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Research Article

Actantial Narrative Schema in Emergency Response Process Modeling for Aircraft Fires

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Analyzing the emergency response process and time characteristics after aircraft fires is extremely important for airport safety. Due to nonprocess-related elements, the Petri net model of the emergency process is generally complex and difficult to revise and expand. In this study, the actantial model was used to analyze the semantic structure of emergency actions in the Petri net emergency process model, and the actantial-timed Petri net (A-TPN) hybrid model was proposed for problem solving. The emergency response process of aircraft fires was analyzed as a case study to explain the application steps of the A-TPN hybrid model. First, the types of elements should be divided into process-related elements and nonprocess-related elements. Process-related elements include status elements and narrative elements, which are equivalent to the places and transitions in the Petri net model. Second, the workflow constructed by the status and narrative elements is converted into a Petri net. An actantial model is used to analyze the semantic structure of emergency response action narratives. Third, according to the analysis of the actants of the helper and the opponent, emergency action time characteristics are considered to construct the A-TPN hybrid model and analyze the time performance of the emergency response process. In this way, an emergency response plan can be analyzed and promoted for smart development.

1. Introduction

Aircraft fires are one of the most common types of fatal accidents in civil aviation, and they can be caused by system failures or crash accidents. To reduce the hazards of aircraft fires and their impacts on airport operations, an effective emergency response after landing is essential. An emergency plan is preestablished to ensure the rapid, orderly, and effective implementation of emergency response actions. In this practice, it is highly important to form a scalable emergency rescue process model, which is also the core and premise of emergency rescue system platform construction.

The emergency response process for aircraft fires can be viewed as a workflow, which is important to support emergency decision makers to effectively respond to emergencies [1, 2]. The Petri net is one of the most well-known formal modeling techniques for workflow analysis [3]. It is a powerful discrete event modeling and analysis tool and widely used in discrete systems for simulation and performance analysis.

In emergency response modeling, Petri nets are mostly used to arrange the structure of emergency organization, personnel, technology, equipment, materials, actions, commands, and coordination for emergency plan evaluation [4]. Evaluations of the emergency response process using Petri nets have been researched in many industries and fields, such as the chemical industry [5, 6], subway fire emergencies [7], coal mine rescue events [8], the nuclear industry [9], airport emergency responses [10], and urban emergency systems [11, 12]. Comprehensively applying the method enhances the applicability of Petri nets for emergency response modeling, e.g., the knowledge element model and hierarchical theory [13], the reversed reasoning approach [14], and Markov chains [15].

However, applying Petri nets in emergency process modeling presents certain difficulties. First, in a real emergency process, emergency resources usually affect emergency efficiency rather than the emergency response process, which is different from most current emergency models. Second, a complex Petri net model that includes nonprocess-related elements is not conducive to promoting such models. Emergency resource and disposal actions vary from different response stages by the development of the accident scenario.

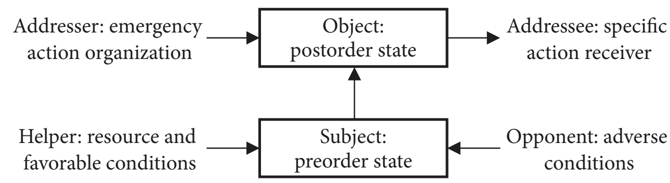


Figure 1: Relationships between actants and explanations in an emergency action.

The more detail a model describes, the harder the model is to generalize. Few studies have used Petri nets to analyze existing emergency planning processes and response time performances [16–18], which is a hot issue among current emergency managers.

The reasons for the above problems are as follows. The mathematical analysis tools of Petri nets emphasize the accuracy of formal description to ensure the semantic clarity of each process element; however, in emergency response problems, emergency actions are affected by complex conditions. It is more difficult for process language to express such an influence than it is for process language to express functions. Therefore, prior to establishing the Petri net model, the modeling objectives must be analyzed and nonprocess-related elements must be converted to functions of certain key elements to simplify the model.

Petri nets use symbols to represent process elements. The study of the relationship between symbols and the objects to which they refer is the category of semantic analysis in semiotics. This paper analyzes the semantic connotation of elements to simplify the Petri net model for the emergency response process and uses an aircraft fire emergency response as an example to analyze the steps of establishing the actantial-timed Petri net (A-TPN) hybrid model. The remainder of this paper is organized as follows: Section 2 introduces the formal specification for actantial narrative schema. Section 3 proposes an aircraft fire as a case study and builds the A-TPN model in steps. Section 4 discusses the modeling and analysis process and future application direction for emergency response. Section 5 presents the concluding remarks.

