Hindawi
International Journal of Aerospace Engineering
Volume 2018, Article ID 2858375, 8 pages
https://doi.org/10.1155/2018/2858375

Research Article

Airport Emergency Rescue Model Establishment and Performance Analysis Using Colored Petri Nets and CPN Tools

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Received 13 April 2018; Accepted 19 July 2018; Published 16 September 2018

Academic Editor: Dan Zhao

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The airport emergency rescue is a typical discrete event dynamic system. In this paper, we can use colored Petri net discrete event modeling technology to establish the airport emergency rescue (AER) model in the CPN tool software according to the rescue process and the rescue activities' relationship. We draw the basic flow chart of AER and, on this basis, propose the basic algorithm of establishing an AER colored Petri net. Firstly, the Weifang Nanyuan Airport emergency rescue (WNAER) drill data is analyzed, and the time function of each activity is obtained. Then, we establish the WNAER colored Petri net model, and the simulation results are analyzed in depth. The results show that the total time is far less than the time required in the AER plan, indicating that the model is feasible for the practical work; by calculation of time of different routes, we find a key route named "Route 2," and it is proposed to increase the number of fire engines. By changing the value of the "num" parameter, the airport adds a fire engine, and an average of 18 s shortened. The rescue time reliability can be obtained at different times; for example, the time reliability in the 963 s is 91%, indicating that the probability of completing the rescue within this time period is very high, and the time reliability in the 958 s is 1.85%, indicating that the probability of completing the rescue within this time period is very low. The research results can not only allow the airport managers to master the level of rescue forces but also guide the formulation of plans and the implementation of activities.

1. Introduction

At present, the AER is conducted, mainly based on the emergency rescue manual and the experience of a commander on the spot, which lacks the support of rescue theory and computer technology, easily leading to optimum rescue time loss and serious personal and property losses. The AER is a very complicated process, including not only firefighting but also sanitary and guard. So, how to make the emergency rescue work scientifically and orderly and how to ensure the safety and efficiency of the emergency work are questions worth pondering over. It is then very important to have a mechanism and a corresponding tool to help airport administrators understand and articulate the AER. Luckily, some findings can give us some insight.

Qian et al. [1] established an emergency scenario analysis model based on the four elements of disaster body, disaster-bearing body, disaster environment, and disaster resistance body and constructed an emergency scenario evolution model based on key time nodes using the dynamic Bayesian network model. Wang et al. [2] present a design idea of the AER management system for civil aviation airports based on the Semantic Web. In order to solve the problem of a quick decision-making program of rescue, Zhou et al. [3] use the idea of semantic flow management and the method of semantic annotation to give the AER modeling process and realize the semantic discourse of the business process. Wang et al. [4] present an autogenerated method of the AER program for airports based on contingency plans and AER business process management notation ontology. Aiming at the characteristics of nonroutine and uncertainty of civil aviation airport emergency, Liang et al. [5] propose an airport emergency rescue decision-making model based on case-based reasoning (CBR) and fuzzy reasoning. The feasibility of the method is proved by simulation checking. The security management model of airport operation is given after Ale et al.'s [6] researches on the Netherlands International airport. Roling and Visser [7] presented a concept for a taxi movement planning tool based on MILP models. Application of the tool results in a revision of the taxi plans for each aircraft to match the constraints while minimizing the costs. Zhao et al. [8] established the airport emergency hierarchical Petri model which settled the definition of issues, ignored the uncertainty of information, and lacked the analysis of the model. Gaohai and Tang [9] proposed the ARWF net based on place P rules and coherent synthesis rules. In the method, the model capsulated the uncertainties and chose the appropriate rescue activity in accordance with the rescue situation and the coherent synthesis rules. However, the model data is based on the expert's experience.

The current research results can be classified into three categories: one is the qualitative analysis method, which provides an in-depth analysis of the rescue work after the aircraft crash, pointing out the problems and the coordinated solutions that may arise during the rescue process. However, the rescue work process itself is not analyzed in-depth, the bottleneck of the rescue work is not identified, and targeted improvements are not made to improve rescue efficiency. The second category is a combination of quantitative and qualitative methods. These models include the Bayesian network model for emergency scenario evolution, the airport emergency rescue business process semantic model, and the airport emergency rescue decision-making model on case-based reasoning. The third category is quantitative analysis methods, which are based on the Petri net model.

