HPN simulation model of carrying capacity of combination station for heavy-haul trains

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Abstract

Combination station for heavy-haul trains imposed restrictions on the whole heavy-haul railway system. Through analysis of particularities of operation of combination station, the paper established HPN simulation model of carrying capacity of combination station based on Petri net theory, a graphical modelling method. The simulation model took technical operations of arrival, combination and departure of trains as interconnected system, and output parameters related to carrying capacity of the station. Finally, the paper, took Hudong station in Datong-Qinhuangdao railway as an example to verify the validity and practicability of the model.

Keywords: carrying capacity, HPN, combination station, heavy-haul railway

1 Introduction

Heavy-haul railway is transportation corridor for goods and materials among the areas in China. Because of variety of goods flow of sources and whereabouts, such a complicated organizational form of train, combination train, operated in the Chinese heavy-haul railway. Combination train is a kind train with greater tonnage of traction made up by several trains with less tonnage of traction in technical stations, which was called combination station. This kind of transportation organization can make the best use of carrying capacity of heavy-haul railway. The trains reception and departure in combination station included unit trains and combination trains. The work of unit train in the station is simple, consisting of duty shift of locomotives and crew. The work of combination train is more complicated, divided into three stages, train reception, train combination and train departure.

The issue of carrying capacity of combination station for heavy-haul trains is a new study field because the combination station is a completely new thing. So there are few literatures studying the issue according to the characteristics of heavy-haul railway.

So, the paper selected Hybrid Petri Net (HPN) to model the combination station for heavy-haul trains, which is a dynamic system mixed discrete and continuous processes, to describe static attribute of trains stopping in the station and dynamic behaviours in the section 1-3. The discreteness refers to the transition of display status of signal lamps and the stop of the train at the station. The continuance means moving process of the trains in the section or inside the station [4, 5].The continuous behaviour is different when trains running in the section and inside the station, because moving process of the train limited by the arrival signal, thus forming the interactive status between continuous system and discrete system. The changes among the trains status of moving, stopping at station and signals, are of the characteristics of dynamic, concurrence and synchronization.

2 HPN simulation model of combination station

2.1 BRIEF INTRODUCTION ON HYBRID PETRI NET (HPN)

In 1962, C. A. Petri proposed the Petri network in his thesis for the Doctorate at first. In recent years, the research has already expanded the basic form of Petri network from different side and different angles, and led many kinds of expanded Petri networks of different characteristics and forms. Among them, HPN model can clearly describe systematic organization, the change course of structure and state and time characteristic. It particularly suited to describe the Characteristics, including parallelism, concurrency, synchronization and resource sharing. HPN is a kind of modelling tool with powerful function. It can combine graphical description and mathematical analysis. So HPN concurrently has intuition of graphical methods and generality of logical methods. It can also model the system mixed with discrete and continuous processes.

2.2 HPN SIMULATION MODEL

This paper, taking it as an example that trains moving into and out of the simulation system of combination station, set up HPN system simulation model of combination station for heavy-haul trains.

Combination station system is made up of home section, home throat area, receiving-departure yard,

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starting throat area and starting section. There are combining-receiving-departure tracks and ordinary receiving-departure track in receiving-departure yard. The combining-receiving-departure tracks are tracks for combining trains and ordinary receiving-departure track for general trains.

When the trains moving in the home section, the train motion states are restrained by indicated states of signals. While entering the home throat area, the trains are influenced by switches with limited speed. When in the receiving-departure yard, the trains undertaking combination operation or other technological work as requested. Then, the trains, acceleration from parking state to leave receiving-departure tracks into starting section, restrained by switches with limited speed.

In order to simplify the problem size, the moving distance of trains at station are all established by sum of the length of home throat, receiving-departure tracks and starting throat (In fact, the moving distances of different kinds of trains are of certain differences, especially the train needing combined).

According to the mathematical definition of Petri network, the paper set up the model as multiple groups, HPN= $\{P, T, h, \mathrm{pre}, \mathrm{post}, \tau, M_0\}$.

$$P=\{P_1,P_2,P_3,P_4,P_5,P_6,R_1,R_2,R_3,R_4,R_5,R_6,S_1,S_2,$$
$$S_3,S_4,S_5,S_6,S_7,S_8,G,G_1^1,G_1^2,G_2^1,G_2^2,G_3^1,G_3^2\}.$$
$$T=\{T_1,T_2,T_3,T_{p1},T_{p2},T_{p3},T_G,T_{G1},T_{G2},T_{G3},T_{G4},$$
$$T_{G5},T_{G6},T_{s1}T_{s2},T_{s3},T_{s4},T_{s5},T_{s6},T_{s7},T_{s8},T_{s9}\}.$$

The HPN simulation model of combination station is shown in Figure 1.

