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Scheduling Method Model Research of Mine Hybrid Locomotive Based-on Petri Net

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Abstract: Problems such as low transport efficiency, low safety factor, and difficulty in the dispatching of hybrid locomotives, which are not optimal in the automated transport of coal mines, are always difficult to study. These serious situations are studied and avoided through petri net (PN) analysis techniques in this paper. Firstly, by analyzing the relationship between locomotives, road sections and elements of petri net, petri net scheduling mode is built for locomotives with three different routes according to three different mine locomotive scheduling methods. Then, based on a certain set of resources in PN, the concepts of a deadlock state equation and a potential deadlock state equation are introduced. The deadlock state equation describes the intrinsic relationship between resources assignation and a deadlock state in PN. This equation is a necessary and sufficient condition for the occurrence of a deadlock situation. In the following part, the deadlock equations of several network models are solved, and the deadlock verification is carried out using the software PIPE, which proves the validity of the equations. The results show that the solution of the deadlock equation and the potential deadlock equation can effectively avoid the deadlock of petri net model, so as to prevent the blocking and collision of locomotives. At the same time, the whole modeling process also verifies the effectiveness of petri net for mining bottom locomotive modeling.

Keywords: Hybrid Locomotive, Scheduling Model, Petri Net, Deadlock State Equation

1. Introduction

In the safe production of underground mines, transportation is the key to affecting production efficiency. With the improvement of automated transportation level of coal mine, large transportation equipment and special transportation equipment are widely used. Such as underground coal transportation equipment: trackless tyred vehicle, monorail locomotive for transporting large production equipment, hybrid transport function locomotive conveying people. In a modern mine, in order to improve the level of production automation, there are often many different types of vehicles working in main haulage at the same time, but the mine underground roadway is special, it will greatly affect production and safety if the vehicle scheduling does not reach a certain level. Therefore, how to establish an optimal scheduling model to improve the dispatch efficiency of hybrid locomotive and improve the transport efficiency and safety under coal mine environment becomes an important problem. In 2005, Jinfeng Wang analyzed the bottom coal bunker of pithead industry coal mine, and give modeling analysis for it through stochastic petri nets. Analyzed the state of coal bunker system and proposed its transformation relation, providing a new idea for the studying of the reliability of coal storage and transportation system [1]. In 2015, Liu Dianjun et al. used color petri nets to conduct theoretical modeling for multiple cases of locomotives running in a complete working path in order, and obtained a complete interlocking process model for locomotives [2].

Petri net is a kind of math-modeling tool to describe the discrete distributed system, it is protocol description technology through formalization method, similar to finite state automata, it can describe the characteristics of concurrent, asynchronous, parallel and non-deterministic in the resource scheduling system. In 2016, Gong Yunfei used petri net hierarchical modeling method to establish the model of molten iron transportation system and used fuzzy time reasoning method to analyze the model, which improved the scheduling efficiency of molten iron transportation system [3]. Wei Zhenhua combined artificial bee colony optimization algorithm theory with petri net theory to model the Jing-ha railway dispatching command system, which opened a new direction for the application of petri net in dispatching [4]. In 2018, Liu Gaiyun develops methods for the robust deadlock control of AMSs with unreliable resources based on petri nets, solved the problem that most existing deadlock control policies inapplicable [5].

The above research results confirmed the feasibility and applicability of petri net to the locomotive dispatching of mine bottom, but only Fang Huan combined the resource deployment of the bottom yard with petri net, however, she was not analyzed the deadlock performance of each scheduling strategy [6]. This paper based on the characteristics of petri net and combines with the characteristics of mine locomotive transportation dispatch, pointed out the suitable scheduling method according to different situation, established the scheduling model for it, and analyzed the deadlock state of the models under each method.

2. Building of Petri Net Model of Locomotive Dispatch

2.1. Description of Mine Locomotive Dispatching Problem

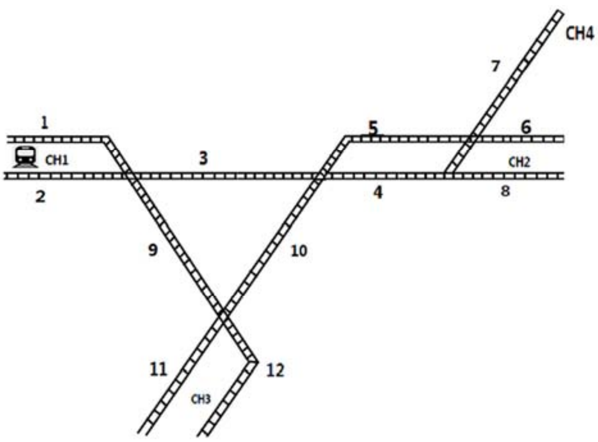


Figure 1. *Mine track map.*

Underground mine transportation in coal mine has the problem of narrow roadway, narrow space and single transportation route, many different types of locomotives travel on one line, which can easily cause blockages, figure 1 shows a typical mixed transportation model of coal bunker, equipment storehouse and personnel in a coal mine. CH represents locomotive depot, depot 1 (CH1) is a ordinary depot, used for loading and unloading personnel and large equipment, depot 2 (CH2), depot 3 (CH3) and depot 4 (CH4) are coal yard depots. The number in the figure represents a section of road. On a section of road, the locomotive cannot turn around, but can only run in one direction; two or more locomotives can only run in sequence, and the speed is determined by the speed of the slowest locomotive. According to the transportation of personnel, large equipment and coal in a shift, reasonable scheduling would allow the largest amount of coal to be transported on the basis of completing the transportation of personnel and large equipment, and can't have problems like collisions and traffic jams.

2.2. Modeling Analysis of Petri Net Under the Coal Mine Transportation Environment

Petri net modeling is a simulation of reality, a petri net is a quadruple: N = (S, T; F, M0), the following hypothesis is made by combining elements in this quadruple with mine scheduling:

Hypothesis 1: the place in petri net shows a graph of "○", it is assumed to be locomotive depot and road section in mine dispatch. Place resources are system-related factors, represented by the letter "S", which represents some information of the system, such as tools, devices, etc. In the model of locomotive dispatch, the place is divided into section place and resource place, for the section place, the place represents the section or depot; for the resource place, the place represents whether the current section resources are available or not.

Hypothesis 2: the transition in petri net shows a graph of "■", it is assumed to be the locomotive operation process, and the timed transition shows a graph of "▯". Transition represents some actions of the system, represented by the letter "T". It is equivalent to resource consumption and new resource generation in the system, and it is a reflection of petri net dynamics. In the modeling process, transition represents the locomotives flow, while for the resource place, transition represents the transfer process of resources.

Hypothesis 3:the directed arc in petri net shows a graph of "⟶", it is assumed to be the locomotive operation process, it means the direction of flow of locomotives and resources. The directed arc connects the place with the C, represented by the letter "F".

Hypothesis 4: the token in petri net shows a graph of "⊙", which represent locomotives or resources. An array of the number of tokens contained in each place at a given time is the identity at the current time, represented by M, while M0 is the initial identity.

The above elements meet the following conditions:

$$S \cup T \neq \emptyset \tag{1}$$

$$S \cap T = \emptyset \tag{2}$$

$$F \subseteq (S \times T) \cup (T \times S) \tag{3}$$

$$dom(F) \cup cod(F) = S \cup T \tag{4}$$

$$\begin{aligned} dom(F) &= \{x \in S \cup T \mid \exists y \in S \cup T : (x, y) \in F\} \\ cod(F) &= \{x \in S \cup T \mid \exists y \in S \cup T : (y, x) \in F\} \end{aligned} \tag{5}$$

The enabling transition t can be triggered under the identity M, after t is raised, a new identity M 'is generated, denoted as M[t>M', R (M0) represents the set of all marks accessible from M0 in petri net. Thus, petri net and mine dispatch are combined for modeling.

