Study on Emergency Response Process of Metro Emergency Based on Stochastic Petri Nets

Junhui Yuan, Jie Xu, Yong Qin and Limin Jia

Abstract Stochastic Petri Nets (SPN) approach is used to model emergency response process of metro emergency in order to analyze the performance of emergency response process of metro emergency. With the method of "top down," we establish the basic models of each stage of metro emergency, then according to the actual rescue process with each stage mode of public places and transitions to construct a SPN model of the emergency response process. According to the possible state set of SPN mode, an isomorphic Markov Chain is developed for measuring and evaluating the performance of emergency response process of metro emergency, and the efficacious of the model is justified through the case of Beijing metro emergency plan response process.

Keywords Stochastic petri nets · Metro emergency · Emergency response process · Markov chain

Introduction

The subway emergency response process is an important part in the subway emergency safety management due to the tightness of the subway space which brings many uncertain factors to the subway emergency and causes inconvenience to forecast the link busy degree and execution efficiency of emergency response. There are many scholars that have carried out a lot of research on the emergency response of metro emergency [1–7], and they mainly focus on subway emergency response mechanism and system structure but they ignore the quantitative analysis

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of emergency response process. The Petri nets modeling method is commendable to reflect the flow of personnel, materials, and other aspects of emergency response process of metro emergency. Fateh et al. [8] establish emergency evacuation process model based on Petri nets. Landry et al. [9] use Petri nets to establish the working flow model of the decision maker in the emergency management, and the simulation is carried out based on fuzzy rules. Sharmin et al. [10] study on the flood emergency management process based on Petri nets, and the feasibility of the model is verified by simulation. Zhong et al. [11] establish model of city emergency response system based on Petri nets, and illustrate the effectiveness of the mode by a simple example. However, in most of these studies analysis, the rationality and validity of emergency process are based on the basic Petri nets, which are not reflected by the time limit of the emergency response process.

In this paper, the SPN is selected to analyze emergency response process, and the isomorphic Markov chain is developed to calculate the stable probability of reachable markings. The time performance and operation efficiency of each link and the operation status of each stage in emergency response process are analyzed to provide the reference for the emergency management decision.

Analysis on Emergency Response Process of Metro Emergency

Subway emergency response process can be divided into four stages that early warning stage, decision-making stage, implementation stage, emergency recovery stage. There is certain relation between stages which constitute the emergency response system of metro.

Early Warning Stage Process

Early warning stage refers to the accident occurred after the subway, from the scene of the relevant personnel to the rescue department rushed to the scene of the accident process which consists of pre-handling, accident alarm, determine the level of information, and information submission, the detailed process is shown in Fig. 1. The relevant disposal of the early warning stage has provided information basis for decision-making stage.

Decision-Making Stage Process

The stage of emergency decision-making mainly includes alarm analysis, expert consultation, emergency plan analysis, and on-site information analysis; the detailed process is shown in Fig. 2. Emergency command group sent related

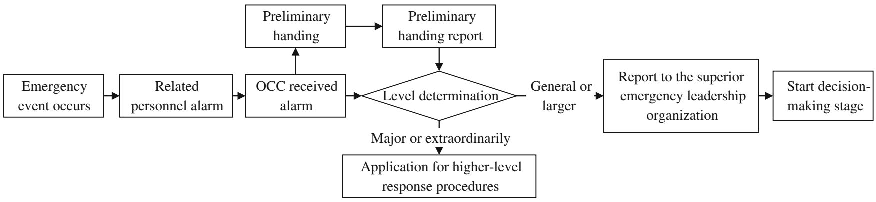


Fig. 1 Process of early warning stage

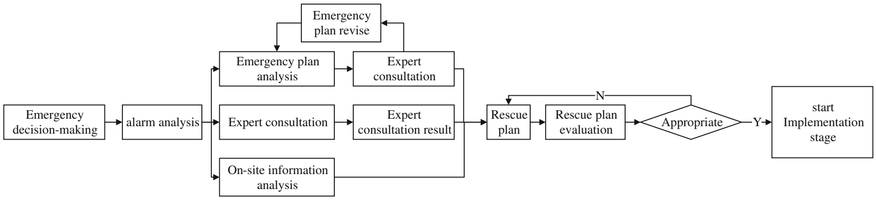


Fig. 2 Process of decision-making stage

personnel to the accident scene to investigate and analyze emergency development trend, organized experts to analyze type of the accident, influence range and emergency measures, analyzed emergency plan. Decision-making stage provides a guide for implementation stage.