The meaning of place and transition are as follows: P_1: distance of trains from home throat section (assumed to be l_1. In order to simplify the problem, in this paper, it is assumed to be the same that the moving distance of all the trains in home throat section). P_2: distance of trains moving in home section. P_3: length of home throat area (assumed to be l_2, which is also stopping distance, containing part of the length of receiving-departure track). P_4: distance of trains moving in home throat area. P_5: length of starting throat area (assumed to be l_3, which is also departure distance, containing part of the length of receiving-departure track). P_6: distance of trains moving in starting throat area. R_1:generating a train according to distribution discipline. R_2: idle status of beginning of home section. R_3: train number plus one in the simulation network. R_4: occupancy status of beginning of home section. R_5: train number minus one in the simulation network. R_6: trains moving out of the simulation network; S_1: trains in home section. S_2: trains in home throat area. S_3: trains in the beginning of combining-receiving-departure yard. S_4: trains in ordinary receiving-departure yard. S_5: departure of ordinary trains. S_6: trains moving in starting throat area. S_7: trains moving out of starting throat area. S_8: trains in starting section. G: trains reaching combining-receiving-departure track. G_1^1: trains stopping at first half of combining-receiving-departure track. G_1^2: occupancy status of first half of combining-receiving-departure track. G_2^1: trains stopping at second half of combining-receiving-departure track. G_2^2: occupancy status of second half of combining-receiving-departure track. G_3^1: two trains in the same combining-receiving-departure track combined to a new train(combination train). G_3^2: departure of combination trains.