According to the working principle of the locomotive and characteristics of petri net in figure1, the following agreements are made according to the operational mechanism of the mine locomotive and the standard definition of petri net:

(1) The track resources of the underground coal mine transportation system are divided into route resources and section resources. As shown in figure1, there are six routes between depot1 and depot2, including r1, r2, r3, r4, r5 and r8, according to the difference between the two path. The section resources contained in the six routes are: section 1, section 2, section 3, section 4, section 5, section 6, and section 8. Therefore, the problem of how to schedule to make full use of the resources exists in a scheduling system. The concept of fairness in petri net is proposed to discuss the relationship between the occurrence of transition, which reflects the starvation-free problem of each part of the system in the competition of resources and the coordination of resources in the process of utilization.

(2) In order to prevent the collision of the locomotive, the dispatch system should have the functions of regional interlock and hostile approach interlock. As shown in figure1, there is a possibility of collision when there is a public section 3 between depot 1 and depot 2. Therefore, the problem of how to schedule to avoid collision exists in the scheduling system. Petri net boundedness reflected capacity requirements of relevant resources in the operation of the system, its safety is closely related with the boundedness, if token number in place less than or equal to 1, then called the place is safe. In the underground locomotive dispatching, due to the narrow roadway, a road only let one locomotive through to ensure can't be a collision, therefore, the properties of petri net is consistent with the principle of locomotive dispatching.

(3) under a mine may contain trackless tyred vehicles transporting coal, monorail crane transporting large equipment and locomotive with a mixed transport function for transport personnel, the locomotive in different situations, different time have different priorities, there is no evident regularity, thus, the optimal dispatching problem of hybrid locomotive exists in the dispatching system.

2.3. Petri net Modeling Method of Locomotive Dispatch

The graphical representation of petri net is a general circle representing the location place, and the text next to it denotes its name, which is unique throughout the net. The number next to the position indicates its capacity. If it is not marked, it is infinite. That means the capacity is large enough and will not affect the behavior of the system. The text beside the transitions is the name of the transitions, and it is the only one in the whole net. The number on an arc indicates the amount of resources produced or consumed.

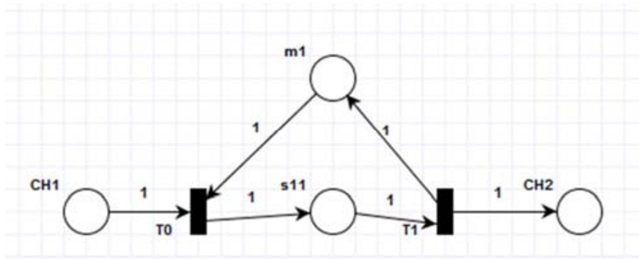


Figure 2. *Resource/section model.*

As shown in figure2, the establishment of resource/section model is one of the important ideas of locomotive dispatching modeling. In the figure, the place CH1 represents the depot 1 and is the starting point of the locomotive. The place CH2 represents depot 2 and is the end point of the locomotive. The place s11 is the section place, which represents a section, and its token capacity is 1, which means that the section can only accommodate one locomotive, the section place in the model is denoted as p_q ;M1 is the resource place, which represents whether the current section is available or not. If there is a token in m1, the section is available. The resource place in the model is denoted as p_r .

The operation track of underground locomotive is divided into route and a section in the upper machine, where each route is composed of one or more sections. The route resource is denoted as $p_{rr} = \{r_1, r_2, r_3 \cdots r_p\}$, and the section resource is denoted as $p_{rs} = \{m_1, m_2, m_3 \ldots m_q\}$, p, q ≥ 1 . The sections contained in the routes r_i are represented by the section place: r_i $\{s_{i1}, s_{i2}, s_{i3} \cdots s_{ipi}\}$. In the model, when the locomotive leaves each section, m_i is used to represent the feedback that is about to enter the section or route, where i is the current section number.

2.4. Scheduling Method and Petri Net Model

According to the practical situation of narrow roadway and difficult passing in the mine, the model designed in this paper follows the following rules:

Each locomotive carries out the round-trip operation of coal loading and coal discharging between the truck depot at the bottom of the mine shaft and the truck yard at the mining area;

Locomotive type is divided into no-load (represented by X) and heavy-load (represented by Y);

The principle of locomotive running is "no-load locomotive detours; heavy-load locomotive runs straight";

At most one locomotive shall be accommodated in each section at each moment; The number of locomotives to be accommodated at each point in time is determined by the dispatch policy.

Three different scheduling methods are used for three different situations [6]:

(1) Situation 1: the road condition of mine is poor, the number of locomotive is less, and the safety coefficient is required strictly, the route contains fewer sections.

Method 1: the first scheduling method issues the pre-occupied application in the last section of the current route of the locomotive. The pre-occupied application can be successful when all sections of the next route and the next route meet the application conditions. The petri net model is shown as follows:

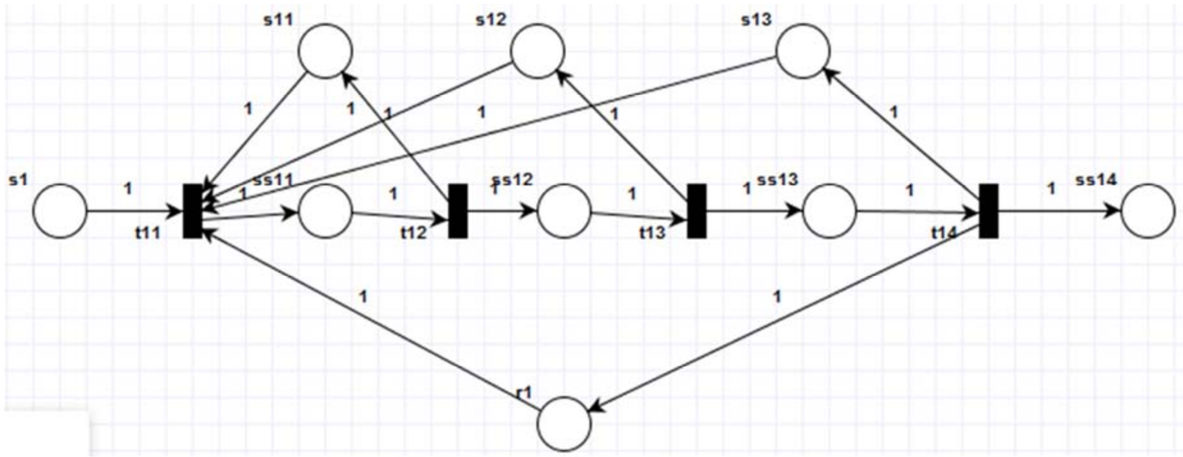


Figure 3. *The first scheduling method model.*

Among them, from transition t11 to transition t14 are three sections 1, 2 and 3 in the route r1, s1 and ss14 are its former and latter routes.

(2) Situation 2: the road condition of mine is in good condition with more locomotives and more sections in routes.