We made full comparative argument for the advantages and disadvantages of the latter two categories of analysis methods. Firstly, the Bayesian network provides a method of quantitative and qualitative, realizes the scenario deduction of the emergency rescue process, and can find the deficiencies in the emergency rescue process, so as to amend and improve the emergency plan and to carry out relevant studies and trainings in the daily training and emergency rehearsal. This is a postevent management method, and the result has a strong subjectivity, depending on the conditional probability of each node variable by the expert's knowledge and experience. Secondly, the CBR rescue decision-making model can search for similar cases according to the matching rules and then adjust the rescue measures to generate rescue plans. The advantage of this model is the use of past rescue experiences in actual accidents or exercises. The disadvantage is that due to the uncertain nature of airport accidents, the case library needs a large number of examples and solutions to achieve a certain practical application value. This method relies on previous cases, but there is no in-depth analysis of the case and drill data, ignoring the impact of the actual rescue process. Thirdly, the semantic model realizes the semantics of the civil aviation emergency rescue business process, so that the civil aviation emergency rescue business process can be understood and processed by the computer. The essence of the model is to interpret the airport emergency rescue business process into a computer-understandable content, so as to conveniently organize the rescue activities of various units. By means of computer reasoning and semantic management techniques, the impact of human error can be reduced, but no quantitative analysis of the rescue process and activities are conducted.

The Petri net takes into account both graphical language and semantics. It can clearly describe state-based events, analyze and evaluate workflows, and simulate complex, concurrent, asynchronous, parallel, uncertain, and random-feature systems. Therefore, the AER Petri net model has the advantages of other models. Moreover, it has intuitive graphical representation, formal semantics, display of state and event, and rich mathematical analysis techniques. The existing AER Petri net model accurately expresses the logical relationship between rescue activities, introduces time variables, and obtains the total time of rescue activities, but does not consider the uncertainty in the rescue process. Moreover, the time for each rescue activity is given by experts based on experience, and there is a lack of scientific and reasonable time statistics methods. There is no quantitative expression for the rescue time reliability, and there are no specific and targeted improvements to critical lines and critical work.

To address these issues, we are motivated in exploring the use of colored Petri nets, introducing the "time" parameters and "num" parameters (number of fire engines), so that it can not only carry out the time analysis of rescue activities but also conduct quantitative analysis of key work. For the processing of time parameters, data is derived from the data statistics results of AER drill, avoiding the subjectivity of expert value. Based on the time distribution of the various rescue activities, the total time reliability of the rescue is quantitatively expressed in the form of probability, providing auxiliary decision-making for making a comprehensive trade-off between rescue costs and rescue efficiency. By changing the num parameters, the rescue time under different extinguishing efficiencies can be obtained, and the quantitative analysis of the key work can be achieved. With the help of software CPN Tools, combined with the real situation, with the support of WNAER drill statistics, we will build a WNAER colored Petri net model, and the performance analysis will be discussed. Based on the above results, we will make pertinent opinions on the formulation of plans and the implementation of activities.

2. Modeling AER in Terms of CPN Tools

2.1. Basic Concepts of the Petri Net. Petri nets, namely, place transition, are classical models depicting discrete event dynamic system characteristics of concurrency, uncertainty, and workflow [10]. The classical Petri net is a directed bipartite graph with two node types called places and transitions which are connected via arcs. Places are represented by circles, and transitions are represented by rectangles. Places of Petri nets usually represent states or resources in the system while transitions model the activities of the system.

The structure of the Petri network is a directed graph that is described by three elements:

$$N = (P, T, F), \tag{1}$$

where $p = \{p_1, p_2, \dots, p_n\}$ is a finite set of places, represented by a circle, $n = |P| > 0$ is the number of places,