2. Actantial Narrative Schema of Emergency Response Actions

Narratives lie at the foundations of our cognitive processes and provide an explanatory framework for the social sciences. A narrative is a telling of some true or fictitious event or connected sequence of events, recounted by a narrator to a narratee. Emergency response actions can be viewed as narratives, and each emergency action is a narrative telling emergency response or disposal events recounted by emergency plans.

The actantial model is a semantic method of describing narrative that was developed in 1966 by the prominent semiotician Algirdas Julien Greimas [19]. Also called the actantial narrative schema, this method was originally used in stories to reveal different functions of the actants in a narrative [20]. This method of narrative analysis provides a discourse structure for researchers and has been extended to education semiotics [21], computer science [22, 23], career counseling, and personality analysis [24–26].

The actantial model consists of six functions called actants: the addresser and the addressee; the subject and the object; and the helper and the opponent. The relations between actants and explanations in emergency actions are shown in Figure 1. The actants correspond to elements in an emergency response action. The relation between the subject and the object is called a narrative utterance, which can be an utterance of state [27]. In the emergency response process, the preorder state and the postorder state of a specific emergency response action can be described as the subject and the object, respectively. Emergency action organization imparts a postorder state to a specific action receiver, as the addresser imparts the object to the addressee. Emergency resources and favorable conditions are considered helpers, and adverse conditions are considered opponents.

A Petri net is a grid formed by connected places and transitions. In the Petri net model, places represent the status of the emergency scenario and each transition represents a response action or combination of actions. A response action can be described as a narrative using the actantial model to analyze the factors affecting the time spent.

Through the actantial model analysis of the response action, favorable and adverse conditions can be described in regard to the helper and opponent actants, which are always regarded as places in the Petri net. In this practice, the emergency response process model is simplified without missing key information. Taking time into consideration, the A-TPN model will be built to analyze the emergency response process and time features in emergency response.

3. A-TPN Emergency Response Modeling Case Study

3.1. Case Study. The emergency response process is the core of the emergency plan. Based on the emergency response plan of Tianjin Binhai International Airport for aircraft fires, the application steps and analysis methods of the A-TPN method are investigated as a case study.

The emergency response process is affected by various factors, such as the airport emergency organization system, the emergency information transmission mechanism, and the sufficiency of emergency supplies. Using the Delphi method and extensive discussion, we show the key elements influencing emergency response actions in Table 1. The types of elements should be divided into process-related elements and nonprocess-related elements. Process-related elements

Table 1: Key elements influencing the emergency response process.

No.	Key elements	Impact on the emergency response process
(1)	Flight phase of the aircraft in the event of an accident	In general, an aircraft accident before takeoff is easy to detect and handle. There is a short emergency response time for the aircraft takeoff and landing phases.
(2)	Airport emergency information transmission mechanism	Mechanism affects the efficiency of decision information acquisition.
(3)	Initial state of the aircraft after landing (external fire, smoke, etc.)	External fires must be extinguished first, and whether there is an internal fire in the cargo bay is determined by touching the hatch to prevent the occurrence of a flashover during disposal.
(4)	Class and division of dangerous goods in the cargo bay	There are differences in the personnel protection equipment and emergency resources required for various hazards. The leakage of radioactive materials and infectious substances requires the assistance of professional rescue teams. Sometimes, the remaining engine fuel also affects the rescue strategy.
(5)	Emergency disposal resource prepared by the emergency department	Protective clothing should be worn when removing infectious substances, and detectors should be used when radioactive items are involved.
(6)	Emergency personnel rescue capability	Emergency personnel training and drills can reflect the level of emergency response capability and are an important component of airport emergency response capability.