Method 2: the main feature of the second dispatching method is that after the locomotive sends out the pre-occupied application in the last section of each route, only the first section of the next route and the first section of the next route can satisfy the pre-occupied application conditions, and in each route, when entering the next section from one section, the interlock conditions shall be satisfied to enter:

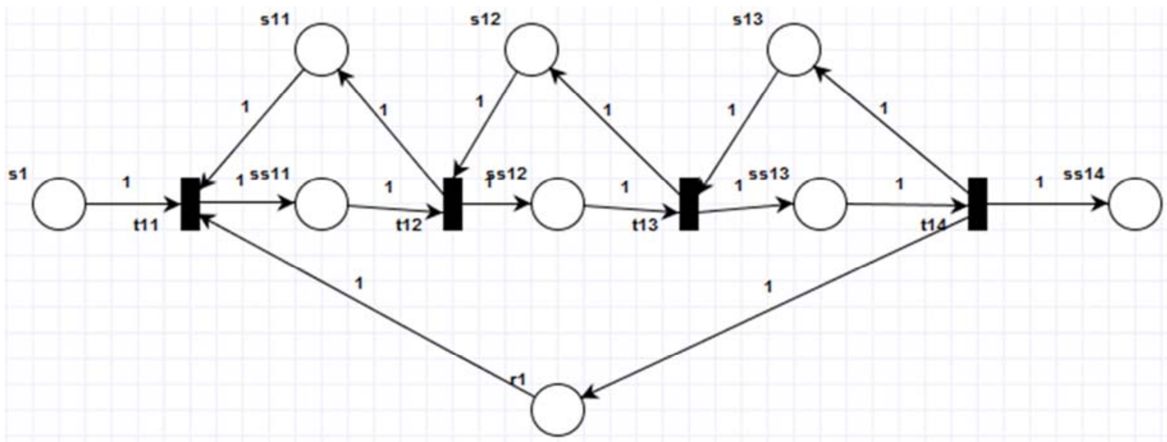


Figure 4. *The second scheduling method model.*

Similar to figure3, from transition t11 to transition t14 are three sections 1, 2, 3 in the route r1, and s1 and ss14 are its former and latter route.

(3) Situation 3: this condition is a special case of condition 2, which is characterized by a route that contains only one section.

Method 3: in this method, each approach only contains one section, and at this point, the route is equivalent to the section, so it can be seen that there is no route allocation and only the section resource allocation can be considered. The petri net model of its scheduling method is shown as follows:

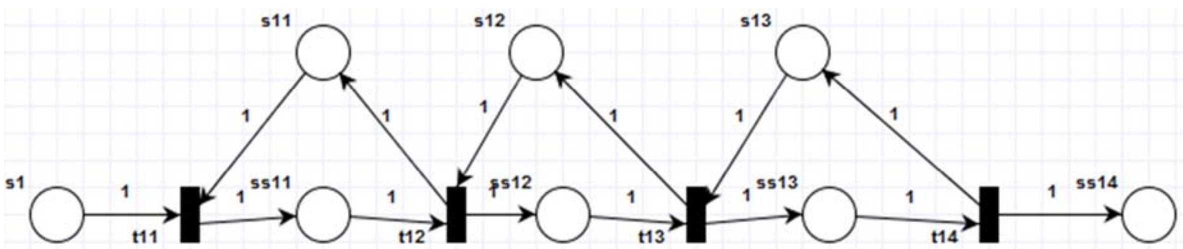


Figure 5. *The third scheduling method model.*

3. Building and Simulation Analysis of Mine Hybrid Locomotive Dispatching Model

The above has made a brief introduction to the running track diagram of the simple underground locomotive in figure 1. In this chapter, petri net is modeled for it according to three scheduling methods.

The corresponding relationship between the route and the section in the figure is:

r1: (1, 3); r2: (5); r3: (6); r4: (4); r5: (8); r6: (13, 7); r7: (1, 9); r8: (3, 2); r9: (11); r10: (12); r11 (9, 2); r12 (7).

List the task route table according to its correspondence:

Table 1. *Task route table.*

the locomotive type	serial number	route task	corresponding section	route
X	1	(r1, r2, r3)	{(1,3)(5)(6)}	CH1→CH2
Y	1	(r5, r4, r8)	{(8)(4)(3,2)}	CH2→CH1
X	2	(r7, r10)	{(1,9)(12)}	CH1→CH3
Y	2	(r9, r11)	{(11)(9,2)}	CH3→CH1
X	3	(r1, r2, r6)	{(1,3)(5)(13,7)}	CH1→CH4
Y	3	(r12, r4, r8)	{(7)(4)(3,2)}	CH4→CH1

Corresponding to the driving route and task scheduling list of the above table that petri nets modeling can be performed according to three scheduling methods. The following is the task model of three locomotives under three different scheduling methods.