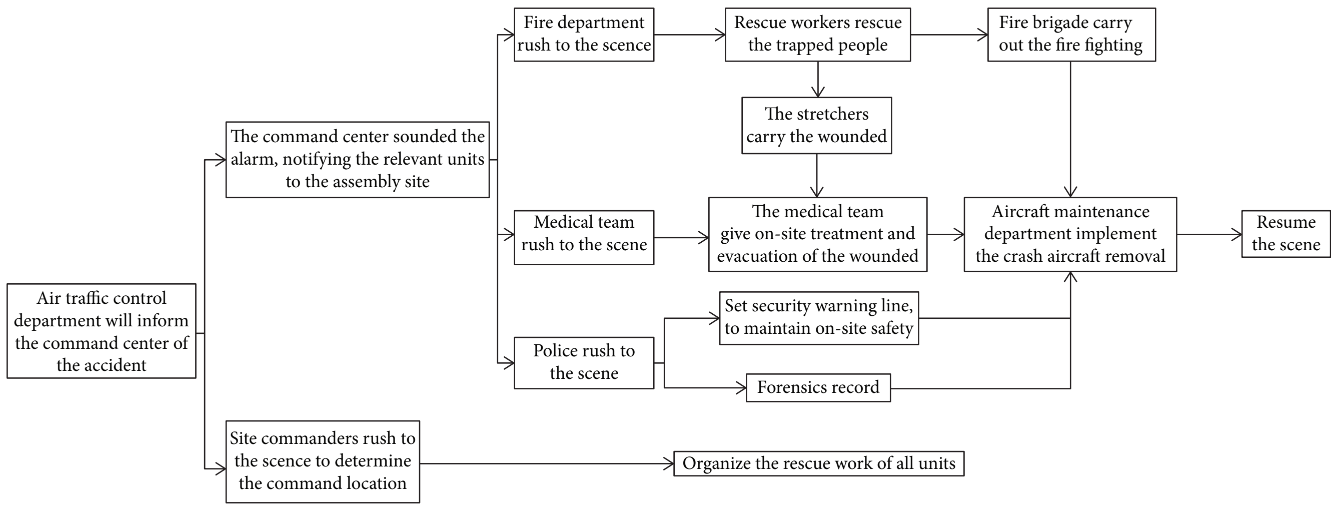

Figure 1: AER flowchart.

$T = \{t_1, t_2, \ldots, t_m\}$ is a finite set of transitions, represented by a rectangle, and $m = |T| > 0$ is the number of transitions; F is called flow relation, represented by on-way arrows, and is a union of binary relation F_1 and F_2, namely, $F = F_1 \cup F_2$, among which F_1 is the binary relation from P to T, $F_1 \subseteq P \times T$, and F_2 is the binary relation from T to P,$F_2 = T \cup P$.

As a Petri network modeling a complete DEDS system [11], another element that reflects the system state is called the marking; the bigram is defined as follows.

$$PN = (N, M), \tag{2}$$

where N represents the network structure defined above, $M : P \longrightarrow N$ is the marking function of the Petri network where $M(p)$ represents the initial token numbers, and N is the natural number, and the tokens are expressed by black dots.

The colored Petri network is different from the general Petri network with different color tokens, to realize the folding and simplification of the network system. Considering the calculation convenience, the colored Petri network is defined by representation of matrices and vectors:

$$CPN = (PN, C, W, V, M) = (P, T, \mathrm{Pre}, \mathrm{Post}, C, V, m), \tag{3}$$

where PN represents a basic Petri network, C is a finite set of colors, $C = \{c_1, c_2, \ldots, c_k\}$, $W : P \times T \cup T \times P \longrightarrow L(C)$, $V : T \longrightarrow L(C)$, $M : P \longrightarrow L(C)$, $L(C)$ is an integer coefficient linear function defined in the color set C, $L(C) = a_1 c_1 + a_2 c_2 + \cdots + a_k c_k$, Pre is an $n \times m$ forward correlation matrix, and Post is an $n \times m$ back correlation matrix. For $t \in T$, if $\forall p \in {}^{\bullet}t$, $M(p) \geq W(p, t)$, then the marking vector is m, and there are enough tokens available in the input places. When a transition t fires, it removes tokens from its input places and adds some at all of its output places [12]. The new reachable marking m' is computed as follows:

$$m'(p) = \begin{cases} m(p) - w(p, t), p\hat{\mathrm{I}}^{\bullet}t - t^{\bullet}, \\ m(p) + w(t, p), p\hat{\mathrm{I}}t^{\bullet} - {}^{\bullet}t, \\ m(p) - w(p, t) + w(t, p), p\hat{\mathrm{I}}t^{\bullet}\text{Ç}^{\bullet}t, \\ m(p), \text{else} \end{cases} \tag{4}$$

2.2. AER Contents and Procedures. According to the civil transport airport emergency rescue regulations (CCAR-139-II-R1), when implementing an emergency rescue, the units and individuals involved in the rescue shall obey the unified command of the airport emergency rescue command center. The participating departments are air traffic management departments, fire stations, the public security department, and the resident medical department. According to the responsibilities of various departments, in accordance with the emergency rescue provisions on the aircraft fire emergency, the emergency rescue procedure is divided into five parts: alarming, rush to the assembly site, firefighting and rescue, on-site evidence, and after treatment. Among the five processes, some processes such as firefighting and rescue are full of uncertainty, which is organized by the scene commander, with the various departments involved in the rescue.