Implementation Stage Process

Implementation stage is under the command of the emergency leading group, carry out a series of rescue operations according to the emergency response plan. It mainly includes on-site disposal, resource scheduling, external coordination, and information classification; the detailed process is shown in Fig. 3. Implementation stage is the core of the whole emergency response, departments need to coordinate and cooperate to complete the rescue mission.

Emergency Recovery Stage Process

Emergency recovery stage mainly includes rehabilitation disposal, investigation, and evaluation. It is shown in Fig. 4. Through the recovery stage of the relevant disposal measures, the subway to resume normal operations, while the investigation of the accident assessment and summary, to provide reference for the future of the accident disposal.

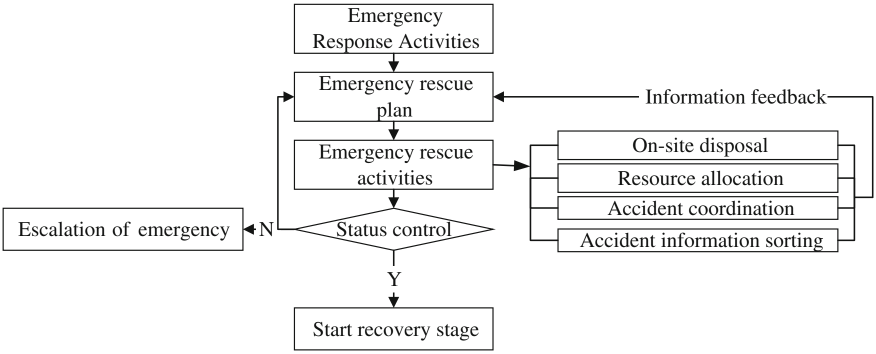


Fig. 3 Process of implementation stage

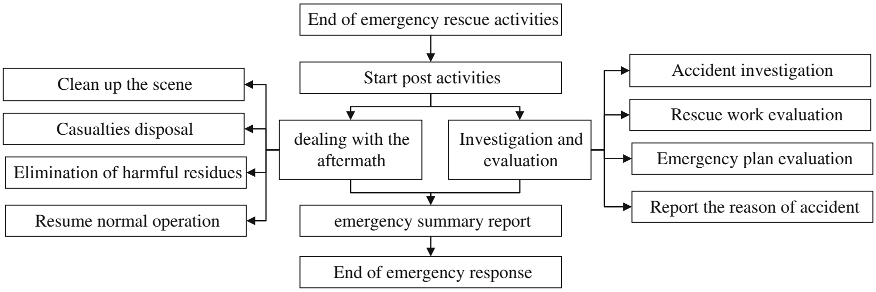


Fig. 4 Process of emergency recovery stage

Metro Emergency Response Process SPN Model

Modeling Basic Principle

According to the basic principle of Petri net, make full use of the advantage of Petri net in process modeling [12], stochastic Petri nets is used to modeling the emergency response process of Metro Emergency in this paper. In the SPN model, the transitions represent the emergency response activities; the places represent data processing and storage. The dynamic properties of the SPN mode can reflect logical order and the generation, storage, transmission, and processing of information and resources of the various activities in the process of emergency response well. Specific principles are embodied as follows:

(1) It is feasibility to model emergency process by using SPN to describe the process system, and the places represent information and other resources of the emergency process; the transition represents information production and transfer of the emergency process and describe the changes of information and other resources of emergency response process through assigning a delay time to the transition.

(2) It is enforceability of emergency process based on SPN. The place contains a token which indicates that the place is active and when the associated transitions are fired, the token is transferred from the place to another place which means that information, resources, and so on from one state to the next state in the process of emergency response. After the data tracking and collection activities are added in the model, the system can be simulated.
(3) It is evaluable of emergency process based on SPN. The response time and the operation efficiency of each link of the emergency response system can be evaluated by assigning the transition rate λ in the model.