3.1. Locomotive Operation Scheduling Modeling Under the First Scheduling Method

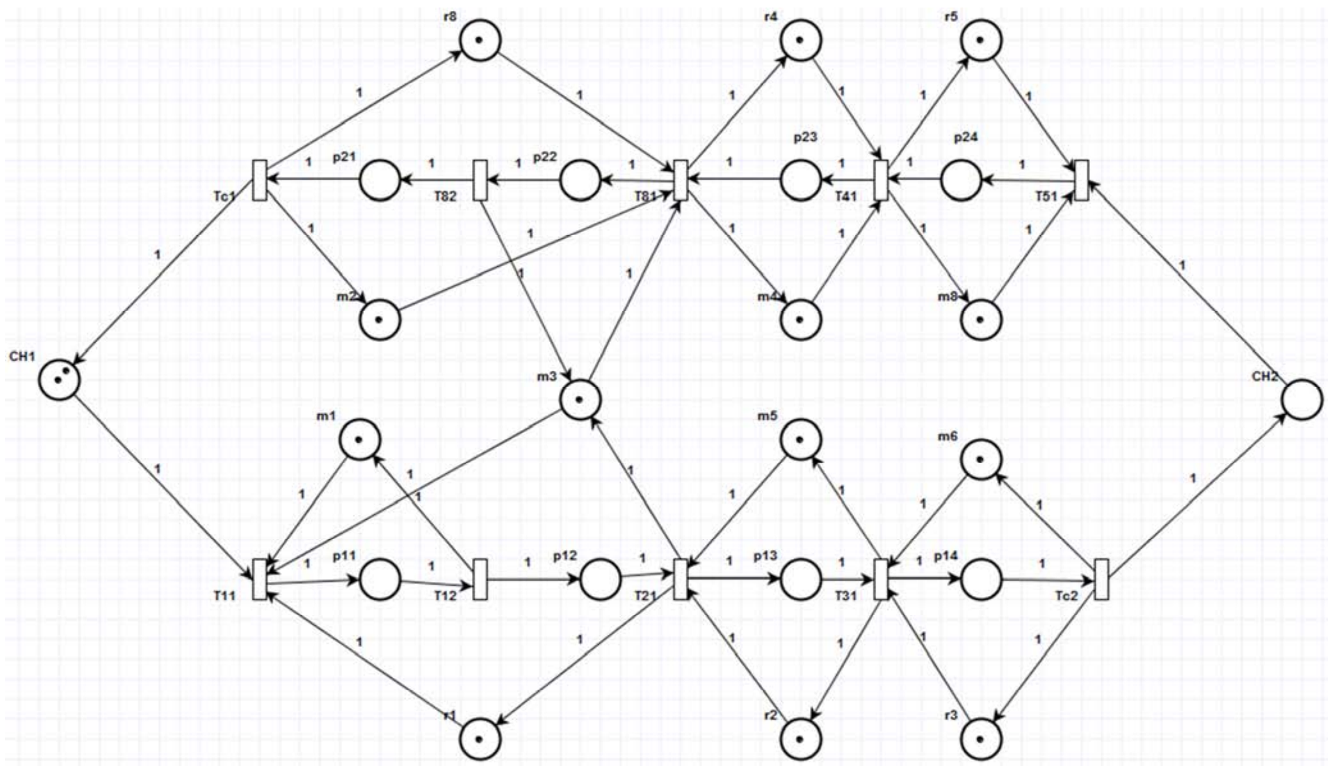


Figure 6. *The scheduling model of locomotive 1 under the first method.*

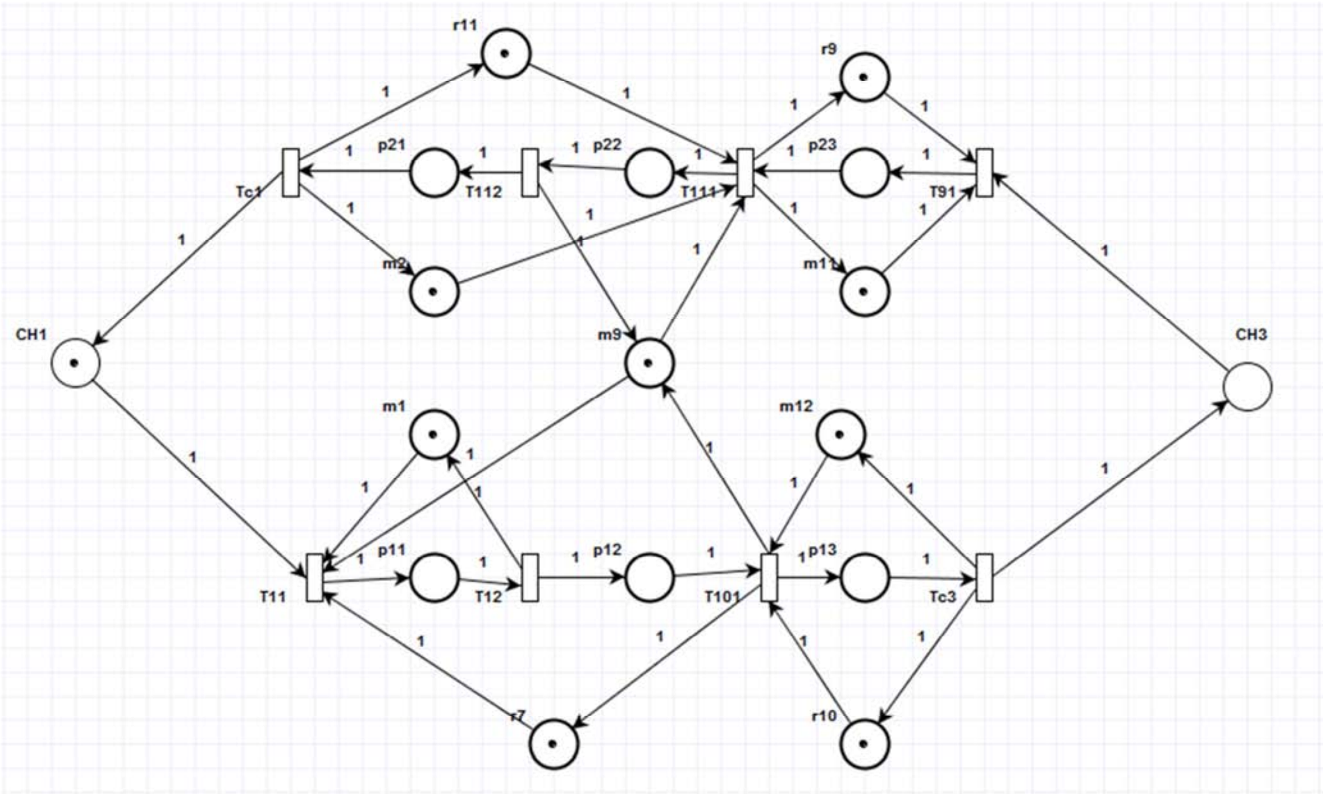


Figure 7. The scheduling model of locomotive 2 under the first method.

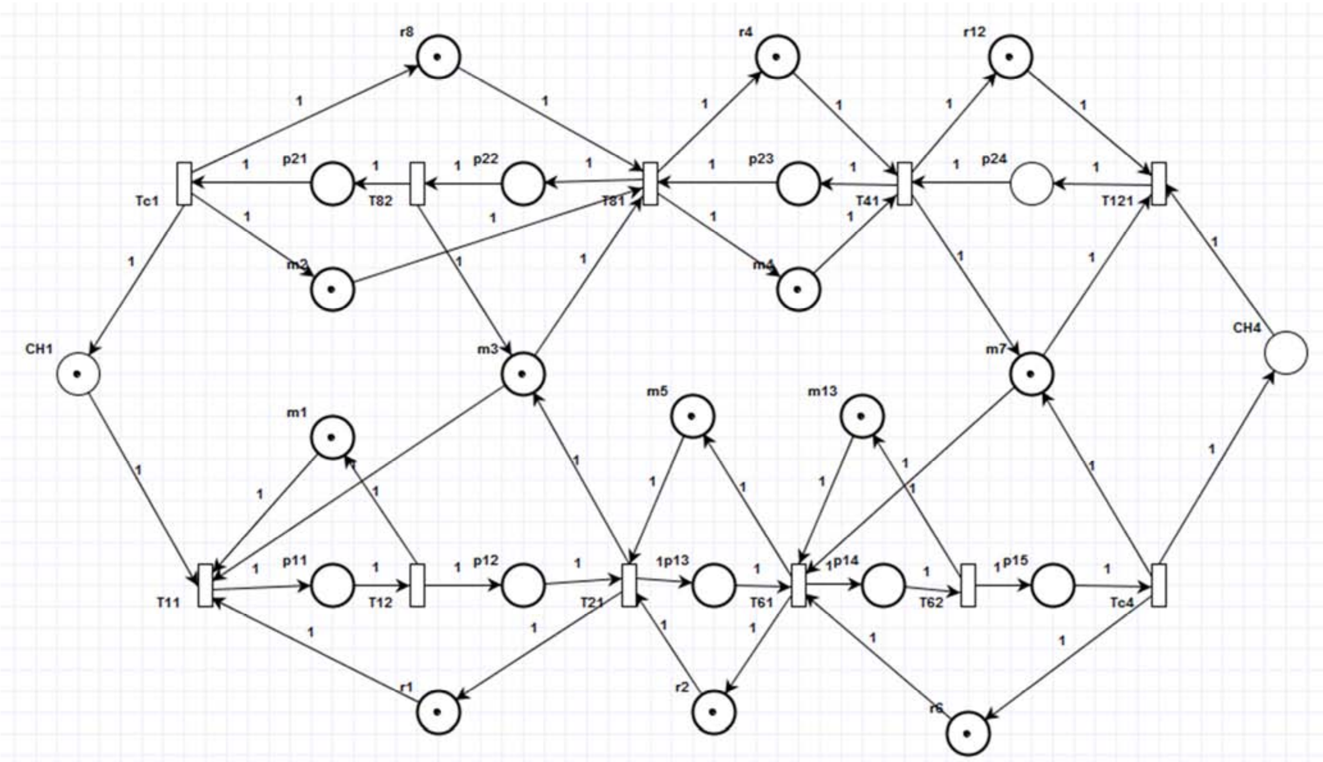


Figure 8. The scheduling model of locomotive 3 under the first method.

The above is the dispatching model of three locomotives under the first method, which is characterized by that when the locomotive sends a pre-occupation application to the next entrance in the last section of a certain route, it must satisfy the permission of the next route and all sections of the next route.

An obvious shortcoming of this model is that it is impossible to "unlock when leave" of the segment. Take the route r1 in figure as an example that described as follows:

In order to avoid the above situation, the initial number of tokens and the token accommodation amount of the place r1 can only be 1, so as to avoid the situation that multiple locomotives are out of control in the same way.

