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MODELING AND ANALYZING PERFORMANCE OF THE EMERGENCY RESCUE LOGISTICS SYSTEM BASED ON PETRI NETS

Ying Qu and Min Wang

School of Economics and Management
Hebei University of Science and Technology
No. 26, Yuxiang Street, Shijiazhuang 050018, P. R. China
quying1973@126.com

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Abstract. *Against the background of large-scale natural disasters or emergencies, according to its characteristics of emergency rescue system such as asynchronous concurrent, timeliness and other characteristics, the stochastic Petri nets modeling method was introduced to solve the problems in it. Based on the homogeneous characteristics with Markov chain of Petri nets, its Markov chains were built, and then quantitative description and analysis for the system's accessibility, boundedness, activity and some key performance sectors were carried out. Finally, an example was introduced to validate the effectiveness and system performance of the model. The results show that the model can explore the key parts which affect the operational efficiency of the system; then suggestions were put forward that provide a basis for optimizing the entire emergency rescue logistics system.*

Keywords: Emergency rescue logistics, Petri nets, Markov chain, Performance analysis

1. **Introduction.** With the frequent occurrence of natural disasters and emergencies, disaster relief and emergency repair work have attracted increasing attention by academic scholars, for the study of emergency logistics system, it is mainly related to emergency services positioning location, emergency material distribution, emergency supplies inventory management and other problems. Li et al. formulate facility location alternatives, through the analysis of city emergency logistics facility location, to establish a multi-project planning model and to solve the model, providing theoretical support for decision makers to choose the appropriate logistics location [1]. Luo and Yuan study new fuzzy and random mixed constraint programming location model based on the comprehensive consideration of random emergency demand and uncertain distribution time under the restricted condition [2]. Fan et al. establish a set of more perfect emergency logistics distribution mechanism according to the current situation of our country to deal with resources distribution for sudden natural disasters [3]. Hu builds a multi-objective optimization model of emergency material distribution with multi reserve location, multi material varieties, and single disaster point according to the diversity and uncertainty of emergency rescue demands on the basis of cost minimization and time urgency [4]. Dai et al. study the joint of emergency supplies distribution and vehicle routing arrangement from the perspective of system integration, and develop a chance-constrained programming model for the fuzzy dynamic location-routing problem and solve the model [5]. Jia and Wang put forward the emergency supplies classification method based on ABC (Activity Based Classification) and AHP (Analytic Hierarchy Process) through analyzing emergency reserve status of our country, according to the characteristics of emergency supplies to build emergency supplies inventory control model of inter-temporal and emergency supplies information model [6].

These studies provided solutions for emergency logistics service network location and the path optimization problems, established perfect mechanism for the caused emergency supplies scheduling and distribution problems, and provided algorithms and models for the control of rescue stocks. However, the models, algorithms and mechanism are only based on one part of the emergency rescue logistics system; there is not much research on the connection between coordination mechanisms of each part. However, for the whole system, it is certain that every part should be effectively completed, but more needs cooperation between all sectors. Large disasters or event happened when, where, what kind of disaster are impossible, these uncertainties make emergency rescue logistics system unable to do well prospective work, and require the system should have rapid response ability, coordinating progress of each part is the premise condition of rapid response, and the constraint of any part will influence the whole process. The integrity of the system, its significant activities, performance and their mutual restriction relations are analyzed to find system's bottlenecks, so as to increase the efficiency of the system. The distinctive feature of the system is that the most events are concurrent, with discrete random, so the overall description and efficiency analysis are particularly important.

As a discrete random and asynchronous concurrent events modeling tool, Petri nets has been popular in various fields, especially for the workflow process modeling. It was also used to construct the emergency process model and analyze it. Zhou [7] proposed a colored hybrid Petri nets to analyze the emergency response actions of chemical accidents. Zhong et al. [8] studied the performance of China typical Urban Emergency Response System and established its Petri nets model for performance analysis. Liu et al. [9] presented an application of Deterministic and Stochastic Petri Nets (DSPN) to evaluate the performance of subsea Blowout Preventer (BOP) system. These studies lay the foundation for our study of modeling emergency rescue logistics system based on Petri nets. This paper introduces stochastic Petri nets and focuses on the analysis of various specific rescue processes, then builds the model of the whole system process under the natural disaster environment, and does performance analysis for the model based on the isomorphic relationships with Markov chain, to ensure the model is correct and available, and provides a theoretical basis for improving the efficiency of emergency rescue logistics system.