When modeling the AER, the AER plan is an important basis, and the time-series relationship among the activities should be mainly considered. The AER flow chart is shown in Figure 1.

2.3. AER Colored Petri Net Modeling Using CPN Tools. AER refers to a series to rescue activities on aircraft and cargo in the event of a plane crash in order to minimize casualties and property losses. Taking into account the complex situation of emergency rescue at airports, this paper establishes an AER colored Petri net model of general aircraft crash,

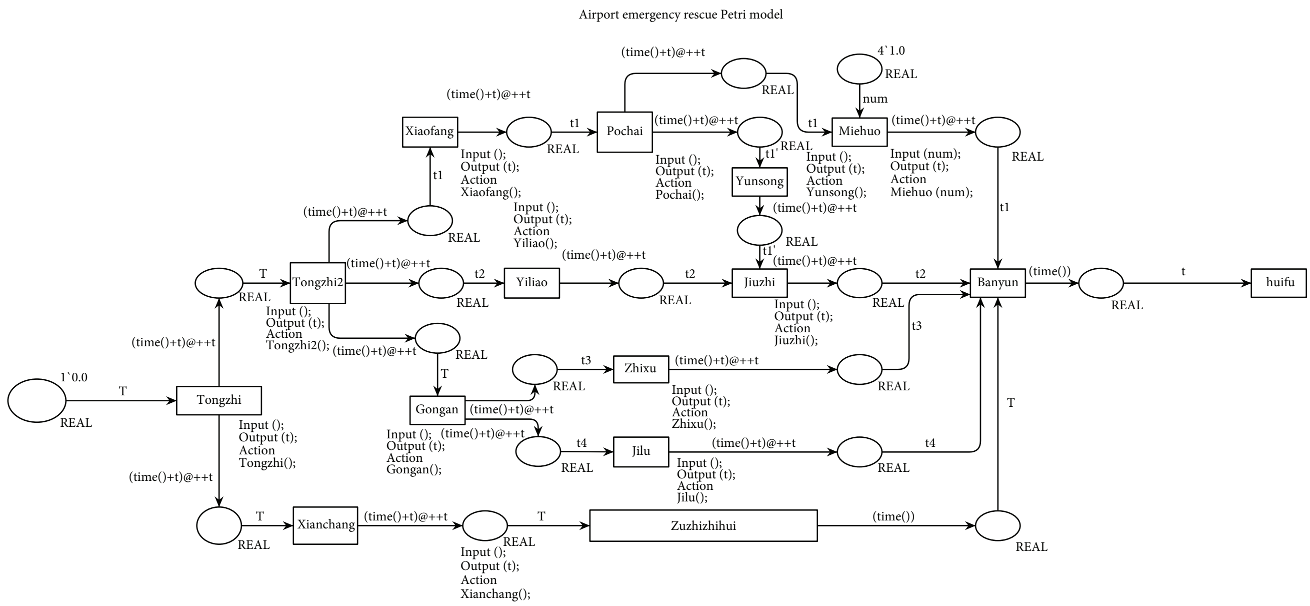

FIGURE 2: AER colored Petri net using CPN Tools.

the results of which can provide scientific basis for policy-makers to improve their plans. As can be seen from the definition airport emergency rescue, the AER can be regarded as a dynamic system that is composed of a plurality of discrete events that interact with each other following certain operating rules and leading to the system's state evolution. Colored Petri nets can clarify the state transition of discrete events and can directly describe the structural information of the system. Therefore, the AER colored Petri net model can be established and simulated.

The airport emergency rescue colored Petri net model is defined as follows:

$$TTPN = (P, T, \text{Pre}, \text{Post}, m_0, D), \tag{5}$$

where P, T, Pre, Post, and m_0 are the same as their definition in basic Petri nets, and D is the time delay defined in the transition.

According to the AER process, in order to obtain the critical path and analyze the rescue time reliability, the algorithm steps to construct the model are as follows [13].

