	1415	1931
12	2594/2595	521	2596/2593	1248	2153
13	2192/2193	476	2194/2191	1343	2013
14	K338	378	K337	1222	4916
15	L7956	1078	L7955	460	618
16	L7968	495	L7967	531	1404
17	L7980	1130	L7979	428	702
18	1628	1397	1627	672	3605
19	K656/K657	429	K658/K655	1130	2179
20	1564/1565	390	1566/1563	1290	1980
21	K152/K153	437	K154/K151	1121	2196
22	K1040/1037	551	K1038/K1039	1262	3609
23	K332/K329	408	K330/K331	1165	2123
24	T198	396	T197	1286	4870
25	4715	1300	4716	527	773
26	4745	653	4746	395	258
27	4749	1220	4750	550	670
28	1625/1624	330	1626/1623	857	2353
29	K458/K455	370	K457/K456	740	3950
30	K910	632	K909	829	2683

Table 2: The optimization result of passenger train sets assignment for Zhengzhou station

Initial solutions																															
Arrival trains	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Departure trains	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Evaluation value	25937 min																														
Satisfying solutions	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Departure trains	23	25	2	27	4	5	6	7	8	9	10	11	12	13	17	20	16	14	18	19	15	21	22	0	24	1	28	3	26	29	30
Evaluation value	17297 min																														

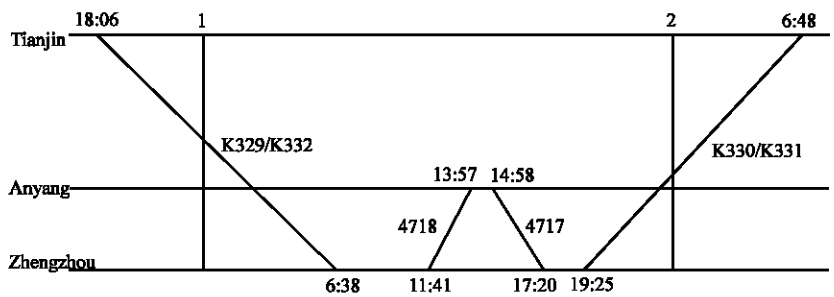

Fig. 1: The operation process of train set labeled with 0 and 23, respectively under condition of consecutive-use

time of the train K332/K329 and the train 4718/4717 is 1858 min, operation of the train K332/K329 and the train 4718/4717 must have two train sets. While, under condition of consecutive-use, the train K332/K329 arrives at Zhengzhou at 6:38, then continue to undertake the task of the train 4718/K329, now, operation of the train K332/K329 and the train 4718/4717 only need one train set and the total void time of the train K332/K329 and the train 4718/4717 is 418 min. These indicate that if using the scheme above mentioned, railway passenger train sets assignment is more reasonable.

RESULTS AND DISCUSSION

Operation mode of train sets assignment delays the void time in passenger station which results in low efficiency in china and operation efficiency of railway passenger train is restricted by the scheme of train sets assignment. These need to be improved immediately.

The routes of long-distance passenger trains are mainly among center passenger stations (Shi *et al*., 2008). So, considering passenger station with large amount of arrival and departure trains as core, a radial star topology is established. The final arrival station of trains is regarded as endpoint in the network. Topology of railway network is shown as Fig. 2.

If there are short-distance passenger trains between $k_1$and k_2. Then after calculation, one train set assigned with short-distance will be reduced.

Large-scale stations with long-distance and short-distance passenger trains can organize consecutive-use of train set by assigned with short-distance.

Train sets often don't match degree of assigned trains. Or, if they match each other, the time interval is long. This situation is mainly caused by train working diagram structure which should be studied on before formulation of diagram (Cordeau *et al*., 2001).

Consecutive-use of trains set should take passenger volume structure into consideration by reason that train sets don't meet the needs of passenger volume. What's more, profits distribution among different railway bureaus and train sets maintenance are needed to consider in current mechanism.

Furthermore, if consecutive-use of train set is implemented, chaos may occur in platform during period with high frequency in trains arrival and departure. workload may increase, too. Meantime, for large-scale terminals with two or more passenger stations, it may involve adjustment on origin stations for trains.

Train sets assignment is one of the efficient ways to improve operation efficiency of railway passenger train. Nevertheless, railway train sets assignment is a complicated system engineering that is influenced by multitudinous factors, such as passenger flow volume, passenger flow structure and so on. Optimal model of train set assignment have been set up based on given train working diagram. Yet, in order to study higher operation efficiency of train sets, studying on train set assignment plan before working diagram generated period or studying on unfixed operation lines for train sets is necessary and these are the mainly subject in the next phase.

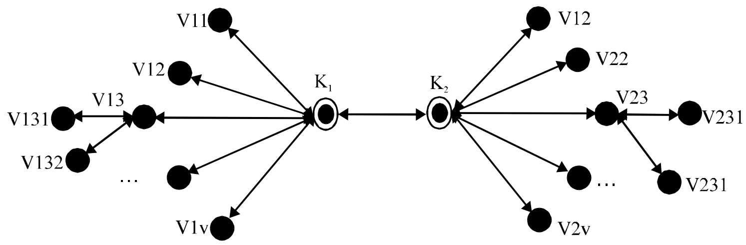

Fig. 2: Topology of railway network

CONCLUSION

The train set assignment is the hot subject for railway managers and scalars. As it relates to train set ownership priority, operation lines, carriage category and financial affairs, it is hard to solve train set assignment. Under the precondition of current train set ownership, train set assignment optimal model have been set up based on current train working diagram, that can improve train set operation efficiency, reduce train set amount and passenger station's scale. But, to reach higher operating efficiency of train sets, studying on train set assignment plan before working diagram generated period or studying on unfixed operation lines for train sets is necessary and these are the mainly subject in the next phase.

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