The rest of the paper is organized as follows. Section 2 gives a brief introduction of the theory of Petri nets; Section 3 illustrates the modeling of emergency rescue logistics system based on Petri nets; Section 4 is performance analysis of Petri nets model for emergency logistics system; Section 5 gives the conclusion and suggestions for our future study.

2. **The Related Theory on Petri Nets.** Petri nets is a mathematical representation of discrete parallel system, it is composed of state elements P (Place) and changeable elements T (Transition), F (Flow) is the bridge contacting them, and with circle '$\circ$' expressing P, with rectangular '$\square$' expressing T, with directed arcs '$\rightarrow$' expressing F; the resources storing in the Place are called Token and with M expressing it, it refers to the factors associated with the system state changes, and use the dot '$\bullet$' to describe it [10]. Petri nets has its intelligent theoretical foundation and mature analysis method, and in this paper we mainly from three major characteristics of Petri nets do analysis: accessibility, boundedness (safety) and activity.

Performance analysis of Petri nets is based on Markov process, because the stochastic Petri nets and the continuous Markov chain are homogeneous, by solving the reachable sets of the stochastic Petri nets, construct the corresponding Markov Chain (MC), according to the steady state probability of MC, analyzing the performance of the system.

Definition 2.1. *A continuous time stochastic Petri nets* $SPN = (P, T, F, W, M_0)$ *is a* P/T *system,* P *is a non empty set of finite place and* $P = \{p_0, p_1, p_2, \ldots, p_n\}$*;* T *is a* *non empty set of finite transition and $T = \{t_0, t_1, t_2, \ldots, t_m\}$; F is the flow relationship between P and T; $W : F \to N$, $N = \{1, 2, 3, \ldots\}$ is the weight function; M_0 is the initial identification, and it can use $M = \{m_0, m_1, \ldots, m_i\}$ to express the state of system in a moment; $\lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_m\}$ is the set of Transition's average implementation rate. λ_i is the average rate of Transition t_i ($t_i \in T$), and it reflects the average implementation number per unit time under the situation can be implemented.*

Method to get MC: Calculate the reachable graph of SPN, change t_i of each arc with its average implementation rate λ_i (or functions about λ_i associated with marks), and then get the MC [11].

3. **Modeling of Emergency Rescue Logistics System Based on Petri Nets.** It is a very complex process for modeling the emergency rescue logistics system, and it involves something various and complicated, mainly including the configuration and procurement of emergency supplies, the arrangement of emergency vehicles, the dispatchment of emergency rescue personnels, the collection of emergency information and the formulation of emergency plans. We use Petri nets modeling method mainly due to that it can reflect the characteristics of the system effectively which other model cannot reflect. And through it we can find the potential problems existing in the system in the modeling process and timely change the model structure for the reanalysis. When modeling a Petri nets, it allows only the Places and Transitions are connected, the independent element is not be allowed, and the model cannot have the phenomenon of conflicts and deadlocks, and should be safe, active and accessible [12].

3.1. **The rescue process of emergency logistics system.** When the disaster occurs, firstly, we should start the emergency center and do response immediately according to the incident location, including start emergency logistics center, commanding the scene and do rescue in time, contact the foreign aid, make emergency decision and according to the feedback information modify the decision timely, etc. The process is shown in Figure 1.