Step 1. Each independent rescue activity is represented by a transition t.

Step 2. If t_i is immediate activity for t_j, then add a place p between t_i and t_j, connecting two arcs from t_j to p and from p to t_j.

Step 3. If there is no forward activity, then add a library before t_b, connect the arc from p_b to t_b, and put a token in p_b.

Step 4. If t_e has no follow-up activities, then add a place p_e behind t_e, connecting the arc between t_e and p_e.

Step 5. Give time for all the transitions.

3. AER Colored Petri Net Case Modeling and Performance Analysis

3.1. Case Modeling. In the last section, we give an AER modeling method. In this section, we will put CPN Tools into the real situation of Weifang Nanyuan Airport, and we establish an AER colored Petri net model for aircraft fire emergency.

First, we can define the library and transition of the model. The description of each library and transition in Figure 2 is as follows:

$$T = (t_1, t_2, \ldots, t_{14}, t_{15}), \tag{6}$$

t_1 = ("tongzhi"; the air traffic control department will inform the command center of the accident)

t_2 = ("tongzhi2"; the command center sounded the alarm, notifying the relevant units to the assembly site.)

……

t_{14} = ("banyun"; the aircraft maintenance department implements the crash removal.)

t_{15} = ("huifu"; resume the scene.)

$$P = (p_1, p_2, \ldots, p_{20}, p_{21}), \tag{7}$$

p_1: (tongzhi. state==running)

p_2: (tongzhi2. state==running)

……

P_{20}: (banyun. state==running)

p_{21}: (banyun. state==finished)

F is a set of directed arcs from P to T or T to P.

We conduct a statistical analysis of the time distribution of each transition T. A total of 15 transitions require statistical analysis; that is, the time of each rescue activity is counted. According to the recorded data of Weifang Nanyuan Airport's 100 emergency drills in recent years, a time-

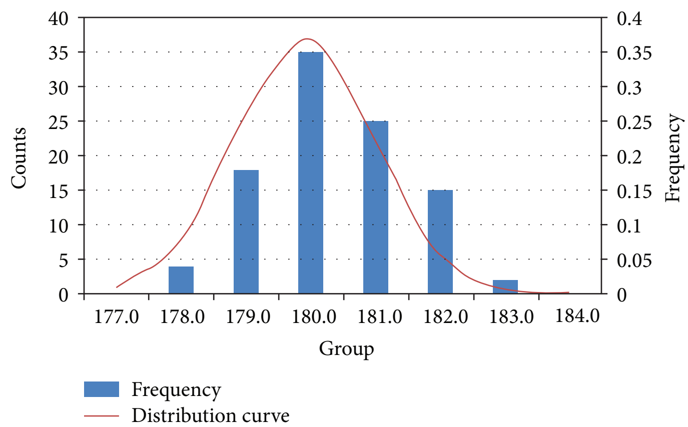

Figure 3: The time distribution of "airport fire arrival time."

Table 1: "Airport fire arrival time" single sample Kolmogorov-Smirnov test.

		The reaching time/s
	N	30
Normal parameters	Mean	180.100
	Standard deviation	1.028
Most extreme difference	Absolute value	0.195
	Positive	0.172
	Negative	−0.195
	Kolmogorov-Smirnov Z	1.066
	Asymptotic significance (two-tailed)	0.206

(1) Test distribution is a normal distribution, and (2) it is calculated according to statistical data.

frequency distribution histogram is made of each rescue activity using Excel 2010, taking the time "airport fire arrival time" as an example, namely, the time of transition "xiaofang," as shown in Figure 3.

As can be seen from Figure 3, in order to verify whether the time "airport fire arrival time" distribution satisfies the normal distribution, we use SPSS software to perform a K-S test, and the results are shown in Table 1.

The K-S test results show that the time distribution meets the normal distribution $T{\sim}N(180{,}1)$.

In the same way, we conduct the K-S test on 15 transitions such as "tongzhi," "tongzhi2," and "gongan." The results of the K-S test show that the time distributions of all 15 transitions satisfy normal distributions $T{\sim}N(\mu, \sigma^2)$, so we can obtain the time function of each transition. These time functions are introduced into the WNAER colored Petri net model as important parameters. We also put the number of fire engines marked as "num" as an influential parameter of the transition "miehuo"; here, we have an approximation of the relationship between fire extinguishing time and the number of fire engines to satisfy the inverse proportional relationship. Therefore, we can build the WNAER colored Petri net model in the CPN Tools, according to the modeling algorithm in the previous section, as shown in Figure 2.