The SPN Model for Each Stage of Metro Emergency Response

Through detailed analysis of each stage of the emergency disposal of Metro Emergency, we can set up the early warning, decision-making, response action, and recovery stages of the SPN model.

Early Warning Stage SPN Mode

The SPN model of early warning stage is shown in Fig. 5. A token placed in place P_1 when an emergency event occurs. The related personnel alarm is enabled expressed by transition T_1, when one placed in P_1. The firing transition T_1 consumes the one token in place P_1 and produces one token in place P_2, representing that Operating Control Center (OCC) received alarm information. Others places P_3–P_6, respectively, represent preliminary handing information, emergency classified information, application for higher-level response procedures, emergency decision scheme information, and emergency summary report. The transitions T_2–T_7,respectively, represent preliminary handing, cancel alarm, OCC determine emergency classification level, application for higher-level response procedures, report to the superior emergency leadership organization, and start rescue programs. The transitions T_1–T_7 rates are, respectively, represented by $\lambda_1 - \lambda_7$. The SPN model of early warning stage is shown in Fig. 5.

Decision-Making Stage SPN Mode

A token placed in place P_1 when the emergency classified level information is determined. Transitions T_1 and T_2 represent a conflict structure, and its firing is determined by token placed in place P_1. The firing transition T_1 consumes the one token in place P_1 and produces one token in place $P_{2,}$ representing that emergency leadership organization received alarm information. The places P_3–P_{17},respectively,

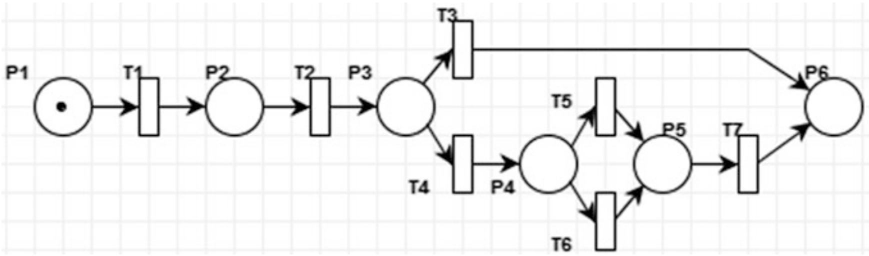


Fig. 5 Early warning stage SPN model

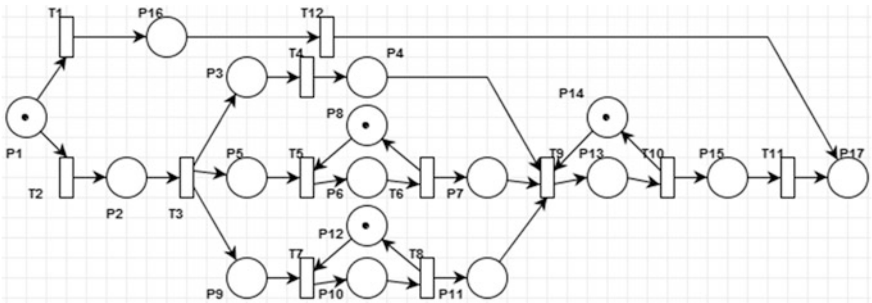


Fig. 6 Decision-making stage SPN model

represent emergency situation information, the result of emergency situation analysis, emergency plan information, preliminary emergency plan information, final emergency plan information, emergency plan revision information, expert database information, expert consultation information, final expert consultation information, expert consultation modify information, preliminary rescue plan, plan modify information, final rescue plan, and higher-level response information. The transitions T_3–T_{11}, respectively, represent that start alarm information analysis, on-site situation analysis, emergency plan analysis, call emergency plan, expert consultation, call expert consultation result, generate rescue plan, rescue plan evaluation, start rescue plan, and assist in higher-level response. The transitions T_1–T_{11} rates are, respectively, represented by $\lambda_1 - \lambda_{11}$. The SPN model of decision-making stage is shown in Fig. 6.