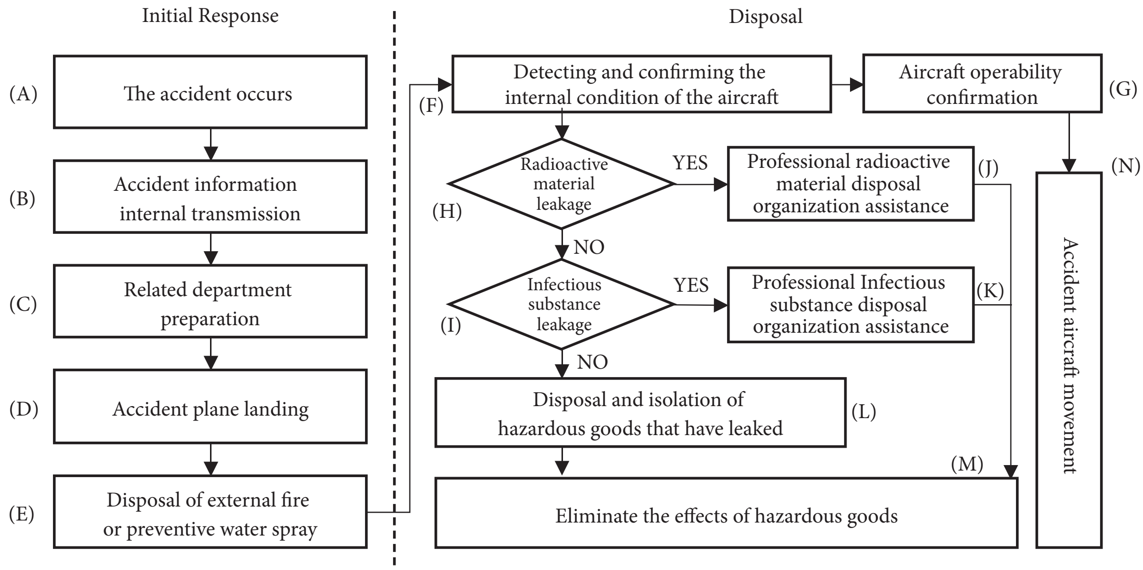


Figure 2: Emergency response process in the emergency response plan.

include status elements and narrative elements, which are equivalent to the places and transitions in the Petri net model. Nonprocess-related elements are helpers or opponents to time performance of actions (narrative elements), although they are not included in the main emergency response process, which is mentioned in the actantial narrative schema. Nonprocess-related elements are usually an important factor in the preparation stage of emergency management, which is the preliminary foundation of affecting the time performance of the emergency response process. Among the key elements, elements (1), (3), and (4) represent the status while elements (2), (5), and (6) represent helpers that affect response actions and are emergency resources or favorable conditions.

Consider the scenario of an aircraft fire emergency response and disposal after landing. The critical missions are to extinguish aircraft fires and to dispose of hazardous goods that have leaked. The emergency response process after an aircraft fire accident prepared by Tianjin Binhai International Airport is shown in Figure 2.

The initial emergency response involves accident information transmission, preparation of the related department, and the landing of the accident plane. Elements (H)-(M) represent the disposal of hazardous goods that have leaked. In the case of radioactive goods or infectious goods that exceed the disposal capacity of the airport fire brigade, a contract professional rescue team shall be notified for disposal. Elements (G) and (N) represent the removal of the aircraft to eliminate the impact on airport operations. Each element in the diagram is a process-related element.

3.2. Actantial Model of Emergency Response Actions. According to the connotation of actantial model functions and the emergency response process, the emergency response process flow must be translated into a flow chart of status and narrative elements, which alternate in the new flow chart.

First, the categories of each process element should be divided. Elements (A), (G), (H), and (I) in Figure 2 are viewed as the status, while elements (B), (C), (D), (E), (F), (J), (K), (L), (M), and (N) are viewed as narratives, which represent emergency response actions. According to the actual meaning and time sequence of the emergency status and actions, the above model in Figure 2 is simplified and reconstructed to obtain the model shown below in Figure 3. S_1 through S_5 in the figure represent the number of statuses, and N_1 through N_5 are the number of narratives. The element numbers represented in the emergency response process are written at the top of the graphics.

Elements (B), (C), and (D) are actions that occur in parallel, and they are combined into N_1 based on the premise of ensuring the rationality of the flow chart. Key element (3) is not contained in Figure 2 and is added to the reconstructed workflow model as S_2. Elements (H) and (I) jointly describe the status of hazardous goods, and their rear narrative actions are consistent; thus, they are combined into S_4. Elements (L), (J), (K), and (M) describe the disposal actions of hazardous goods that have leaked, and they are combined into N_4. Element S_3 is added to alternate the status and narrative elements in the process.