3.2. Performance Analysis

3.2.1. Key Route Analysis. As shown in Figure 2, a total of four routes all need time statistics, marked as "t1," "t2," "t3," and "t4." In the case, there are a total of four routes which are named "route 1," "route 2," "route 3," and "route 4." In order to make the results statistically significant, the WNAER colored Petri net model is simulated and a total of 1000 operations are performed. The results are drawn in Excel, as shown in Figure 4.

As can be seen from Figure 5, in order to verify whether the rescue time distribution for each route satisfies the normal distribution, we use SPSS software to perform the K-S test, and the results are shown in Table 2.

The K-S test results show that the time of the four routes obeys the normal distribution. The time function of the four routes are, respectively, $T{\sim}N(599.9{,}1.9)$, $T{\sim}N(809.9{,}2.4)$, $T{\sim}N(960{,}2.2)$, and $T{\sim}N(600{,}2)$.

The AER total time depends on the time of the key route, which is the most time-consuming route on all routes. Take the average of the 1000 simulations of these four routes, as shown in Table 3.

As can be seen from Table 3, the average time of Route 2 is the largest, so this route is the key route, which has the greatest impact on the AER. Route 2 includes a firefighting operation. The speed of extinguishing a fire is mainly determined by the fire situation and firefighting power. For the key route, we should try our best minimize the duration of the work. In this case, the firefighting force is dominated by four fire engines. From the viewpoint of shortening the operation, the number of the fire engines can be increased. If we add a fire engine, according to the WNAER colored Petri net model, the 1000$'$ simulation results show that Route 2$'$'s time is 942 s because the time of the firefighting operation is shortened by 10 s, and valuable time is saved for saving lives and property.