Implementation Stage SPN Mode

A token placed in P1 when the rescue plan is determined. The firing transition T_1 consumes the one token in place P_1 and produces one token in place P_2, P_3, P_4, and P_5, respectively, represent that on-site disposal information, resource allocation information, accident coordination information, and accident information sorting information. The places P_6–P_{12}, respectively, represent that on-site disposal

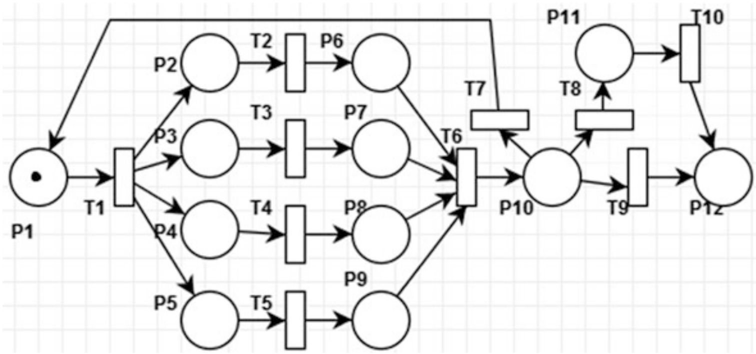


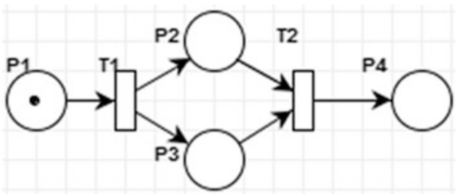
Fig. 7 Implementation stage SPN mode

feedback information, resource allocation feedback information, accident coordination feedback information, accident information sorting feedback information, situation analysis information, higher-level response information, and emergency summary report. The transitions T_2–T_{10}, respectively, represent that on-site disposal, resource allocation, accident coordination, accident information sorting, situation analysis, modifying rescue plan, escalation of emergency, start post activities, and assist in higher-level response. The transitions T_1–T_9 rates are, respectively, represented by $\lambda_1 - \lambda_9$. The SPN model of decision-making stage is shown in Fig. 7.

Emergency Recovery Stage SPN Mode

There is not detailed to investigation and assessment of emergency process. A token placed in place P_1 when start post activities. The transition T_1 represents post-activities. The firing transition T_1 consumes the one token in place P_1 and produces one token in place P_2, P_3, respectively, represent that dealing with the aftermath information and investigation and evaluation information. The place P_4 represents emergency summary report. The transition T_2 represents emergency summary. The transitions $T_{1,}$ T_2 rates are, respectively, represented by λ_1, λ_2. The SPN model of recovery stage is shown in Fig. 8.

Fig. 8 Emergency recovery stage SPN mode



The SPN Mode of Metro Emergency Response

According to the preamble of metro emergency response, the contents of each step of process analysis and modeling, fully integrated Petri net theory of information disposal, with SPN model of each stage of public transitions and places, we establish a comprehensive subway emergency disposal of the whole process of Petri net model, which shown in Fig. 9. The definitions of the places P_k and transitions T_k are listed in Table 1 and Table 2.

