Inf Technol Manag (2012) 13:363–376
DOI 10.1007/s10799-012-0128-7

Modeling of emergency response decision-making process using stochastic Petri net: an e-service perspective

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Published online: 1 June 2012

Abstract In this paper, we address the emergency response decision-making process based on stochastic Petri net from an e-service perspective. The emergency response decision-making process is modeled and designed considering service management. The process is modeled based on stochastic Petri net and a solution methodology is proposed to solve the model. In addition, an isomorphic Markov Chain model and a service performance model are developed for measuring and evaluating the service performance of emergency response decision-making process. Finally, a case study is presented to show the viability of our method.

Keywords Emergency response · Decision-making process · Stochastic Petri net · Modeling · e-service · Earthquake

1 Introduction

A variety of natural disasters or accidents due to human negligence occur frequently which has caused considerable loss of life, and property as well as a placing a substantial burden on the response teams of the affected constituencies. Thus, there is a considerable effort being placed on the need for an expeditious response from the responding units to minimize the overall loss due to the calamity [5, 10, 23–25, 27, 30, 43, 48–51, 54, 55, 60, 61]. The emergency response is an extremely difficult and challenging task to save lives and prevent major economic losses as well as future potential environmental problems. The main features of emergency response include unpredictability, speed of events, number of people involved, short decision and action times, unavailability of resources, uncertainty about the situation, pressure and stress on those involved [45, 46]. The emergency response process begins immediately after an event with an adverse impact on a community occurs and ends when the situation has been stabilized. The process consists, in principle, of placing previously developed and exercised plans into action. However, as each emergency is unique, plans usually cannot be executed directly and require adaptation [19]. Therefore, the emergency response is often a complex decision-making problem because of conflicting constraints, uncertain information, and time-sensitive pressure.

Emergency response decision-making can be defined as an outcome of emergency evaluation processes leading to the determination of the most appropriate rescue choice among several alternatives. Every process produces a potential rescue choice. The output of the decision-making process can be a rescue action, a rescue program, or a rescue opinion. Emergency response process is a sequence of rescue activities. The main activities in the process include the mobilization and coordination of relief resources, risk assessment, risk analysis, medical, search and rescue guidance, and providing shelter for the people in the affected region. Therefore, participants involved in emergency response need to make multiple decisions during the response to the disasters or incidents. Emergency response decision-making implies that there are alternative

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rescue choices that need to be considered, and in such emergency situations, we usually desire not only to identify as many alternatives as possible but to select the one that best fits with the rescue goals: the highest probability of rescue effectiveness and the highest possible satisfaction for the affected. How to improve emergency response decision-making effectiveness and the satisfaction is a challenging task.

Although there is an abundance of studies in literature related to emergency response decision-making, the specific challenges discussed above have not been thoroughly examined. This paper is to model and provide a decision-making process that concentrates on the emergency response requirements from the perspective of e-services. The main features include e-service, IT service management, quantitative measure of the e-service quality, and stochastic Petri net. First, the emergency response is a public e-service provided by the e-government [37]. It is feasible to research emergency response decision-making from the perspective of e-services. However, the literatures relate to emergency response decision-making from the perspective of e-government services are quite limited. There are two ways to improve the quality of services. First, to improve service quality in the process design stage is to create the appropriate relationships between the activities in the process. Second, to improve the quality of service in the process execution phase is to effectively implement the various activities. In this paper, we utilize IT service management in the design phase to effectively improve the effectiveness and satisfaction of the emergency response decision-making process. Also, we provide some measurable indicators of the service quality that ensure the effectiveness of the emergency response decision-making process in the implementation stage.

Petri nets are powerful formal models that have been applied to many practical situations [8, 29, 31, 33, 47, 52]. Petri nets are based on strict mathematical theories which are appropriate for modeling and analyzing processes and systems with parallelization, synchronization, and confliction. A stochastic Petri net is an extension of a Petri net where each transition is associated with a random variable. In stochastic Petri net models, we can explicitly describe the causal relation of uncertain events by using places, transitions, and arcs. The random variable is exponentially distributed and expresses the delay from the beginning of enabling to the firing of the transition. Thus, modeling and solving the emergency response decision-making process based on stochastic Petri net seems an apt direction.

In this paper, we validate the proposed model by applying our approach to the Wenchuan Earthquake emergency response decision-making process. This application demonstrates that the emergency response decision-making process model based on stochastic Petri net from the e-service perspective can offer a more effective emergency response service. The contributions of the paper are four fold. The first contribution brings together the existing literature on the modeling of emergency response decision-making and identifies several important requirements for the emergency response decision-making that have not been fully investigated. The second contribution is that the methods of modeling are researched from the perspective of e-service in order to carry out effective emergency response decision-making activities. The third contribution is the design of the methods of modeling that is based on IT service management framework in order to fundamentally improve emergency decision-making service satisfaction. The fourth contribution is that the stochastic Petri net is used to optimize the decision-making process of the emergency response.

The rest of this paper is organized as follows. A literature review is provided in Sect. 2. The emergency response decision-making process model using stochastic Petri net is presented in Sect. 3. In addition, the effectiveness of the proposed model is discussed in the same section. The application of our model to an actual scenario is presented in Sect. 4. In the last section, the conclusion is provided and future research direction is discussed.

2 Literatures review

The relevant literature related to the topic of this paper is limited. However, we can classify the literature according to the characteristics of emergency response decision-making process, the IT service management and e-service quality, and process modeling based on Petri net technique.