All statuses and narratives involved in this process are listed as follows:

S_1: accident occurs

S_2: initial state of the aircraft after landing

S_3: status after external fire disposal

S_4: status of hazardous goods

S_5: status of the damaged aircraft

N_1: initial response including accident information internal transmission, preparation of the related department, and the landing of the accident plane

N_2: external fire disposal

N_3: detecting and confirming the internal condition of the aircraft

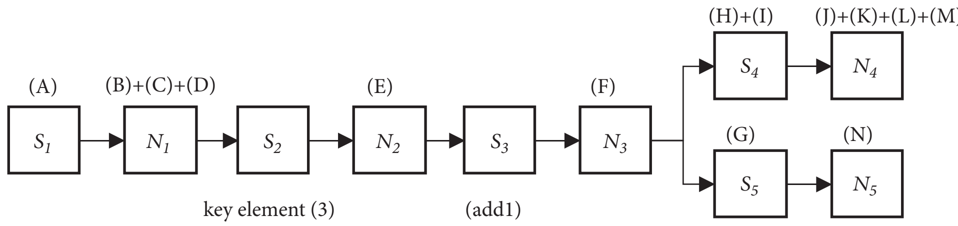


Figure 3: Reconstructed workflow model for the emergency response process.

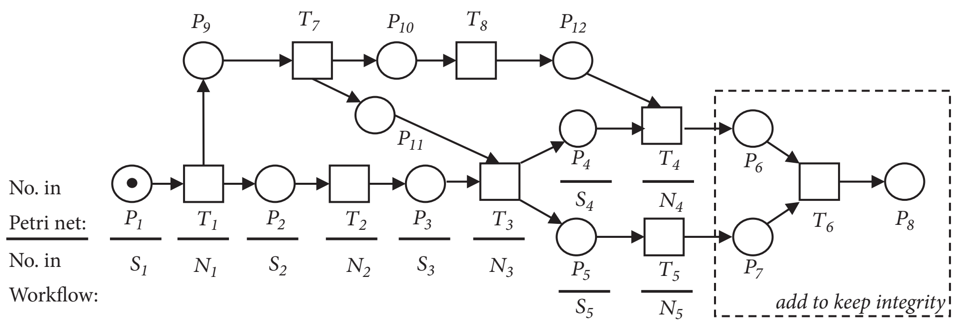


Figure 4: Petri net model of aircraft fire emergency response after landing.

N_4: disposal actions regarding hazardous goods that have leaked

N_5: removal of the accident aircraft

Each narrative can be analyzed by the actantial model and is shown in Table 2.

3.3. Modeling the Emergency Process with Petri Nets. When modeling a system with Petri nets, places (represented by circular graphs) are generally regarded as resources, states, conditions, and media in the system while transitions (represented by rectangular graphs) are regarded as changes in the system, such as events, operations, and transfers. The actantial model was used to reconstruct the workflow model for the emergency response process, which contains key emergency actions based on an airport emergency rescue plan. Rescue time delays caused by transportation business information, emergency decision information, and insufficient resources in emergency rescue are not reflected in this main process. Considering the above factors, the emergency process can be analyzed via Petri nets, which are mature in parallel distributed system analysis.

This example case considers the impact of information on emergency process time performance. Consider an aircraft fire with dangerous goods. Cargo information and expert disposal advice are important, and difficulties during information acquisition may lead to emergency response delays, which will be modeled using Petri net theory as a parallel process of the major emergency action process.

Based on the above description, A-TPN is an application combination of the actantial model and TPN model. The formal definition of the TPN is given as below.

A-TPN is a six-tuple TPN = (P, T, Pre, Post, M_0, SI), where

(1) P and T are finite (nonempty) disjoint sets and their elements are called places and transitions;

(2) Pre: P × T ⟶ N is the forward incidence matrix;

(3) Post: P × T ⟶ N is the backward incidence matrix;

(4) M_0: P ⟶ N is the initial marking;

(5) SI: T ⟶ IR+ is a mapping called the static firing interval, and ∀t ∈ T, SI(t) represents t's static firing interval relative to the time at which t is enabled.

The elements in this Petri net model are given new meanings associated with the emergency rescue. In the Petri net equivalent of the Actantial model, a place represents the status of the accident scene, while a transition represents the action taken during emergency rescue. The Petri net model of an aircraft fire ground emergency is shown in Figure 4. In the part that represents the impact of information on the emergency process, a place represents specific information, and a transition represents the process of information transmission. The activities and statuses are the same as the workflow elements in Figure 2. Transition T_6 and final status P_8 are added to form the integrated Petri net model.