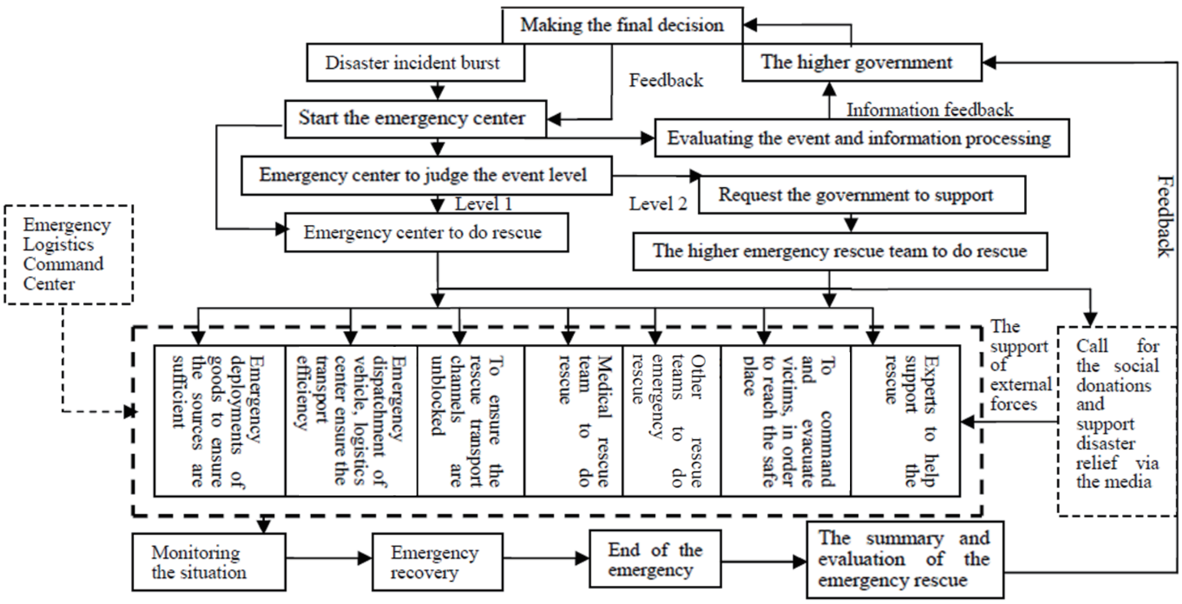

FIGURE 1. The emergency response process of disaster

3.2. **Constructing the emergency logistics system process model based on Petri nets.** According to the figure of emergency rescue logistics system process (Figure 1) and the principle of modeling Petri nets, we build the model of the emergency logistics system, as shown in Figure 2, and in this figure, the tokens in the model refer to the triggered information of disaster events; we explained the meaning of the Places and Transitions in the Petri nets separately, as shown in Table 1 and Table 2.