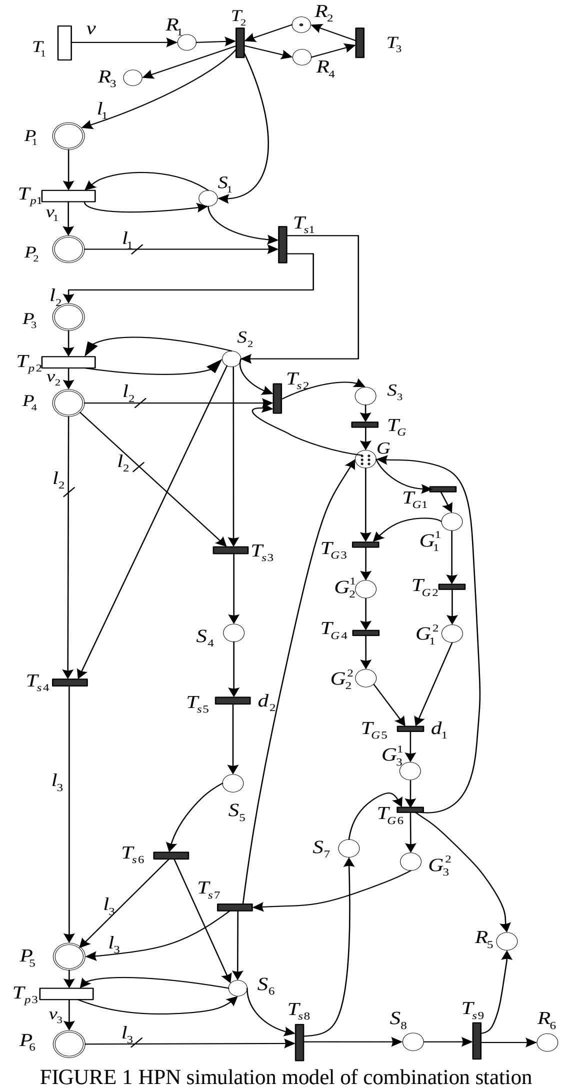

FIGURE 1 HPN simulation model of combination station

T_1: trains randomly generated at the speed of v. T_2: trains moving into simulation network. T_3: occupied to idle status of the beginning of home section. T_{p1}: trains moving at the speed of $v_1(t)$ in home section. T_{p2} : trains moving at the speed of $v_2(t)$ in home throat area. T_{p3} : trains moving at the speed of $v_3(t)$ in starting throat area. T_G : trains moving into the second half of combining-receiving-departure track, which is in idle status. T_{G1} : idle status of the first half of combining-receiving-departure track which can receive trains. T_{G2} : idle to occupied status of the first half of combining-receiving-departure track. T_{G3} : destination of arriving train same to the train in the first half of combining-receiving-departure track for trains. T_{G4} : idle to occupied status of the second half of combining-receiving-departure track. T_{G5} : combining the two trains in the same combining-receiving-departure track. T_{G6} : occupied to idle status of starting throat area. T_{s1} : trains moving from home section to home throat area. T_{s2} : trains moving from home throat to beginning of combining-receiving-departure track, which is in idle status. T_{s3} : trains moving from home throat to ordinary-receiving-departure track, which is in idle status. T_{s4} : through trains occupying starting throat area. T_{s5} : trains undertaking technology operations in ordinary-receiving-departure yard. T_{s6} : idle to occupied status of starting throat area when trains departure from ordinary-receiving-departure yard. T_{s7} : idle to occupied status of starting throat area when combination trains departure from combining-receiving-departure yard. T_{s8} : idle status of starting section. T_{s9} : trains moving out of simulation network.

On the basis of the above definitions, the inferences can be obtained:

$$h(P_1,P_2,P_3,P_4,P_5,P_6,T_1,T_{p1},T_{p2},T_{p3}) \to C,$$

that is a continuous process.

$$h(R_1,R_2,R_3,R_4,S_1,S_2,S_3,S_4,S_5,S_6,S_7,G,G_1^1, G_1^2,G_2^1,G_2^2,G_3^1,G_3^2,T_2,T_3,T_{G1},T_{G2},T_{G3},T_{G4},T_{G5}, T_{G6},T_{s1}T_{s2},T_{s3},T_{s4},T_{s5},T_{s6},T_{s7},T_{s8},T_{s9}) \to D,$$

that is a discrete process.

Input correlation mapping associated with the output are shown in Figure 1 directed arc labelling. For example, $pre(P_2,T_{s1}) = l_1$ and $post(P_3,T_{s1}) = l_2$, and the rest are no longer expatiated on. The non-labelled indicates $pre(P_i,T_j) = 1$ and $post(P_i,T_j) = 1$.

As to transition T_1, a nonnegative real number, v represents the speed of train planned to generate. As to transition T_{G5}, d_1 represents the time of combining trains, including technical operation time. As to transition T_{s5}, d_2 represents technical operation time of trains. If home section is in idle status, there is $M_{R_2}^0 = 1$.

Because there is not only one combining-receiving-departure track used in combination station, the value of M_G^0 can be set up according to the size of the actual situation. If there are 6 combining-receiving-departure tracks, thus there is $M_G^0 = 6$.

3 Analysis on operation of simulation model

3.1 ANALYSIS ON OPERATION OF SIMULATION MODEL

According to the given initial state shown in Figure 1, transition T_1 generates the train at the speed of v. Because $M_{R_2}^0 = 1$, so transition T_2 is enabled. The train moves into simulation network, the number of the trains plus one, and the status of beginning of home section become occupied from idle.

Then the train moves into home section, so transition T_3 is enabled, and the status of beginning of home section become idle from occupied so the next train can move into the simulation network.

At the moment, the train is moving at the speed of v_1 in the home section. After the train running the distance of l_1, transition T_{s1} is enabled, so the train moving into the home throat area; when the train is the home throat area, the train moves at the speed of v_2.

There are three situations for the train according to the fact whether the train needs combining operation. In the first situation, the train needs combining operation, so transition T_{s2} enabled, and the train running the distance of l_2 into the combining-receiving-departure yard. If the second half of a certain combining-receiving-departure is in idle status, and the destination of the train is same to the train in the first half of the track, transition T_{G3} is enabled, and the train moves into the second half of the track to wait for combining operation. If the first half of a certain combining-receiving-departure is in idle status, transition T_{G1} is enabled, and the train moves into the first half of the track to wait for the successor train. When G_1^2 and G_2^2 exist at once, transition T_{G5} is enabled. The both trains in the same combining-receiving-departure track undertake combining operation. The delay time d_1 is the time of combining operation, which is random Numbers following a certain statistical distribution. If the starting throat is in the idle status, transition T_{G6} is enabled, and the combination train moves into starting throat area. Meanwhile, because the combination of two trains, the number of trains in simulation network minus one.