Meanings of P_9-P_{12} and T_7 and T_8 in the process branching model of information flow are as follows:

P_9: flight emergency information;

P_{10}: dangerous goods cargo information (for experts);

P_{11}: dangerous goods cargo information (for fire brigade);

P_{12}: expert's disposal advices;

T_7: dangerous goods cargo information query;

T_8: seek advices from experts on disposition of dangerous goods.

Table 2: Actantial model analysis of the narratives in the emergency response process.

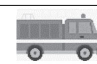
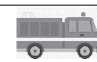
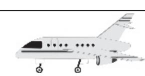
Narrative	Subject	Object	Addresser	Addressee	Helper	Opponent
N_1	S_1	S_2	 AOC	Relevant departments	Communication platform	—
			Relevant departments	Relevant departments	—	—
			 Crew	Aircraft	Navigation facilities	Distance
N_2	S_2	S_3	 Fire brigade	Aircraft	Fire-fighting equipment, protective equipment	Fire severity
N_3	S_3	S_4	 Fire brigade	Aircraft	Detection equipment, protective equipment	High temperature in cargo bay
N_4	S_4	End	 Fire brigade	Dangerous goods	Protective equipment, disposal equipment	The class of hazardous goods, amount of leakage
			Contract professional rescue team	Dangerous goods	—	Class of hazardous goods, amount of leakage
N_5	S_5	End	 Aircraft removal team	Damaged aircraft	Damaged aircraft handling equipment	Large aircraft size, serious damage

Table 3: Time characteristics of the transitions.

Transition No.	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8
Narrative No.	N_1	N_2	N_3	N_4	N_5	—	—	—
time expression	$t_1 = \mathrm{a}_3$	t_2	t_3	$t_4 = b_1$	t_5	—	t_7	t_8
Time/min	Normal (15,5)	Normal (15,10)	Normal (10,5)	Normal (25,10)	Normal (15,10)	Instantaneous	Normal (5,2)	Normal (10,5)

3.4. Transition Time Characteristics Based on the Actantial Model. According to the structure of emergency response action described by the actantial model, transitions T_1 and T_4 can be divided into basic action units. The time of the basic action unit can be obtained through statistics on the daily emergency drill time.

t_1 represents the duration of transition T_1; a_1 and a_2 represent the information transmission and emergency preparedness time of the department, respectively; and a_3 represents the time required for the landing of the aircraft. t_1 is expressed as follows:

$$t_1 = \max\{a_1 + a_2, a_3\} \tag{1}$$

where t_4 represents the duration of transition T_4; b_1 represents the time required for the emergency disposal of hazardous goods by the airport fire brigade; and b_2 represents the time required for the emergency disposal of hazardous goods by a contract professional rescue team. t_4 is expressed as follows:

$$t_4 = \begin{cases} b_1, & \text{airport fire brigade} \\ b_1 + b_2, & \text{contract professional rescue team} \end{cases} \tag{2}$$

The helpers and opponents in the actantial model consider the impact time characteristics of the factors. Based on the premise of sufficient action time data from daily emergency drills, action data can be grouped according to these factors to represent the time characteristics in a specific emergency scenario. The sufficiency of materials can be analyzed at the same time.

3.5. Time Characteristic Analysis of the A-TPN Model. Imagine a specific emergency scenario in which a fire alarm occurs after takeoff on an aircraft carrying hazardous goods without radioactive or infectious materials. According to the prior airport emergency drills, the emergency response action time basically conforms to the trend of normal distribution. The data assigned to emergency response actions considering helpers and opponents are shown in Table 3. Emergency response action time can be optimized by taking measures based on the analysis of nonprocess-related elements. Variables t_1 to t_5, t_7, and t_8 in Table 3 represent the time duration of transitions T_1 to T_5, T_7, and T_8, respectively. The time duration of dangerous goods cargo information and expert disposal advice queries represented by T_7 and T_8 are affected by emergency plan preparation, enterprise cargo transport system function integrity, and other factors.

The Petri net tool was used to establish a model simulation with 1000 iterations, and the prediction of the ending time of the emergency response was calculated as shown in Figure 5. Changes in the variance of the time prediction data are shown in Figure 6 and Table 4. With the progress of the emergency response event and the certainty of event information, the variance of the time estimation decreases and the estimated time distribution presents a centralized trend. According to the simulation results, as the sample data change, the sample mean does not change much and the sample variance decreases. The practical significance lies in guiding the emergency response decision and the restoration work of airport operations.