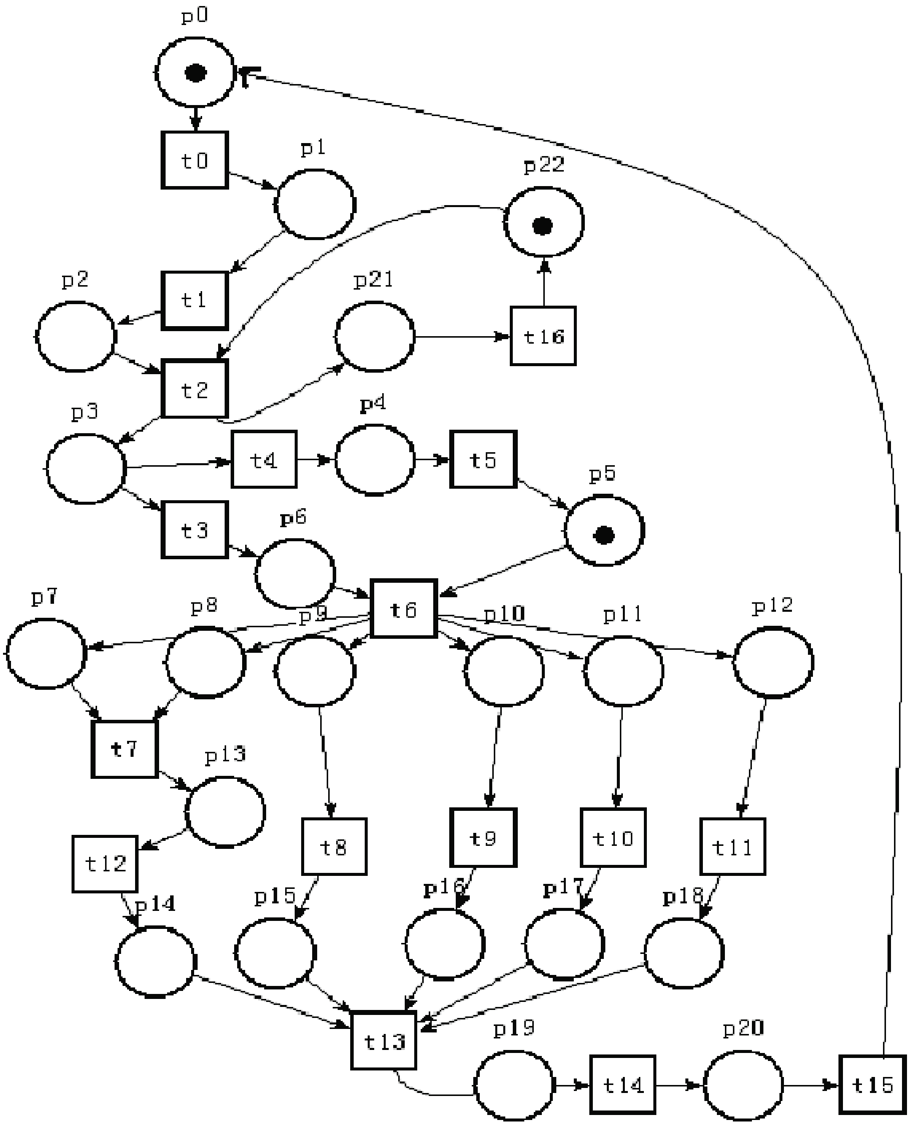

FIGURE 2. The Petri nets model

4. **The Performance Analysis of Petri Nets Model for Emergency Logistics System.** The performance analysis of Petri nets includes qualitative analysis and quantitative analysis, and this paper mainly through the Markov chain analyzes the Petri nets model, to judge whether it is accessible, bounded, safe, active, etc. In the performance analysis of the model, we use the analysis method of literature [13], but in the literature, the authors just gave the preliminary method of quantitative analysis, and did not calculate the probability of each state. Based on this, in this paper, we introduced examples for further analysis, converted the linear equation into a rate matrix, and calculated the probability of each steady state, and in the basis of the probabilities, we proposed three main performance indexes, and then calculated them in detail, and through the concrete analysis we get the conclusion.

Table 1. The explanation of the Places in the Petri nets model

Place	Explanation
P_0	disaster incident burst
P_1	alarm information
P_2	master the disaster event information
P_3	emergency command center information
P_4	the processing information of level 2 event
P_5	the information of higher rescue team in place
P_6	the processing information of level 1 event
P_7	the information of emergency supplies reserves
P_8	the information of dispatching emergency vehicle
P_9	the information of medical staff in place
P_{10}	the information of rescue teams in place
P_{11}	the information of exports support
P_{12}	the information of media report
P_{13}	the information of supplies distribution and transportation
P_{14}	the information of using supplies
P_{15}	the information of rescuing the injured
P_{16}	the information of transferring the injured
P_{17}	the information of employing the rescue plan
P_{18}	the information of social donations
P_{19}	the information of emergency recovery
P_{20}	the information of summing and evaluating rescue
P_{21}	event evaluation and information processing
P_{22}	the information of government decision-making process (Feedback to the emergency center to direct the rescue work)

Table 2. The explanation of the Transitions in the Petri nets model

Transition	Explanation
t_0	event alarm
t_1	reception of the alarm
t_2	start the emergency center
t_3	the event is classified at level 1
t_4	the event is classified at level 2
t_5	request the government to support
t_6	carrying out emergency rescue
t_7	start the logistics center
t_8	to do medical rescue
t_9	to do emergency rescue and transfer the crowd population to ensure the safety of personnel, the smooth of road
t_{10}	making urgent rescue prediction scheme to support the rescue
t_{11}	call for the social donations and support disaster relief
t_{12}	using the emergency supplies to do rescue
t_{13}	monitoring the situation
t_{14}	the completion of the rescue work
t_{15}	the end of the process and information feedback
t_{16}	report to the superior government

(1) The qualitative analysis of the Petri nets

Figure 2 shows the structure of the Petri nets model for emergency logistics system, it contains the sequence, concurrency and conflict structure, t_3, t_4 are conflict relationship, t_8, t_9, t_{10}, t_{11}, t_{12} are associated with concurrent structural relationship, and the others are the sequence structure relationship. And in this process, every Transition has its own input and output Place, showing that every completion of the emergency rescue needs certain conditions. What is more, there is no died task in the process, and the conflict relationship between t_3 and t_4 is based on the actual level of emergency event; this indicates that all the tasks can be achieved, so the emergency rescue process can be completed smoothly.