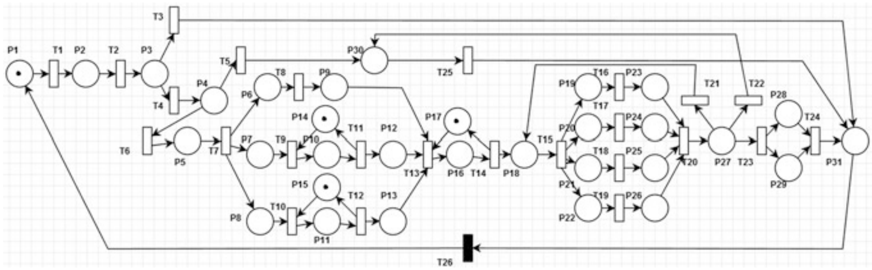


Fig. 9 Metro emergency response process SPN mode

Table 1 Definitions of places

Place	Definitions	Place	Definitions
P_1	Emergency message	P_{17}	Plan modify information
P_2	OCC received alarm information	P_{18}	Final rescue plan
P_3	Preliminary handing information	P_{19}	On-site disposal information
P_4	Emergency classified information	P_{20}	Resource allocation information
P_5	Emergency leadership organization received alarm information	P_{21}	Accident coordination information
P_6	Emergency situation information	P_{22}	Accident information sorting information
P_7	Emergency plan information	P_{23}	On-site disposal feedback information
P_8	Expert database information	P_{24}	Resource allocation feedback information
P_9	The result of emergency situation analysis	P_{25}	Accident coordination feedback information
P_{10}	Preliminary emergency plan information	P_{26}	Accident information sorting feedback information
P_{11}	Expert consultation information	P_{27}	Situation analysis information
P_{12}	Final emergency plan information	P_{28}	Dealing with the aftermath information
P_{13}	Final expert consultation information	P_{29}	Investigation and evaluation information
P_{14}	Emergency plan revision information	P_{30}	Higher-level response information
P_{15}	Expert consultation result modify information	P_{31}	Emergency summary report
P_{16}	Preliminary emergency plan information		

Table 2 Definitions of transitions

Transition	Definitions	Transition	Definitions
T_1	Related personnel alarm	T_{14}	Rescue plan evaluation
T_2	Preliminary handing	T_{15}	Start rescue plan
T_3	Cancel alarm	T_{16}	On-site disposal
T_4	OCC determine emergency classification level	T_{17}	Resource allocation
T_5	Application for higher-level response procedures	T_{18}	Accident coordination
T_6	Report to the superior emergency leadership organization	T_{19}	Accident information sorting
T_7	Start alarm information analysis	T_{20}	Situation analysis
T_8	On-site situation analysis	T_{21}	Modifying rescue plan
T_9	Emergency plan analysis	T_{22}	Escalation of emergency
T_{10}	Expert consulting	T_{23}	Start post activities
T_{11}	Call emergency plan	T_{24}	Emergency summary
T_{12}	Call expert consultation result	T_{25}	Assist in higher-level response
T_{13}	Generate rescue plan		

The instantaneous transition T_{26} is added in the input place P_{30} and the output place P_{30} to guarantee the continuous process of the network which the steady-state solution can be obtained, but count nothing actually. Transitions $T_{3–4}$ and $T_{5–6}$ represent a conflict structure. Transitions $T_{8–10}$ and transitions $T_{16–19}$ represent a simultaneous structure. There is loop structure in SPN model.

The SPN Mode Performance Analysis

Reachability Graph of SPN Mode

According to the SPN model shown in Fig. 9, from the initial state S_0 of the system, using the Petri net modeling tool, we can put all the state of the system and the relationship between the states. Reachability graph is shown in Fig. 10.

S_i represents the state of the system; S_4 represents the virtual state associated with the transition T_{25}. The reachability state of S_0 has 44. It can be determined that the model is live and bounded by reachable graph. Assign a relevant rate λ_i of transition Ti on each arc that can obtain isomorphic Markov chain. There are 43 states in reachability graph. Initial marking is denoted by m_0 = (1, 13, 14, 16), representing the tokens that are these places P_1, P_{13}, P_{14}, P_{16} simultaneously. Assumed transitions T_1–T_{25} rates associated with correspondence parameter