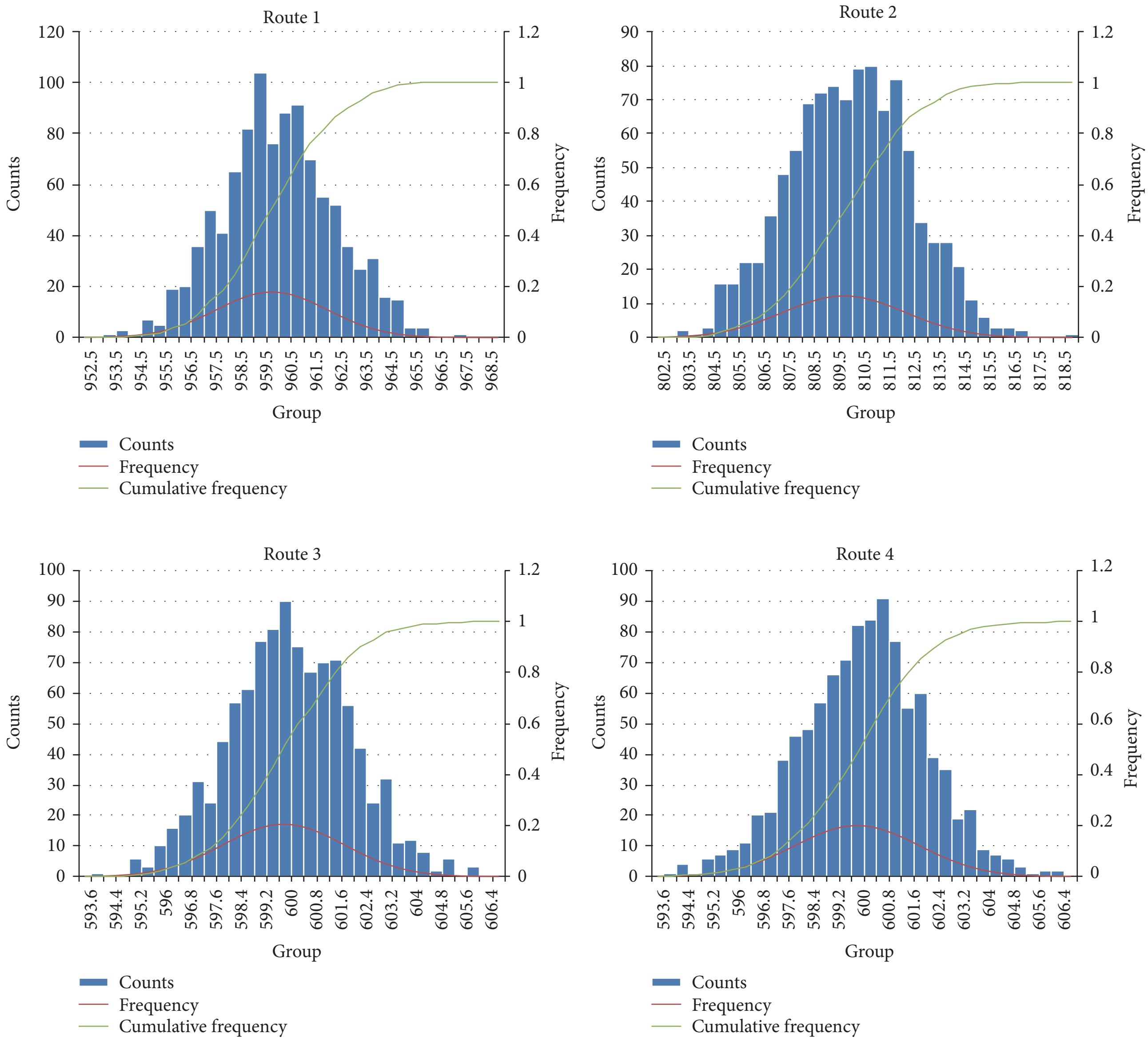

Figure 4: Four routes' time distribution of the WNAER colored Petri net model.

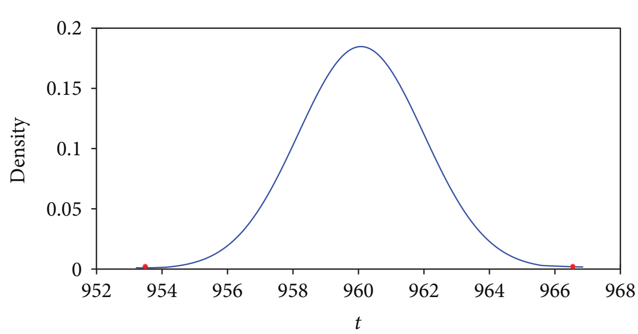

Figure 5: The emergency rescue total time normal distribution.

3.2.2. Time Reliability Analysis of Airport Emergency Rescue. The normal distribution function of the AER total time is $T \sim N(960{,}2.2)$. The normal distribution is drawn using Matlab 10 software, as shown in Figure 5.

As shown in Figure 5, the interval between the two red dots is (953.4, 966.6); according to the "3σ" principle of normal distribution, $(\mu - 3\sigma, \mu + 3\sigma)$ is regarded as the interval of the actual value of the total time, and the probability outside the interval is less than 0.3%, which does not occur in the actual problem. In this case, the fastest rescue can be completed in 953 seconds, and the slowest can be completed in 967 seconds.

For the AER, in order to save lives and properties for the first time, the AER plans to provide the total time of the emergency rescue. As shown in Figure 5, we can find the probability density under different times. Integrating the time can get the probability of finishing the rescue under a certain time, that is, the reliability of finishing the rescue within a certain time.

If the AER plan provides 958 seconds or 963 seconds to complete the rescue, for example, we can get the reliability of rescue time, as shown in Figure 6.

Table 2: Four routes' time distribution single sample Kolmogorov-Smirnov test.

		Route 1	Route 2	Route 3	Route 4
	N	1000	1000	1000	1000
Normal parameters	Mean	599.940	809.915	959.968	599.976
	Standard deviation	1.941	2.440	2.231	1.991
Most extreme difference	Absolute value	0.18	0.019	0.021	0.027
	Positive	0.018	0.017	0.021	0.016
	Negative	−0.014	−0.019	−0.015	−0.027
	Kolmogorov-Smirnov Z	0.559	0.612	0.670	0.845
	Asymptotic significance (two-tailed)	0.914	0.848	0.761	0.472

(1) The test distribution is a normal distribution and is (2) calculated according to statistical data.

Table 3: Simulation results average.