3.2. Locomotive Operation Scheduling Modeling Under the Second Scheduling Method

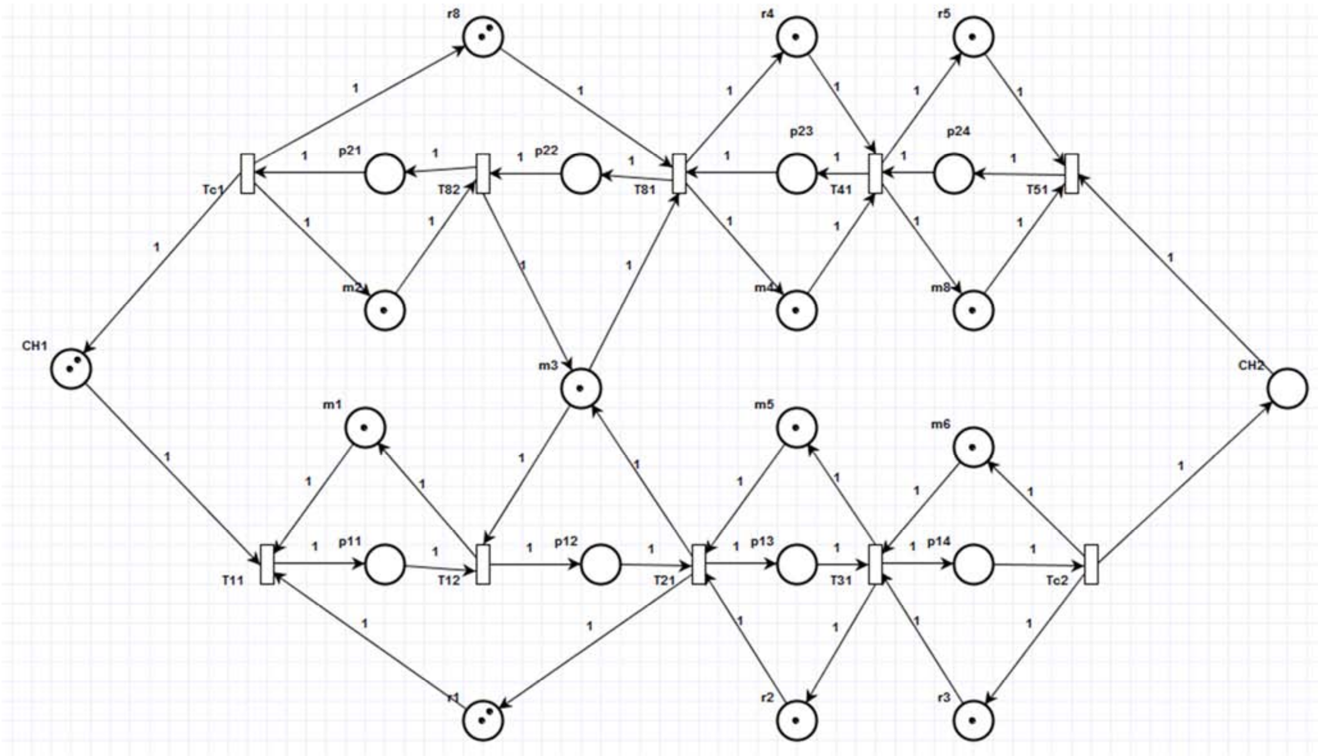


Figure 9. *The scheduling model of locomotive 1 under the second method.*

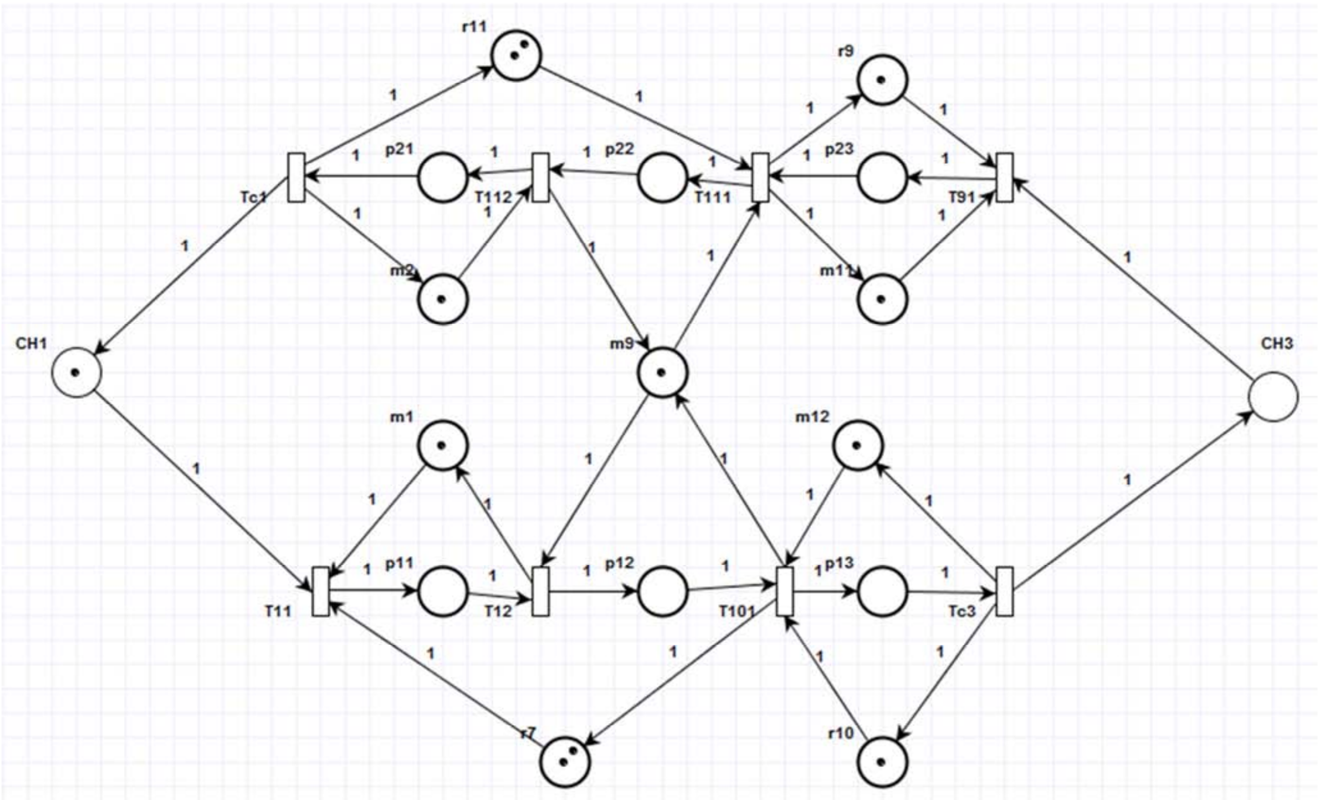


Figure 10. *The scheduling model of locomotive 2 under the second method.*

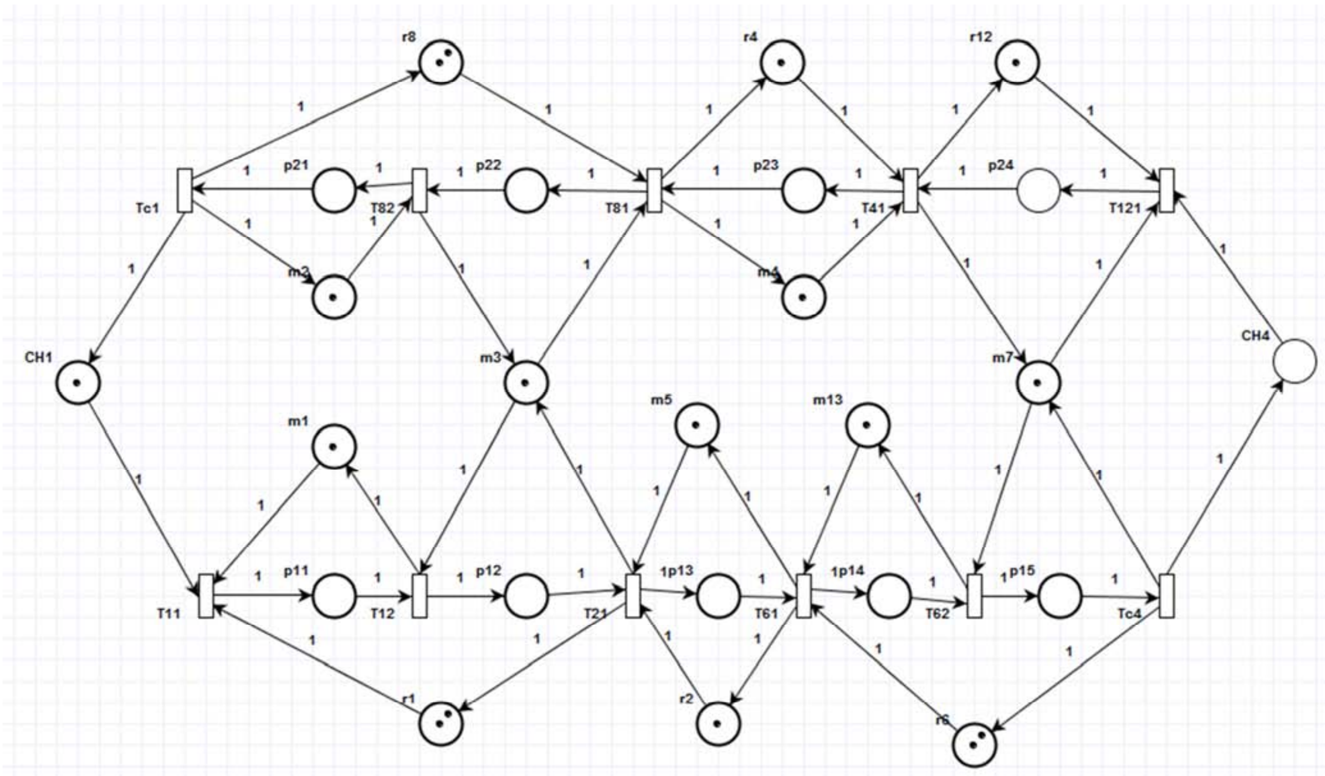


Figure 11. The scheduling model of locomotive 3 under the second method.

The above model is the modeling of three locomotives under the second scheduling method, and this scheduling method is an improvement to the first scheduling method. In this scheduling strategy, the