Moreover, the method can be used to estimate the beginning or ending time of a certain disposal action. The ending time of several key emergency response actions in this model is estimated as shown below in Table 5. The end of a key disposal action means that the next disposal action is about to begin. The next action is going to start within the time range of the mean plus or minus the standard deviation with a high probability, which provides time guidance for emergency decision making.

4. Discussion

According to the case analysis, the time characteristics of transitions can be described by actantial model analysis and can be used to guide emergency time estimation. In airport emergency response, all emergency team members need to pay more attention to the information related to their own emergency actions, identify the sender and receiver of scene information, and better clarify the objectives and scene conditions of emergency actions without obtaining information on and analyzing all accident situations.

The A-TPN hybrid model combines the actantial model and the timed Petri net, and it retains the advantages of the Petri net in emergency response workflow analysis and reduces the difficulty of model construction caused by various influencing factors during the development of emergency scenarios. The emergency flow model built by this method is more intuitive. The application of the A-TPN hybrid model can be used to guide daily emergency training to divide emergency drill actions and analyze time characteristics to guide emergency decisions. Because the Petri net is simplified, it is convenient for Petri net applications in emergency system construction and the process analysis of emergency plans.

The analysis steps of the A-TPN hybrid model are proposed. The applied steps, which are consistent with the case study, are shown in Figure 7.

Step 1. Prepare the workflow of key factors and known process and then form the reconstructed flow chart.

Table 4: Estimated emergency time obtained from simulation.

Estimate of the emergency response time		Stage of the simulation					
		Initial time prediction		Time prediction after T_1		Time prediction after T_2	
mean	90% confidence level	68.230	68.766	48.226	48.734	35.058	35.432
	95% confidence level	68.178	68.818	48.178	48.782	35.022	35.468
	99% confidence level	68.077	68.919	48.082	48.878	34.952	35.538
standard deviation	90% confidence level	5.352	4.972	5.064	4.705	3.733	3.468
	95% confidence level	5.391	4.938	5.101	4.672	3.760	3.445
	99% confidence level	5.468	4.873	5.174	4.611	3.814	3.399

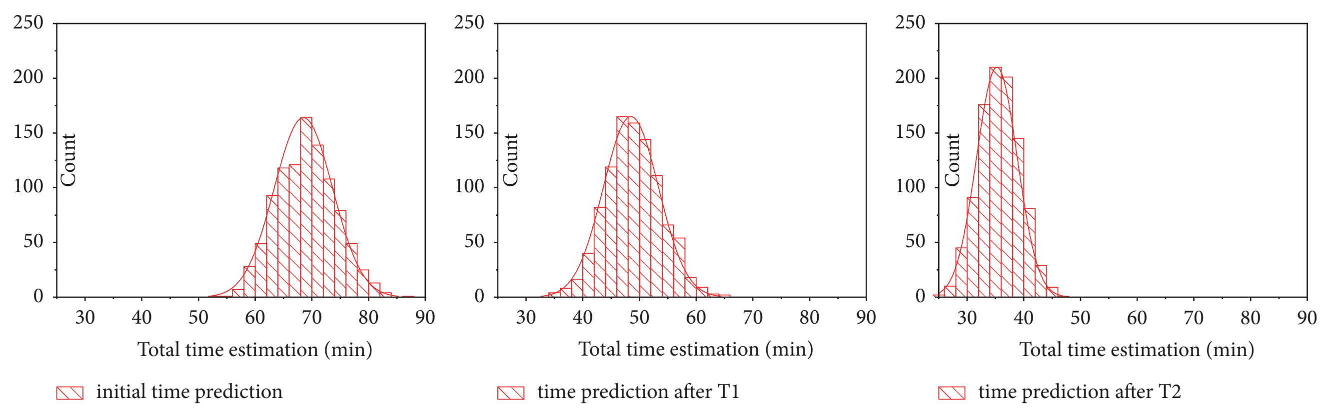


Figure 5: Prediction of the ending time of the emergency response.