In the second situation, the train does not need combining operation, so transition T_{s3} enabled, and the train running the distance of y into the ordinary-receiving-departure yard to wait for technical operations, then, transition T_{s5} is enabled. The delay time d_2 is the time of technical operation, which is random numbers following a certain statistical distribution. At present, the train can start. So transition T_{s6} is enabled, and the combination train moves into starting throat area.

In the third situation, if the train does not need any operations and directly through the station, transition T_{s4} is enabled, and the train moves into the starting throat.

When in the starting throat area, the train is moving at the speed of v_3. After the train runs the distance of l_3, transition T_{s7} is enabled, and the train moves into the starting section. Then, transition T_{s8} is enabled, and the train moves out of simulation network, so the number of trains in simulation network minus one.

At present, there are a lot of simulation tools for Petri net design, for example, widely used Visual Object Net++, GPNT, and OPMSE. But simulation ability of some software is limited [6-10].

The paper used Matlab as simulation tool. Matlab, as a large commercial software in engineering calculations, has obvious advantages on computing capability, expansibility and openness [11-13].

Stateflow is a tool for modelling, simulation and analysis on complicated system integrated with Simulink in Matlab. It unites the theories together that finite state machine theory, flow diagram and state transition diagrams. It is a creation and simulation tool on complex response system and event-driven system, very suitable for simulation of Petri net.

3.2 BASIC FRAMEWORK OF THE SIMULATION MODEL

Flow chart of simulation of combination station for heavy-haul trains is shown in Figure 2.