(2) The quantitative analysis of the Petri nets

The quantitative analysis is carried out based on the Markov chain, according to the model of Figure 2, we construct the MC, and change the implementation Transition t_i into implementation rate λ_i, and they are respectively λ_0, λ_1, λ_2, λ_3, $\ldots$, λ_{16}. We set the initial identification of the Petri nets model as $M_0 = (1,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1)$, it says P_0, P_5, P_{22} has a token respectively, in order for convenient writing, we write M_0 as $(0,5,22)$, we can get different reachable sets through the Transitions, and they are in the list Table 3.

Table 3. The reachable state sets

Name	Reachable set	Name	Reachable set
M_1	$(1,5,22)$	M_{18}	$(5,10,11,12,14,15,22)$
M_2	$(2,5,22)$	M_{19}	$(5,9,11,12,14,16,22)$
M_3	$(3,5,21)$	M_{20}	$(5,9,10,12,14,17,22)$
M_4	$(3,5,22)$	M_{21}	$(5,9,10,11,14,18,22)$
M_5	$(4,5,22)$	M_{22}	$(5,11,12,14,15,16,22)$
M_6	$(5,6,22)$	M_{23}	$(5,10,12,14,15,17,22)$
M_7	$(5,7,8,9,10,11,12,22)$	M_{24}	$(5,10,11,14,15,18,22)$
M_8	$(5,9,10,11,12,13,22)$	M_{25}	$(5,9,12,14,16,17,22)$
M_9	$(5,9,10,11,12,14,22)$	M_{26}	$(5,9,11,14,16,18,22)$
M_{10}	$(5,7,8,10,11,12,15,22)$	M_{27}	$(5,9,10,14,17,18,22)$
M_{11}	$(5,7,8,9,11,12,16,22)$	M_{28}	$(5,12,14,15,16,17,22)$
M_{12}	$(5,7,8,9,10,12,17,22)$	M_{29}	$(5,11,14,15,16,18,22)$
M_{13}	$(5,7,8,9,10,11,18,22)$	M_{30}	$(5,10,14,15,17,18,22)$
M_{14}	$(5,10,11,12,13,15,22)$	M_{31}	$(5,14,15,16,17,18,22)$
M_{15}	$(5,9,11,12,13,16,22)$	M_{32}	$(5,19,22)$
M_{16}	$(5,9,10,12,13,17,22)$	M_{33}	$(5,20,22)$
M_{17}	$(5,9,10,11,13,18,22)$		

Note: Here if the Transition t_5 occurs, there are two tokens in P_5, and after the Transition t_6 occurs, there is still a token in P_5.

According to M_0, M_1, $\ldots$, M_{33}, we get the homogeneous Markov chain, as shown in Figure 3, and the directed arcs represent transitions from one state to another state. From the Markov chain of Figure 3, we can get the following conclusions.

(1) There is no block in the whole process, and no infinite waiting for a task, this indicates that every task will be completed in certain time and the completion of each task is the foundation of a successful completion of the next task. In the emergency logistic rescue process, the most important factor is the time; we can conduct the investigation and analysis according to the specific situation and previous data, and then assign value for each λ_i, constructing a linear equation according to the Markov chain, as shown in Equation (1).