Route	Route 1	Route 2	Route 3	Route 4
Time/s	810	960	600	600

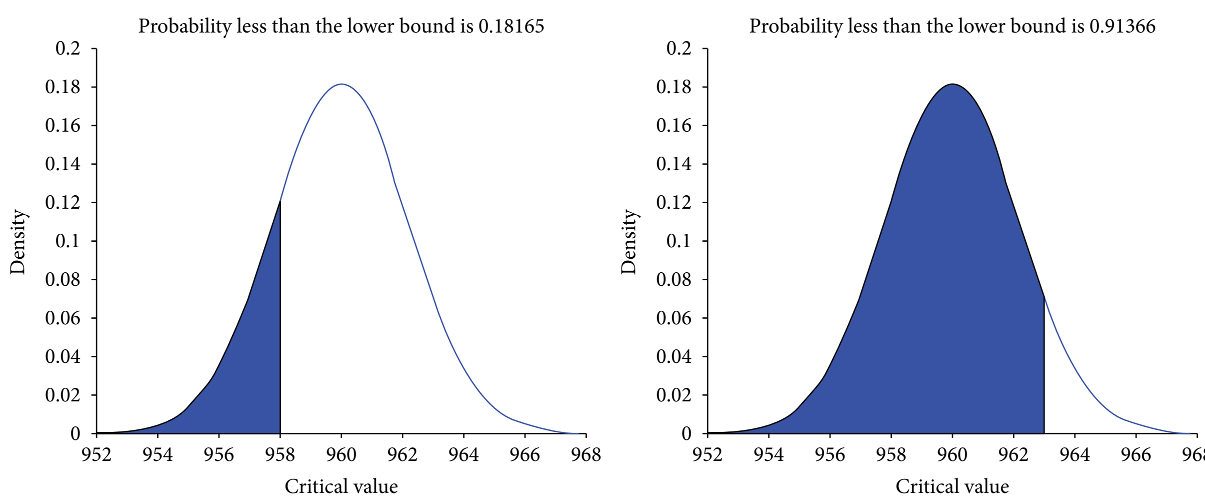

Figure 6: Emergency rescue time probability.

As can be seen from Figure 6, the probability of the AER being completed within 958 s is 1.85%, and the probability of completion in 963 s is 91%. Through the calculation of the time reliability under different times, the airport administrators can determine the rescue time and arrange the rescue work reasonably.

In this case, the total rescue time interval calculated by the WNAER colored Petri net model is $(953.4, 966.6)$, less than 20 minutes stipulated in the airport plan, indicating that the model can better simulate the actual situation and also shows that the airport's rescue power can be competent for the current AER work.

3.2.3. Suggestions on the AER Plan. Based on the simulation results of the model, the airport can increase the number of fire engines, raise the efficiency of firefighting, and shorten the key work duration time. In revising the plan, the importance of reliability is taken into full consideration because reasonable provisions for rescue time can increase rescue reliability and reduce casualties and property losses. Whether to minimize rescue time, especially to reduce the duration of key work, is key to determining the success or failure of emergency rescue. But we cannot increase investment indefinitely in order to improve rescue efficiency. This requires us to make a trade-off between the current situation of the airport and the rescue reliability. In this case, it is feasible to add a fire engine because the airport has the ability of purchasing it. For the emergency plan, the 20-minute rescue time can be modified because the model simulation results show that the maximum rescue time is 16.11 minutes, so the rescue time can be set to 17 minutes, which is conducive to guiding the formulation of plans and the implementation of activities.

4. Conclusions

In view of the status of the airport emergency rescue work implemented empirically, we establish an AER model based on colored Petri net discrete event modeling technology, which can help to solve the problem of uncertainty in the rescue process and provide a simple and feasible method for modeling the airport rescue process. We analyze the emergency rescue drill recorded data of Weifang Nanyuan Airport and obtain the time functions of each rescue activity. According to the process of emergency rescue, the AER model is established in the CPN Tools. The simulation results analysis show that Route 2 is the key route, and we suggest that the rescue time can be shortened by increasing the number of fire engines. The time reliability can be used in the formulation of the rescue plan, in order to ensure a high degree of time reliability while shortening the rescue time. The case study shows that the model is suitable for AER and can provide scientific guidance for the AER plan, compared with the traditional AER plan by experience, so that the model can well simulate the actual situation and help the decision-makers to formulate the plan. For the next work, we will simplify the modeling method, making it easy and quick to model and analyze in CPN Tools.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Qingkun Yu designed the methods and models and wrote the manuscript, Liangcai Cai analyzed the results, and Xiao Tan conducted data collection and statistics.

Funding

All research funding comes from postgraduate training funding.

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