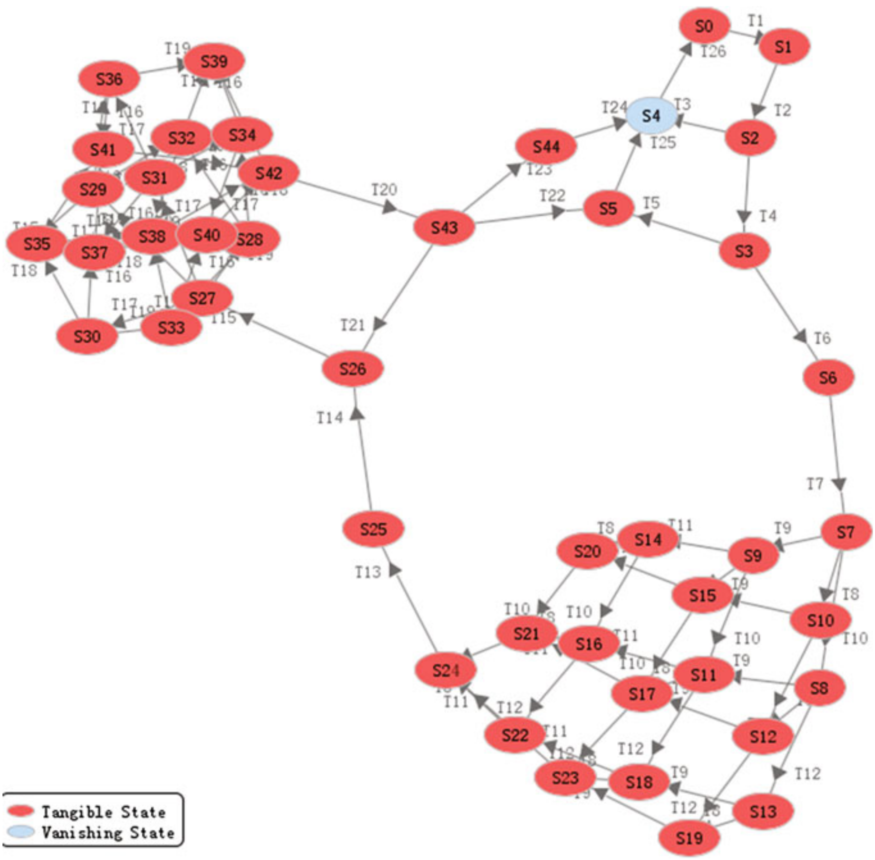


Fig. 10 Reachability graph

$\lambda_1 - \lambda_{25}$ and $x = (x_1, x_2, \ldots x_{44})$ are a set of steady-state probability of reachability states of Markov chain. We can obtain the steady-state probability based on correlation theorem of Markov chain [13], and calculate busy probability of places indicator and utilization indicator of transitions.

A Case Study of Beijing Metro

Any finite place, finite transition, marked stochastic Petri net are isomorphic to a one-dimensional discrete Markov process [14]. The performance of the average token number of places and the utilization of transitions are analyzed by steady-state marking probabilities of Markov chain.

In this paper, a simulation analysis of Beijing Metro Emergency Plan response process is developed. This emergency plan divide emergency response process into four stages such as early warning stage, decision-making stage, implementation stage, emergency recovery stage, and we can obtain SPN mode of this case based on metro emergency response process model in this paper. The Beijing metro emergency plan response process SPN model is shown in Fig. 11. The transitions of the decision-making stage is combined with the change of T14, and the transitions of emergency recover stage is merged into T24.

According to the experience of Beijing subway emergency experience data, we can assign each transitions T_i corresponding rate parameter λ_i which is shown in Table 3.

Solving the isomorphic Markov chain, we can obtain steady-state making probabilities shown in Table 4.

Calculate average token number of places and utilization of transition based on steady-state making probabilities shown in Tables 5 and 6.

(1) The average token number of places

It reflects the busy probability of the places. The average token number of places P23–P26 and P30 shown in Table 5 is significantly greater than other place, and in the process of emergency, information feedback and higher level of emergency response takes much longer compared to other links. Because in the process of emergency, emergency leading group of unified command departments launched rescue operations, which lead to multi departments rescue receiving feedback