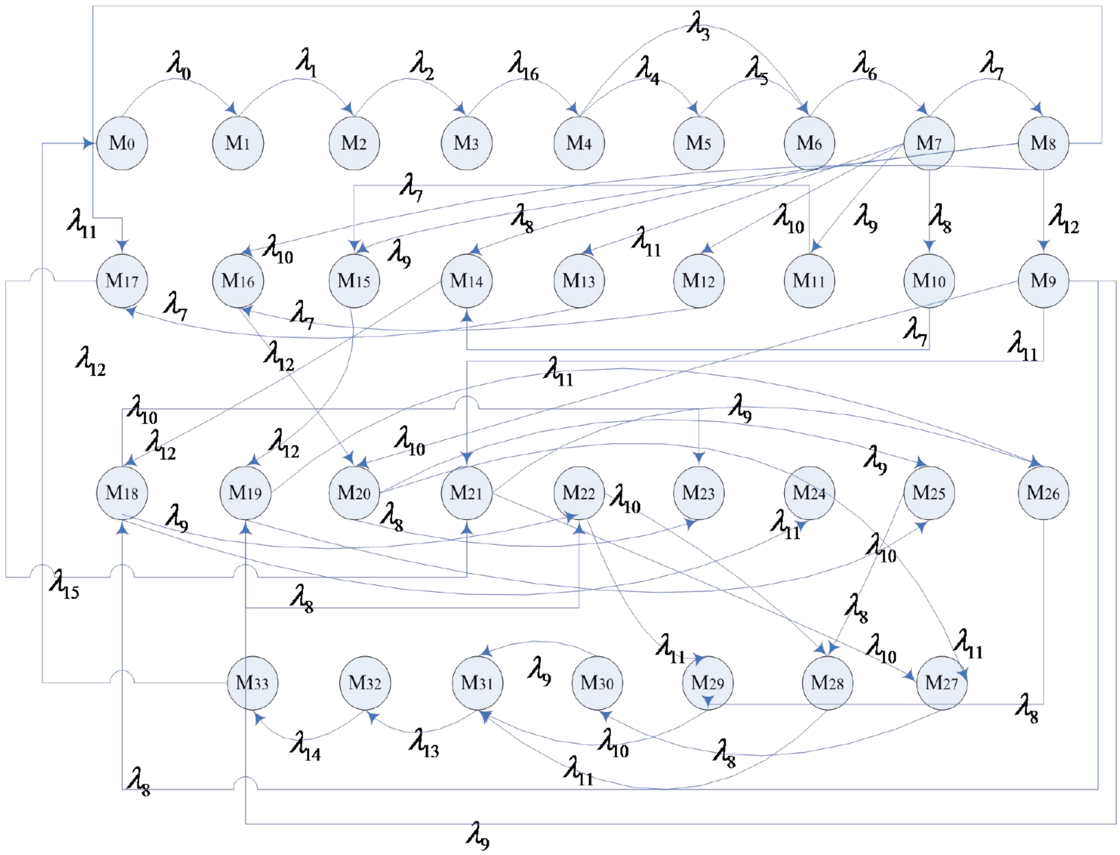

FIGURE 3. The Markov chain

(2) In the whole process, each state is reachable, meaning that each task could be realized in the condition of corresponding Transition, there does not exist any deadlock, and it is active.

(3) In the whole process, from the state M_0 to M_{33}, and M_{33} to M_0, the tokens' number has not changed, indicating that the model is safe.

According to the Markov chain, we establish the linear equations, as Equation (1) shows:

$$\begin{cases} PQ = 0 \\ \sum p_i = 1 \quad (0 \le p_i \le 33) \end{cases} \tag{1}$$

In the equation, for the vector $P(P(M_0), P(M_1), P(M_2), \ldots, P(M_{33}))$, $P(M_i)$ is the probability of the reachable marks which are up to the steady state; Q is the transfer rate matrix of Markov process, when there is a directed arc from mark M_i to mark M_j, the matrix element q_{ij} $(i \neq j)$ is the rate value of the arc, that is λ_i; if there is no arc, q_{ij} $(i \neq j) = 0$, the diagonal elements $q_{ii} = -\sum_{i \neq j} q_{ij}$ (the sum of all the Transitions' rates that can be triggered starting from M_i) [14]. We assume that the implementation rates λ_i are $(6, 6, 1, 2, 4, 1, 2, 1, 1, 1, 1, 1, 1, 5, 5, 1, 6)$, and then we can get a rate matrix. According to Equation (1) and the matrix, we solve the linear equation, and get the probability of the each reachable mark which is up to the steady state (there we take the approximation), and they are $P(M_0) = P(M_1) = P(M_3) = P(M_4) = P(M_{25}) = P(M_{26}) = P(M_{27}) = 0.02$, $P(M_2) = P(M_{33}) = 0.12$, $P(M_5) = 0.08$, $P(M_6) = 0.06$, $P(M_8) = 0.005$, $P(M_9) = 0.001$, $P(M_7) = P(M_{10}) = P(M_{11}) = P(M_{12}) = P(M_{13}) = P(M_{31}) = P(M_{32}) = 0.024$, $P(M_{14}) = P(M_{15}) = P(M_{16}) = P(M_{17}) = 0.029$, $P(M_{18}) = P(M_{19}) = P(M_{20}) = P(M_{21}) = P(M_{22}) = P(M_{23}) = P(M_{24}) = 0.01$, $P(M_{28}) = P(M_{29}) = P(M_{30}) = 0.04$.

According to the calculated probability, we get the performance index of the system: the busy probability of Places, the idle probability of Places and utilization rate of Transitions, so as to analyze the efficiency of the system. Analysis of indicators is as follows.