section feedback place m_i can accurately control each section the number of tokens assigned to the place r1 is 2. A route can accommodate multiple locomotives at the same time that increasing rail efficiency.

3.3. Locomotive Operation Scheduling Modeling Under the Third Scheduling Method

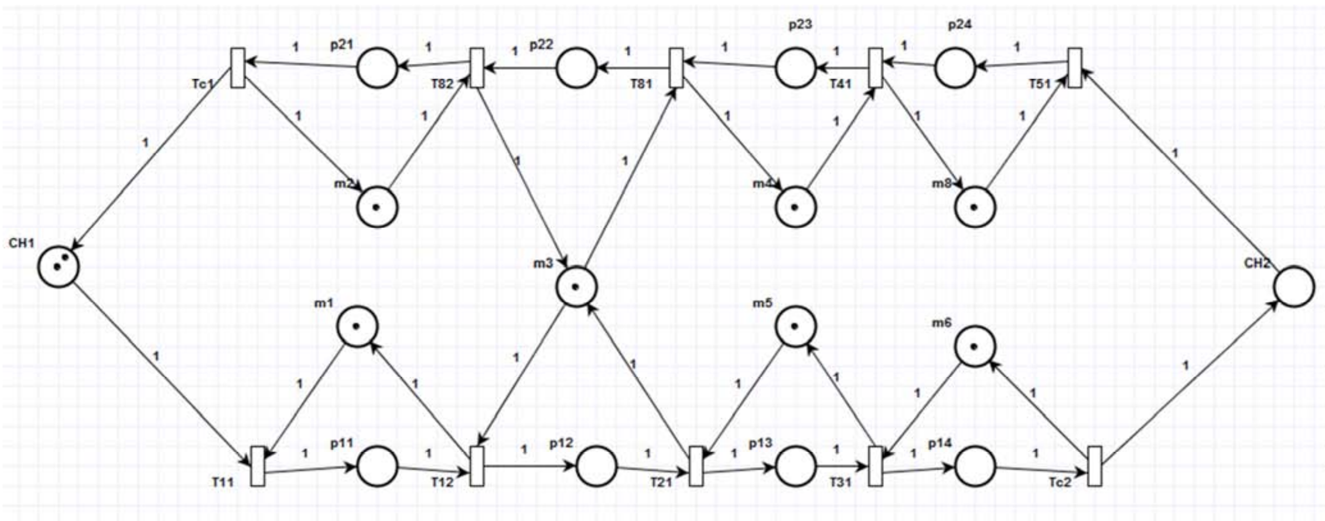


Figure 12. The scheduling model of locomotive 1 under the third method.

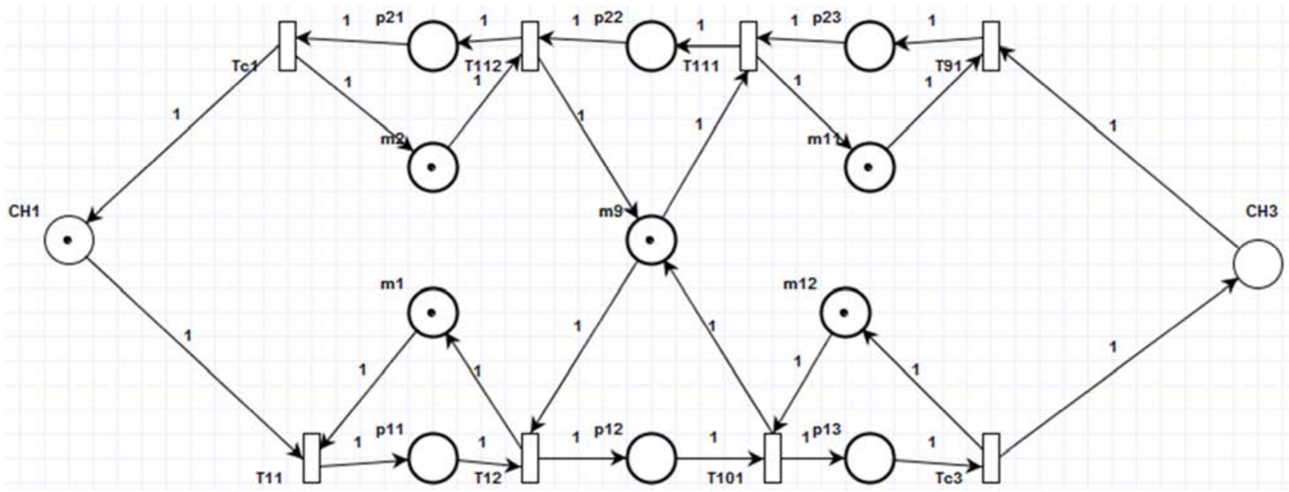


Figure 13. The scheduling model of locomotive 2 under the third method.

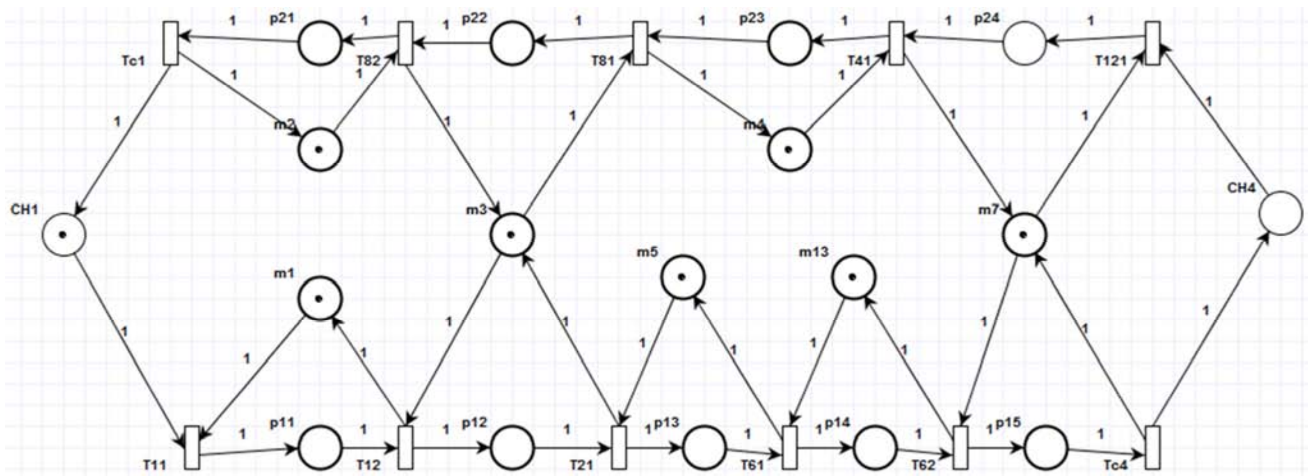


Figure 14. The scheduling model of locomotive 3 under the third method.