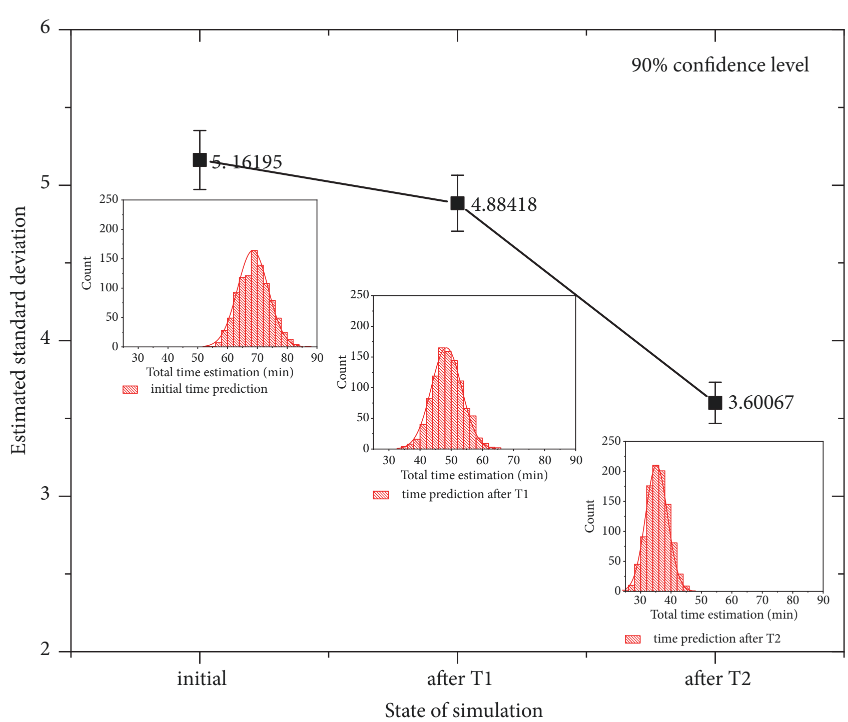


Figure 6: Estimation of the disposal time varying with the emergency stage (90% confidence level).

Table 5: Interval estimation at the 95% confidence level for the ending time of key actions.

Transition No. (action)	95% confidence interval for the time mean	95% confidence interval for the time standard deviation
T_2	14.5-14.7 min	2.2-2.4
T_3	28.9-29.4 min	3.6-3.9
T_6	68.2-68.8 min	4.9-5.4

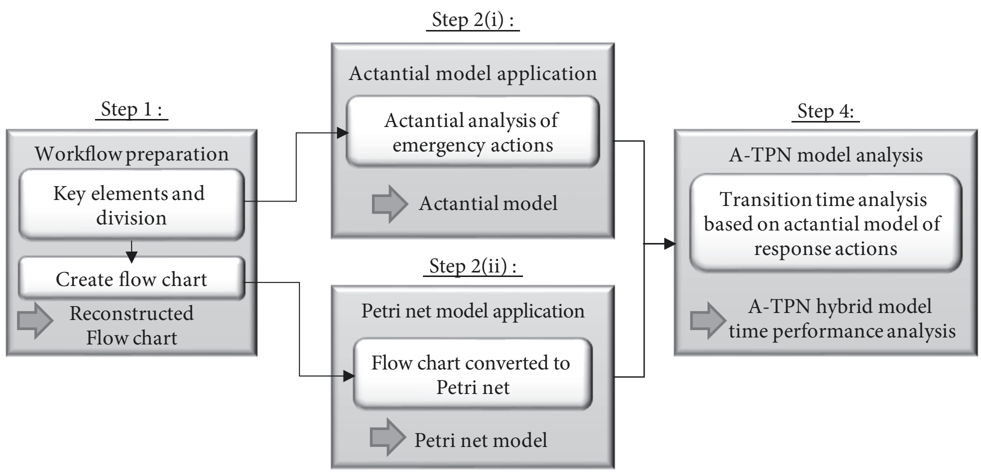


Figure 7: Modeling and analysis process of the A-TPN method for the emergency response process.

Step 2. (i) Use the actantial model to analyze the actants in emergency action narratives.

(ii) Build the Petri net model according to the reconstructed flow chart.

Step 3. Obtain the time characteristics from the actantial model analysis of actions, form the A-TPN hybrid model, and analyze the net characteristics and time performance of the emergency process.

Limited by the current level of knowledge, the analysis of helpers and opponents may not be comprehensive. Thus, the practical experience and accurate meaning of the actants of response actions must be further summarized, especially that of the helper and opponent actants, to obtain scientific data on time characteristics.

In addition, this model can be used to expand the description of emergency resource requirements, where helpers and opponents are the favorable and unfavorable factors affecting resources. If a hierarchical Petri net is incorporated, then the emergency response can be divided into modules to form an emergency plan network to realize the expansion and connection of the emergency plan unit to promote smart development.