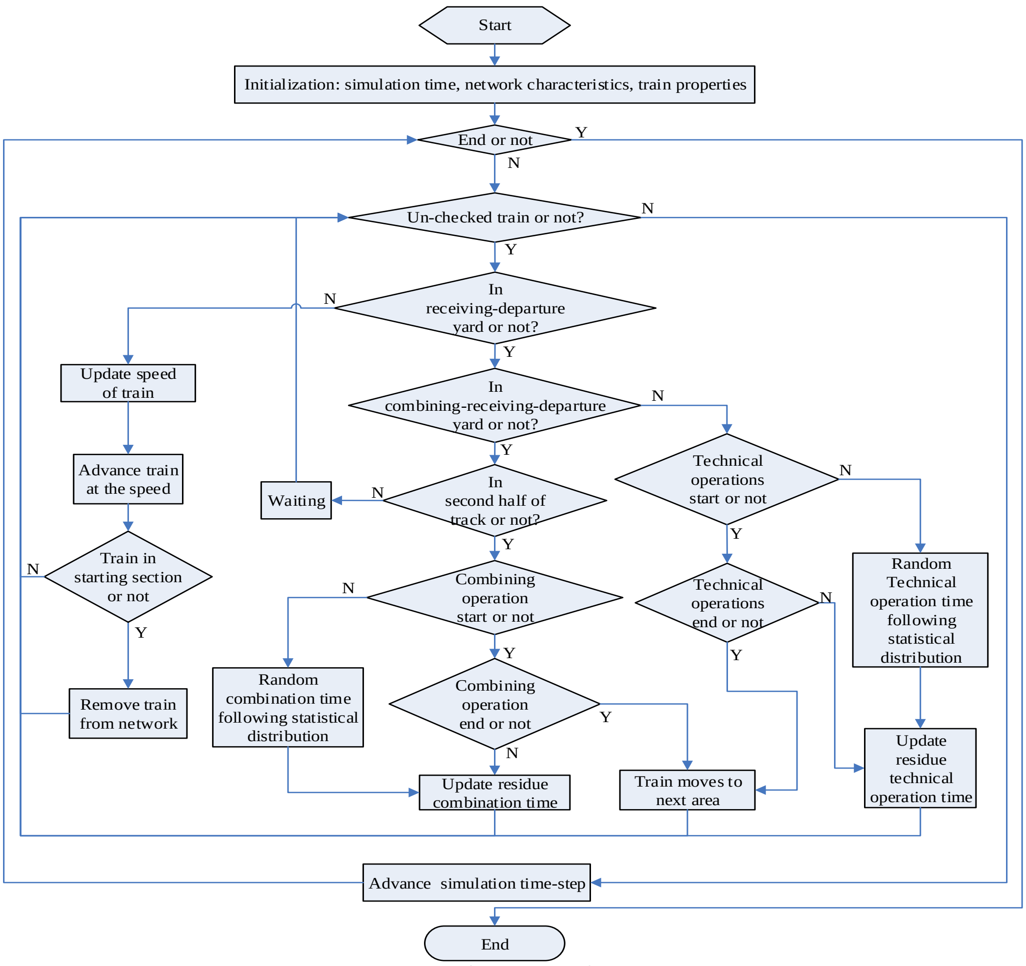

FIGURE 2 Flow chart of simulation of combination station

The simulation system needs traverse detailed information of each train in the network every simulation cycle, computing speed, moving position, and corresponding operations of the trains.

4 Case study on HPN simulation model

The paper, according to the above simulation theory and model, carried on simulation calculation of carrying capacity of Hudong station in Datong-Qinhuangdao railway, based on the yard layout, traffic flow and operation organization method.

The paper mainly aimed at the experiment simulation of the operation that 2 trains weighing 10000 tons are combined to 1 train weighing 10000 tons, and the simulation cycle is for 24 hours.

At start of the simulation, arrival time of trains, which is determined according to the actual statistics data of Hudong station, is randomly generated. When the simulation is operated, the time table of a certain number of train is prior generated, which is read in sequence when simulation is running.

When a train generated reaches a certain combining-receiving-departure track in totally idle status, the train can stop in the first half of the track, and wait for the successor train. While, if just the second half is in idle status, the train can stop in the second half of the track, the combination operation can be undertaken, and the time of combination operation is generated according to the random probability distribution.

According to the realistic situation of train operations in Hudong station, the arrival and departure data and operation time distribution are as follows.

Firstly, train arrival time interval analysis: the average train time interval is 624 seconds, by using statistical analysis software, the train arrival time interval basically obeyed normal distribution.

Secondly, train combination operation time: according to the realistic data, the average time of a train weighing 20000 tons combined by 2 trains weighing 10000 tons is 25.6 minutes, the shortest time is10 minutes, and the longest time is 54 minutes. By using statistical analysis software, the data basically obeyed normal distribution.

Thirdly, according to statistics data of cross interference situation of station operation, the interference time approximately obeyed normal distribution, the minimum time is 2 minutes, the largest time is 40 minutes and the average time is 12 minutes.

The paper introduced random cross interference when simulation of the train operation in the station. In simulation process, the various cross interference possibly occurring in the station are transformed into the impact on the operation time, so, the given operation time were to be added the interference time.

Therefore, the time from the second train reaching to the combination train moving out of the track were as follow: the average time is 161minutes, the minimum time is 68mins and the maximum time is 330 minutes. By using statistical analysis software, the data basically obeyed γ distribution, and the two parameters respectively were $\alpha = 8$ and $\beta = 0.05$.

There are 6 combining-receiving-departure tracks in Hudong station, so, the ability restriction of combination operation should be considered. While the ability restriction of ordinary-receiving-departure yard and carrying capacity of through trains weighing 20000 tons need not be considered.

According to the future tendency, the destinations of combination trains were set to three, including Qinhuangdao Port, Caofeidian Port and other stations, and the ratio is 2.2:2:1.

In the case, the length of trains weighing 10000 tons is 1.2km, the length of trains weighing 20000tons is 2.4km, the limited speed in throat area is 30km/h, the value of l_1, l_2 and l_3 are 1.5km, 4km and 4km, and the value of v is 60km/h.

The speeds were updated according to the functions as follows:

$$v_1(t+1) = v_1(t) - 8.33t\,, \tag{1}$$

$$v_2(t+1) = v_2(t) - 1.44t\,, \tag{2}$$

$$v_3(t+1) = v_3(t) + 1.17t\,. \tag{3}$$

According to the need to promote the simulation process, on above functions, the unit of speed is km/h, and the unit of time is minutes.

In simulation process, the skylight time of 120 minutes were deducted.

In every simulation circle, the given traffic volume was large enough and the simulation time was set to 30 hours. The result is that the traffic volume can be handled by the station within the later 24 hours.

In the 50 times simulation, the daily combination 20000-ton trains are 46 on average, 43at least and 49 at most. The statistical data was shown in Figure 3.