The above is the modeling of the three-locomotive operation scheduling under the third scheduling method. The third scheduling method refers to the situation where all the routes contain only one section, which is a more extreme special case and relatively rare in practical applications, and only understand here.

4. Deadlock Analysis and Calculation of the Model

Because the total model data of the final fusion is huge and the model simulation and analysis have great similarities, this section only applies PIPE simulation and software analysis to the built model under the three scheduling strategies of locomotive 1 and compare and summarize the performance of each model through software analysis, and the other no longer tautology.

Click "Animation model" to run the simulation, and set the number of running steps here to 10 steps that the interval between steps is 1000ms, then click "determine" to start running.

After starting the operation, you can see that the transition turns red when it occurs, and the step setting of 16 steps finally returns to the origin - the parking depot 1. The transition of the model in the running process is shown in figure15.

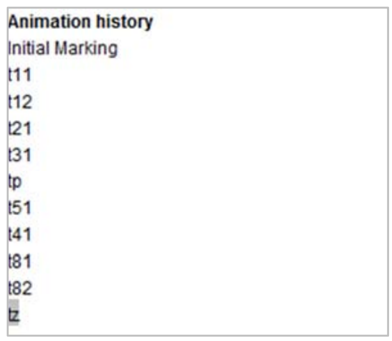


Figure 15. Transition sequence of model running.

4.1. Deadlock Status Analysis

For better deadlock analysis, the following definitions are derived:

Definition 4.1: For a given petri net,$^*t = \{p \mid (p, t) \in I\}$ and $t^* = \{p \mid (t, p) \in O\}$ are the input places set and output places set of t. $^*p= \{t \mid (t, p) \in O\}$ and $p^*=\{t \mid (p, t) \in I\}$ are the input transitions set and output transitions set of p. Where (x, y) represents an arc form x to y [7].

Definition 4.2: A set of resources $R_D \in$ R is said to be in a deadlock state under marking M if it satisfies the following two conditions: (1) All the resources in R_D are occupied, i.e., M(p r) = 0 for r∈ R_D . (2) All the jobs occupying resources of R_D are waiting for other resources of R_D , i.e., $*(p_q*)_r \in \{p_r \mid r \in R_D\}$ for $p_q \in \{p_q \mid R(p_q) \in R_D, M(p_q) > 0\}$ where $R(p_q)$ denotes the resource occupied in processing step p_q [8].

The firing of t∈ p_r * will remove one token from p_r, and reside a token in t*∈ { $p_q \mid p_q \in (p_r*)*_q$ }The firing of t∈ *p_r will reside a toke to p_r and remove one token from *t∈ { $p_q \mid p_q \in *(*p_r)_q$ }. Therefore, for a PN and a resource r∈ R, there must exist a P-invariant:

$$M(p_r) + \sum_{\{p_q \mid R(p_q)=r\}} M(p_q) = C_r \tag{6}$$

Where C_r denotes the initial number of tokens in the network.

Definition 4.2 and the exist of P-invariant establish a sufficient condition that leads to the following theorem.

Theorem 4.1: R_D is in a deadlock state under marking M, if and only if M satisfies the following equation.

$$\sum_{\{p_q \mid R(p_q)\in R_D, *(p_q*)_r \in p_r, r\in R_D\}} M(p_q) = \sum_{r\in R_D} C_r \tag{7}$$

This equation is called a deadlock state equation.

At this point, if a token resource is shared by $p_{1,i}$ and $p_{2,i}$, Eq.7 can be written as:

$$\sum_{\{p_q \mid R(p_q)\in R_D, *(p_q*)_r \in p_r, r\in R_D\}} M(p_q) = \sum_{r\in R_D} C_r - 2 \tag{8}$$

For the running model of locomotive 1 under the first scheduling method, C_r is the number of total section resources. p11 and p12 share the same section resource, so they can be regarded as one process. In figure6, for resources R_D ={m1, m3, m5, m6, m8, m4, m2}, the deadlock state equation is:

$$\text{M(p12)+M(p13)+M(p24)+M(p23)}= C_{m1} + C_{m3} + C_{m5} + C_{m6} + C_{m8} + C_{m4} \text{-2=4} \tag{9}$$

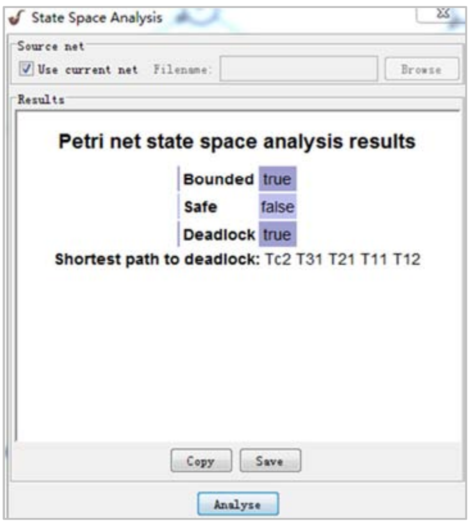
Similarly, the model of locomotive 1 under the second scheduling method, for the deadlock equation of resource R_D ={m1, m3, m5, m6, m8, m4, m2} is:

$$\text{M(p11)+M(p12)+M(p13)+M(p24)+M(p23)+M(p22)}= C_{m1} + C_{m3} + C_{m5} + C_{m5} + C_{m6} + C_{m8} + C_{m4} + C_{m2} \text{-2=5} \tag{10}$$

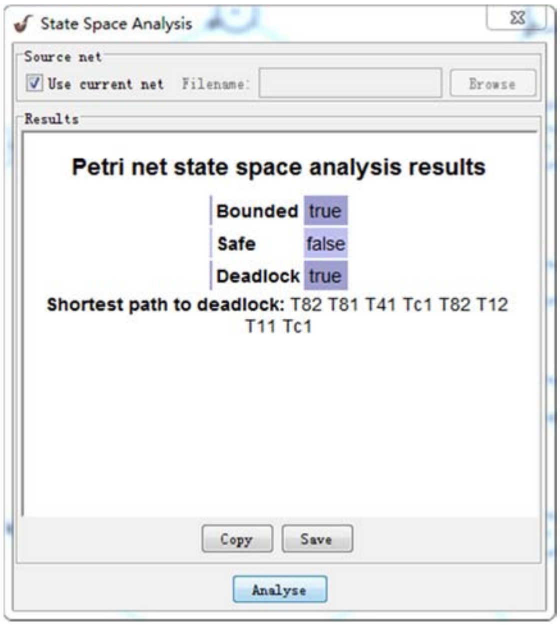
The model of locomotive 1 under the third scheduling method, for the deadlock equation of resource R_D ={m1, m3, m5, m6, m8, m4, m2} is:

$$\text{M(p11)+M(p12)+M(p13)+M(p24)+M(p23)+M(p22)}= C_{m1} + C_{m3} + C_{m5} + C_{m5} + C_{m6} + C_{m8} + C_{m4} + C_{m2} \text{-2=5} \tag{11}$$