5. Conclusion

In summary, although many modeling methods are available to describe emergency processes, there are significant advantages to using this approach. An actantial model was used to analyze the emergency action semantics in the Petri net model of emergency response, and it retains the formalized features of Petri nets and features available for mathematical analysis and provides a feasible analysis approach for emergency preparation and daily training through semantic analysis. The key to using this hybrid method is to distinguish whether the types of elements that affect the emergency process are process related and to conduct semantic structure analysis of process-related emergency action elements using the actantial model. This research can be directly used in the emergency preparedness and emergency process modeling of airport aircraft fire emergencies, and it can be extended to other emergency processes. The influencing factors and semantic connotations in various emergency scenarios are problems that require investigation and experience to overcome. In short, the application of this method will undoubtedly provide an intuitive process analysis and thinking model for the emergency response process and preparation.

Data Availability

The data used to support the findings of this study are included within the article.

Additional Points

Highlights. (1) Elements are divided into process-related elements and nonprocess-related elements to establish a simple Petri net model for the emergency response process. (2) An actantial-timed Petri net (A-TPN) hybrid model was developed to describe the emergency process. The transitions, which represent response actions, in the Petri net were regarded as narratives. The actantial model was used to analyze the semantic structure of emergency response action narratives. (3) A case study of an aircraft fire emergency response in an airport is used to illustrate the application steps to establish the A-TPN hybrid model.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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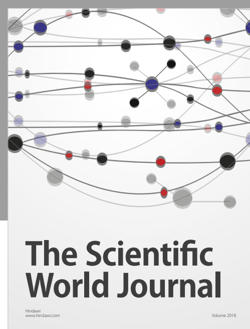
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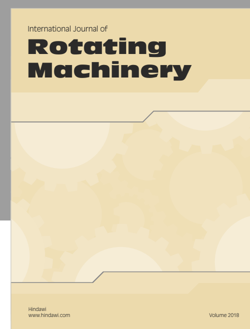
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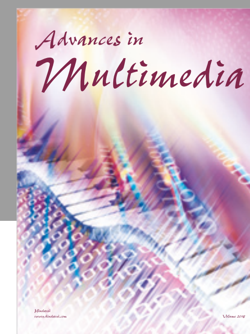
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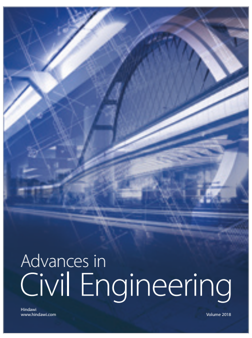
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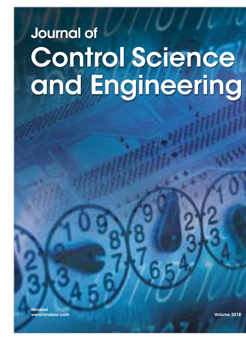
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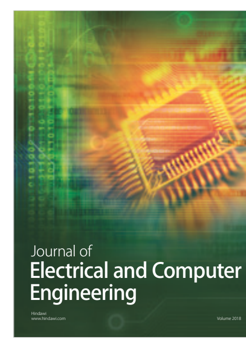
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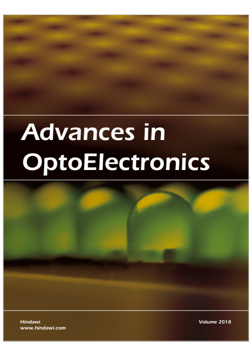
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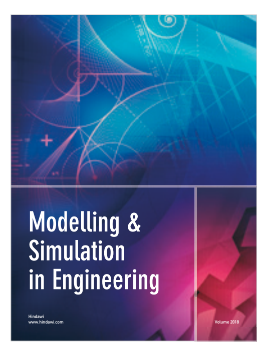
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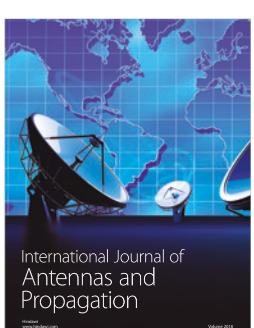
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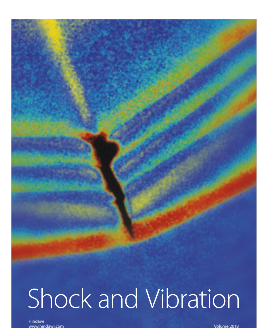
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