(1) The busy probability of Places. It refers to the probability of the various departments, emergency center, the command center, the rescue team in the busy state, so we can get the probability of each busy Place by the probability of each reachable state. The maximum probabilities are $P(M_5 = 1) = 0.94$ and $P(M_{22} = 1) = 0.98$.

After analysis, we can know that the superior rescue team to process information and the government at a higher level decision-making information processing part is most likely to have accumulated information and information jam. Due to that the information of higher departments is coming from multiple departments, in the rescue process, the information of each rescue department feeds back to the superiors, and then the superiors do comprehensive analysis and information processing. It is visible that our calculated results are coinciding with actual situation. Therefore, the efficiency of information processing for superior can be the core of the whole system, and be used as the key point of process optimization system.

(2) The idle probability of Places. It can be obtained according to the busy probability of Places, that is 1 minus the busy probability, and through analysis we can get that the Places P_0, P_1, P_3, P_4, P_6, P_{19} are relatively idle. According to their practical sense, we can know that emergency response of relevant departments is in time when confronting natural disasters.

(3) The utilization rates of Transitions. It reflects the length of each activity of the whole process of emergency response; it is the sum of all the stable probability of marks to make every Transition can be implemented [15]. They are $U(t_0) = 0.02$, $U(t_1) = 0.02$, $U(t_2) = 0.12$, $U(t_3) = 0.02$, $U(t_4) = 0.02$, $U(t_5) = 0.08$, $U(t_6) = 0.06$, $U(t_7) = 0.12$, $U(t_8) = 0.12$, $U(t_9) = 0.12$, $U(t_{10}) = 0.12$, $U(t_{11}) = 0.12$, $U(t_{12}) = 0.12$, $U(t_{13}) = 0.024$, $U(t_{14}) = 0.024$, $U(t_{15}) = 0.12$, $U(t_{16}) = 0.02$.

From the above data we can see that the utilization rate of Transitions T_2, T_7, T_8, T_9, T_{10}, T_{12}, T_{15}, T_{11} is higher, and it mainly includes the specific emergency rescue operation procedures and information feedback after the end of emergency rescue. These parts are time-consuming, but also reflect the entire rescue process efficiency of emergency logistics, so we need to improve these parts efficiency. Meanwhile, we find that the implementation of Transition t_8, t_9, t_{10}, t_{11}, t_{12} had a great influence on the whole rescue system; the implementation of them directly affects the subsequent events, and then affects the entire rescue process efficiency.

5. **Conclusions and Suggestions.** This paper uses Petri nets to construct model and analyzes it for the emergency rescue logistics system, through the analysis we found that using Petri nets to construct model is in conformity with the relationship between system process, and it can confirm which parts have a larger impact on the system through quantitative data. The performance analysis methods of Petri nets provide theoretical support for us to explore the key part in the system, provide a basis for the relevant rescue departments for further optimization, and provide decision-making basis for more direction optimization scheme for senior management. Through the above example data analysis, we can put forward the following suggestions for system optimization.

(1) Strengthen the information construction of emergency rescue logistics system. On the one hand, nurturing more information technology talents and experienced decision making experts, vigorously developing information collection, multi-channel information processing, real-time tracking and monitoring high-tech equipments, improve the efficiency of information processing, making efficient, fast and accurate decisions. On the other hand, using the propaganda media (information dissemination tools) effectively, strongly calling for social volunteers to participate in the rescue work, calling on the people from

all walks of life appearing to brainstorm, donate help for the efficient implementation of the rescue work.

(2) Strengthen the construction of emergency management. Firstly, improve the overall efficiency by cultivating more professional emergency rescue personnel, including medical aid and evacuate the affected population. Secondly, the labor division shall be proper, rational allocation of human resources and material resources, reasonable organization and command emergency rescue work and shorten the work time.

(3) Set up specialized emergency logistics center. The efficiency of logistics center directly reflects the running of the emergency rescue system. We have to set up nationwide emergency logistics center with emergency supplies and emergency transport as the main body, and at the same time it should have powerful functions, and be adaptable, responsive and so on.

In the future studies, we can make equivalent reduction for the concurrent structure, circulation structure, selection structure of the Petri nets, extrude the main parts, and then combine with the weight calculation method of AHP (Analysis Hierarchy Process), to find out the key part which influences the system flow rate most.

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