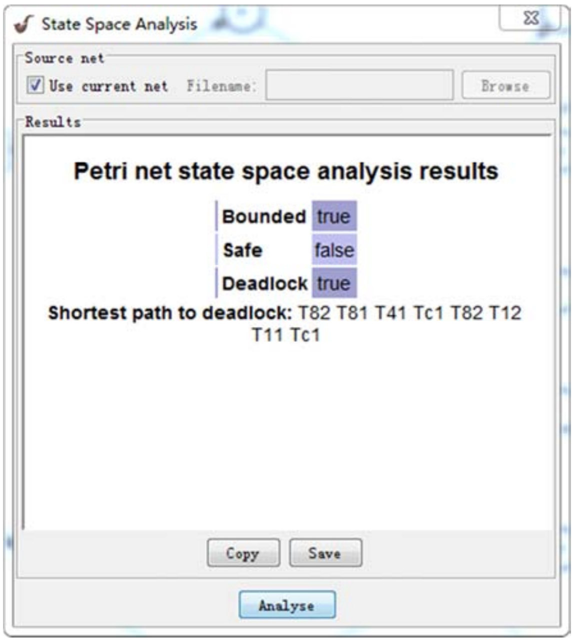
According to the above Eq. 9, Eq.10 and Eq. 11, tokens are placed in the place of each network, and the deadlock analysis of the software PIPE is as follows:



(a)



(b)



(c)

Figure 16. *Petri net state space analysis result.*

Figur (a), (b) and (c) respectively represent the simulation of the deadlock state equation of locomotive 1 under the first, second and third scheduling methods. The shortest deadlock path of locomotive 1 under the current state is also shown in the figure. From the perspective of the whole system, the locomotive capacity of dispatching method 1 is not as good as that of dispatching method 2 and dispatching method 3.

4.2. Potential Deadlock Status Analysis

4.2.1. Potential Deadlock State Algorithm

For better potential deadlock analysis, the following definitions are derived:

Definition 3.3: A set of resources $R_D \in$ R is said to be in a potential deadlock state (PDS) under marking M if it satisfies the following two conditions: (1) All the resources in R_D are occupied, i.e., $M(p_r)$ =0 for r∈ R_D. (2) There is at least one job that can release resource r, but will result in another deadlock state in the future.

The potential deadlock state equation is different from the deadlock state equation, so the potential deadlock state equation construction algorithm in [9] is cited to construct the deadlock state equation. According to the particularity of mine scheduling, the algorithm is improved slightly. The algorithm steps are as follows:

Step 1: Let all the resources r ∉ R_D be available, i.e., $M(p_r)=C_r$, r∉ R_D.

Step 2: From the above analysis of P-invariant, it can be seen that:

$$\sum_{r\in R_D} M(p_r) + \sum_{\{p_q|R(p_q)\in R_D\}} M(p_q) = \sum_{r\in R_D} C_r \tag{12}$$

Step 3: according to the definition of potential deadlock,

$$\sum_{r\in R_D} M(p_r) = 0 \tag{13}$$

Substitute Eq. 12 into Eq. 13, can get:

$$\sum_{\{p_q|R(p_q)\in R_D\}} M(p_q) = \tag{14}$$

At this point, if a token resource is shared by $p_{1,i}$ and $p_{2,i}$, Eq.14 can be written as:

$$\sum_{\{p_q|R(p_q)\in R_D\}} M(p_q) = \sum_{r\in R_D} C_r - 2 \tag{15}$$

Step 4: If $R(p_{q,i}) \in R_D$, and for any k >i, $R(p_{q,k}) \in R_D$, then let

$$M(p_{q,i})=0 \tag{16}$$

Substitute Eq. 16 into Eq.14, have:

$$\sum_{\{p_{q,i}|R(p_{q,i})\in R_D, \exists k>i, R(p_{q,k})\in R_D\}} M(p) = \sum_{r\in R_D} C_r \tag{17}$$

In the same way, if a token resource is shared by $p_{1,i}$ and $p_{2,i}$, Eq.17 can be written as:

$$\sum_{\{p_{q,i}|R(p_{q,i})\in R_D, \exists k>i, R(p_{q,k})\in R_D\}} M(p) = \sum_{r\in R_D} C_r - 2 \tag{18}$$

Step 5: For all $p_{q,i}$ $R(p_{q,i}) \in R_D$, $R(p_{q,i+1}) \notin R_D$, and exist k > i +1, $R(p_{q,k}) \in R_D$, if the token in $p_{q,i}$ can arrive at the place $p_{q,i}$ by a firing sequence from any marking satisfied Eq. 18, then let

$$M(p_{q,i})=0 \tag{19}$$

Step 6: Substitute Eq. 19 into Eq. 17 or Eq.18, can get the PDS equation.

The above algorithm can also be applied to construct a deadlock state equation. In some cases, it is difficult to determine if there exists a PDS for a set of resources in general, therefore, we apply the above algorithm to obtain a deadlock state.

4.2.2. Application of Potential Deadlock Algorithm in Scheduling Model

Model of locomotive 1 under the first scheduling method: for resources R_D = {m1, m3, m5, m6, m8, m4, m2}, since p11 and p12 share resource m3 and p21 and p22 share resource m2, it can be seen from Eq. 12 that:

$$M(p11) + M(p12) + M(p13) + M(p14) + M(p24) + M(p23) + M(p22) + M(p21)$$

$$= C_{m3} + C_{m5} + C_{m6} + C_{m8} + C_{m4} + C_{m2} = 6 \quad (20)$$

From Eq. 13, get

$$M(p11) + M(p14) = M(p21) = 0 \quad (21)$$

Combine Eq. 20 and Eq. 21, from Eq. 15, have

$$M(p12) + M(p13) + M(p24) + M(p23) + M(p22) = 6\text{-}2 = 4 \quad (22)$$

Eq. 22 is the potential deadlock state equation of Petri net model established in figure 6.

Model of locomotive 1 under the second scheduling method: for resources R_D ={m1, m3, m5, m6, m8, m4, m2}, it can be seen from Eq. 12 that:

$$M(p11) + M(p12) + M(p13) + M(p14) + M(p24) + M(p23) + M(p22) + M(p21)$$

$$= C_{m1} + C_{m2} + C_{m3} + C_{m5} + C_{m6} + C_{m8} + C_{m4} = 7 \quad (23)$$

From Eq. 13, get

$$M(p14) = M(p21) = 0 \quad (24)$$

Combine Eq. 24 and Eq. 23, from Eq. 15, have

$$M(p11) + M(p12) + M(p13) + M(p24) + M(p23) + M(p22) = 7\text{-}2 = 5 \quad (25)$$

Eq. 25 is the potential deadlock state equation of petri net model established in figure.9.

Model of locomotive 1 under the third scheduling method: for resources R_D ={m1, m3, m5, m6, m8, m4, m2}, it can be seen from Eq.12 that:

$$M(p11) + M(p12) + M(p13) + M(p14) + M(p24) + M(p23) + M(p22) + M(p21)$$

$$= C_{m1} + C_{m2} + C_{m3} + C_{m5} + C_{m6} + C_{m8} + C_{m4} = 7 \quad (26)$$

From Eq. 13, get

$$M(p14) = M(p21) = 0 \quad (27)$$

Combine Eq. 24 and Eq. 23, from Eq. 15, have

$$M(p11) + M(p12) + M(p13) + M(p24) + M(p23) + M(p22) = 7\text{-}2 = 5 \quad (28)$$

Eq. 28 is the potential deadlock state equation of Petri net model established in figure 12.

As can be seen from equations 25 and 28, since the analysis is based on the same resources, the second method and the third method have same potential deadlock equation.

5. Conclusion

In this paper, the characteristics of underground locomotive scheduling are explained. According to the scheduling characteristics and petri net, the principles of three scheduling strategies are explained in detail, and the advantages and disadvantages of each scheduling method are illustrated. The intuitiveness and flexibility of petri net for discrete event modeling are applied to locomotive scheduling. Then the deadlock state of the first locomotive model under three scheduling methods is analyzed, and the deadlock state equation is obtained, and the PIPE is used for state space analysis to prove the validity of the deadlock state equation. Finally, the potential deadlock equation of each network is obtained by using the relevant algorithm, so as to avoid the clogging and collision of locomotive at the source. All models are safe, bounded, and active. The whole modeling process proves the effectiveness of petri net in optimization scheduling modeling.

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