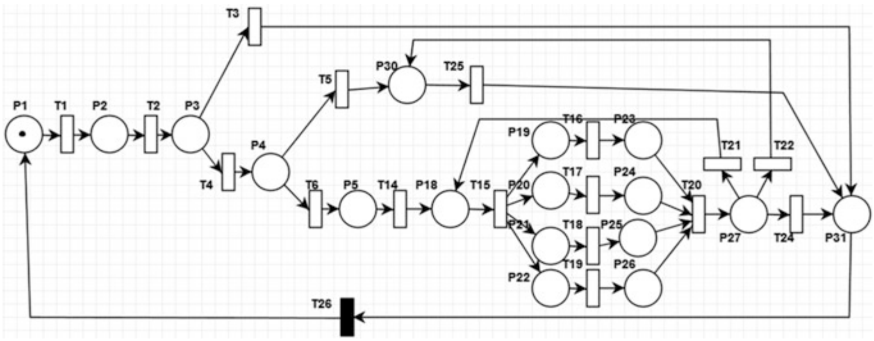


Fig. 11 Beijing metro emergency plan response process SPN model

Table 3 Transitions rate

Parameter	Rate value	Parameter	Rate value	Parameter	Rate value	Parameter	Rate value
λ_1	1	λ_6	1	λ_{11}	0.5	λ_{16}	1/12
λ_2	1	λ_7	1	λ_{12}	0.5	λ_{17}	1/24
λ_3	1	λ_8	1	λ_{13}	1		
λ_4	1	λ_9	0.5	λ_{14}	1		
λ_5	1	λ_{10}	0.5	λ_{15}	1		

Table 4 Steady-state making probabilities

Steady-state making probabilities	Value	Steady-state making probabilities	Value	Steady-state making probabilities	Value
P(M0)	0.04375	P(M8)	0.00467	P(M16)	0.00467
P(M1)	0.04375	P(M9)	0.00467	P(M17)	0.00467
P(M2)	0.02916	P(M10)	0.00467	P(M18)	0.01402
P(M3)	0.01458	P(M11)	0.00467	P(M19)	0.01402
P(M4)	0.01458	P(M12)	0.00467	P(M20)	0.01402
P(M5)	0.66777	P(M13)	0.00467	P(M21)	0.01402
P(M6)	0.02805	P(M14)	0.00467	P(M22)	0.02805
P(M7)	0.01402	P(M15)	0.00467	P(M23)	0.01346

Table 5 Average token number of place

Places	Average token number	Places	Average token number	Places	Average token number	Places	Average token number
P1	0.04375	P18	0.02805	P23	0.08881	P30	0.66777
P2	0.04375	P19	0.05609	P24	0.08881	P31	0
P3	0.02916	P20	0.05609	P25	0.08881		
P4	0.01458	P21	0.05609	P26	0.08881		
P5	0.01458	P22	0.05609	P27	0.01346		

Table 6 Utilization of transition

Transition	Utilization	Transition	Utilization	Transition	Utilization	Transition	Utilization
T1	0.04375	T6	0.01458	T18	0.02805	T24	0.00112
T2	0.04375	T14	0.01458	T19	0.02805	T25	0.02805
T3	0.01458	T15	0.02805	T20	0.02805		
T4	0.02916	T16	0.02805	T21	0.01346		
T5	0.01458	T17	0.02805	T22	0.01346		

information, and in a short period of time of information for decision-making, this case easily lead to information blockage, in addition to catastrophic events, the emergency response to the need for a cross organizational, cross area of city level emergency response, easy to produce a plethora of information, which leads to the accumulation of information. Therefore in the rescue process and need to pay attention to all kinds of information sorting, the improvement of emergency decision-making mechanism and other sectors of society to emergency response, strengthening of Metro emergencies emergency drills which is a key of optimizing the process of emergency.

(2) Utilization of transition

It reflects that the time is occupied by the activities in emergency response process. The utilization of Transition T1, T2, T4, T15–T20 from Table 6 is significantly higher than that of other changes high. In the process of emergency accident reporting, grade judgment, resource scheduling on-site, external coordination, the situation analysis activity for a longer period of time. Because the on-site disposal involves the multi-body, emergency command group coordination difficulty bigger, received too many accident information, decision required a longer period of time, in addition to meet emergency needs more resources, scheduling to step in place. Therefore, the emergency response organization should strengthen management, clear the duties of each department in emergencies, so as to enhance the various departments in the process of emergency coordination, enhance the efficiency of subway emergency disposal.

Conclusions

In this paper, a SPN model of metro emergency response process is constructed based on the stochastic Petri net. An isomorphic Markov chain constructed after the model is proved that it is active and bounded by constructing reachability graph. The average token number of places and the utilization of transitions are calculated based on Markov chain. According to the Beijing metro emergency plan response process, simulation analysis is carried out and we get busy probability of emergency response process of each link and the time of activities in emergency response process and we put forward suggestions to improve the emergency rescue efficiency. It plays a guided role to the information construction and improves the efficiency of multi department linkage of the metro emergency response.

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