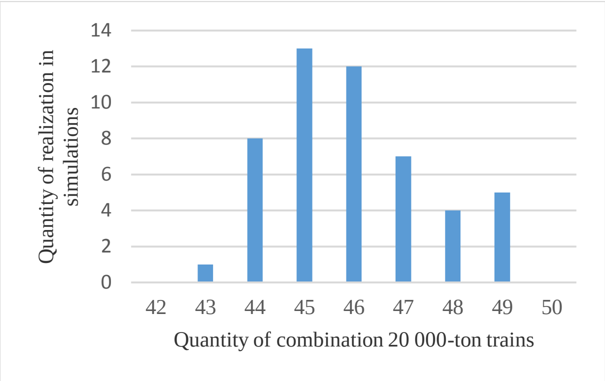

FIGURE 3 Quantity of combination 20,000-ton trains realized in simulations

After 50 times simulations, each simulation can realize the quantity of trains as shown in Table 1.

Attainable probability of quantity of combination 20000-ton trains was shown in Table 2.

TABLE 1 Statistics of simulation results

NO.	Quantity of 10000-tons trains by ordinary technical operation	Quantity of directly through 20000-tons trains	Quantity of combination 20000-tons trains	Total number of trains	Conversion quantity of 10000-tons trains
1	36	11	44	91	146
2	35	11	46	92	149
3	36	12	45	93	150
4	35	12	45	92	149
5	35	13	45	93	151
6	34	13	43	90	146
7	37	11	45	93	149
8	37	10	49	96	155
9	36	11	46	93	150
10	37	12	45	94	151
11	36	12	45	93	150
12	35	12	44	91	147
13	35	11	47	93	151
14	34	12	44	90	146
15	34	12	45	91	148
16	35	10	49	94	153
17	35	13	46	94	153
18	34	13	48	95	156
19	38	12	47	97	156
20	36	11	47	94	152
21	35	13	46	94	153
22	35	12	44	91	147
23	35	13	44	92	149
24	36	12	45	93	150
25	33	13	46	92	151
26	34	12	49	95	156
27	33	12	46	91	149
28	36	11	45	92	148
29	35	13	47	95	155
30	34	11	49	94	154
31	34	13	46	93	152
32	35	11	48	94	153
33	35	12	46	93	151
34	36	11	45	92	148
35	37	12	44	93	149
36	35	12	45	92	149
37	37	12	44	93	149
38	33	12	48	93	153
39	35	14	45	94	153
40	38	11	44	93	148
41	35	12	46	93	151
42	35	12	47	94	153
43	37	13	45	95	153
44	34	13	47	94	154
45	35	13	46	94	153
46	34	10	49	93	152
47	36	10	48	94	152
48	35	12	46	93	151
49	36	12	46	94	152
50	34	12	47	93	152

TABLE 2 Attainable probability of quantity of combined 20,000-ton trains

Quantity of combination 20000-ton trains	≥43	≥44	≥45	≥46	≥47	≥48	≥49	≥50
Attainable probability	1	0.98	0.82	0.56	0.32	0.18	0.1	0

The annual transporting capacity of Datong-Qinhuangdao railway can be calculated through the above realization probability of traffic volume. Suppose the 10000-ton trains all were made up by C80-wagons, so the annual transporting capacity achieved by a single 10000-ton train is $10000 \times 0.8 \times 365 = 2920000$ tons.

According to the carrying capacity of Hudong station, the attainable probability of annual traffic volume of 425 million tons in Daqin railway is 1, the attainable probability of annual traffic volume of 429 million tons is 0.94, the attainable probability of annual traffic volume of 435 million tons is 0.82, the attainable probability of annual traffic volume of 451 million tons is only 0.16.

The analysis shows that when traffic volume from 429 to 435 million tons, attainable probability fell by 0.12 and when from 435 to 451 million tons, attainable probability fell by 0.66, which fully shows that when the transporting capacity was 435 million tons, under the condition of existing equipment, the carrying capacity of Hudong station was saturated and there is no space to increasing the transporting capacity.

5 Conclusion

The paper, on the base of analysis of particularities of operation of combination station, established HPN simulation model of carrying capacity of combination station by using Petri net theory, which was a graphical modelling method. The simulation model took technical operations of arrival, combination and departure of trains as interconnected system, and output parameters related to carrying capacity of the station. Hudong station in Daqin railway was taken as an example to prove the validity and practicability of the HPN simulation model.

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