2.1 Characteristics of emergency response decision-making process

Research on emergency response decision-making process has focused on emergency response process characteristics, specific decision-making problems, and special applications. Franklin et al. [11] stated that emergency response decision making is very difficult to optimize. Chen et al. [6] described emergency management as a responding process to incidents that require the effective integration of various social resources with the aim to decrease and diminish the harm through appropriate decisions. Hasan and Ukkusuri [17] presented a threshold model of social contagion to characterize the social influence in the evacuation decision making process. Ju et al. [18] concluded that emergency response capability was a comprehensive capability to deal with critical situations such as natural disasters, sudden public health and public safety incidents, military conflicts and so forth. Yu and Lai [59] proposed a distance-based group decision-making methodology in which a standard multi-criteria decision-making process was performed on specific decision-making problems in order to solve unconventional multi-person multi-criteria emergency decision-making problems. Gunawan et al. [16] stated that the situation map can show an overview of a disaster situation and could be considered as a valuable tool to assist the disaster response teams in a disaster response collaborative decision-making process. Bevilacqua et al. [3] concluded that IDEF0 application used in emergency management can provide a clear view of the whole system which includes a communication system between emergency actors, a rich information source, and a structured base for the reengineering the emergency process. Sayegh et al. [36] proposed a conceptual model of managerial decision-making that underscored the role of emotions in an intuitive decision process under crisis conditions. Nivolianitou and Synodinou [34] identified some critical factors that contributed to the effective emergency response in Greece and other European countries concerning both natural disasters and critical accidents. Lindell [26] described the emergency response decision process by which protective action recommendations were developed in nuclear power plant emergency exercises.

2.2 IT service management and e-service

Research on IT service management and e-service has concentrated on IT Infrastructure Library (ITIL) process, characteristics of e-service, e-service quality and measurement. IT service management is a key issue in the management of an organization's IT function [9]. The ITIL represents an influential framework for applying IT service management. The core of ITIL is service management which consists of service support and service delivery. These two areas are the most commonly implemented components of the framework with each one prescribed as a set of predefined processes. The main processes of service support are the service desk, incident management, problem management, configuration management, change management, and release management. The core processes of service delivery are service level management, financial management for IT service, capacity management, IT service continuity management, and availability management [14, 32].

Researchers stated that e-services were comprised of all interactive services that were delivered on the Internet using advanced telecommunications, information, and multimedia technologies. Anthopoulos et al. [1] concluded that e-government projects were mainly service-oriented which have focused on the implementation and diffusion of digital public services through one-stop points of access for citizens. Kennedy et al. [19] discussed some concerns associated with the decision-making processes in post-tsunami Aceh and Sri Lanka from the perspective of community involvement. Gremler [15] thought that the critical incident technique (CIT) had been used in a variety of service contexts that explored service research issues and had been instrumental in advancing our understanding of these issues. Briefly, CIT offers a systematic and sequential research process that consists of the five steps: establish the general aims; establish plans and specifications; collect the data; analyze the data; and interpret and report the data. The CIT allows respondents to indentify which of the incident events are the most important to them from the service perspective. Papadomichelaki and Mentzas [35] proposed an e-government service quality model and developed a multiple-item scale for measuring e-government service quality of governmental sites where citizens seek either information or service.

2.3 Process modeling and optimization based on stochastic Petri net

Research on process modeling focuses on process situations, Petri net modeling, and process optimization [22, 38, 39, 42, 53].

Balduzzi et al. [2] concluded process modeling and optimization was a challenging task in the complex situations such as sequential execution, conflict, concurrency, synchronization, merging, confusion, or prioritization. Sequential execution refers to the processing of precedence constraints; conflict refers to mutually exclusive activities or results; concurrency refers to simultaneous task operation; synchronization refers to multiple resource usage in a single operation; merging refers to multiple precedence constraints; confusion refers to the combination of conflict and concurrency; and prioritization refers to the determination of the priorities of activities. Petri net has been shown to provide a versatile approach in modeling complex scenes [28]. Tavana [40] used Petri nets for dynamic process modeling of the emergency management system at a nuclear power plant and concluded that the developed model was especially useful in reducing the number of false evacuations at the plant. Furthermore, it was shown that the Petri net approach was adequate for modeling complex emergency processes which exhibited sequential execution, conflict, concurrency, synchronization, merging, confusion, or prioritization. Friedler [12] ascertained that the research associated with process integration, modeling, and optimization for energy saving and pollution reduction played a pioneering role in contributing to the solution of the related problems through the development of new methodologies which initiated cooperation among participants that often resulted in international projects.

3 Mathematical modeling

In this section, we present our mathematical model associated with the emergency response process. In addition, we propose an approach that is based on stochastic Petri net to analyze and execute the emergency response process.

3.1 Design of the emergency response process

To integrate service management into the process, an emergency response process can be divided into two parts, the service-providing process and the service-supporting process. In the paper, we consider that the service-providing process is the emergency response decision-making process responsible for managing and carrying out the on-site rescue work. The process is a sequence of rescue activities including preliminary handling, emergency program development and implementation, and post-activity. The service-supporting process is the emergency response support process for supporting a variety of management and decision-making aspects of the rescue process. The main processes included in the emergency response support process are classification management, consultation management, emergency plan management, relief supplies management, and so on.

In order to support the emergency response information systems and e-government functions, the emergency response process considers the main factors affecting the activities, such as input, output, implementation, mechanisms, and constraints. Knowledge bases and the databases supporting the decision-making are also considered in the process design.

The emergency response process designed based on e-service is shown in Fig. 1. There are two main components of the emergency response process system, namely the emergency response decision-making process and the emergency response support process. Activities that are directly related to emergency management are included in the emergency decision-making process. On the other hand, those activities, indirectly related to emergency management activities, or recurring activities, or independent or professional activities, are included in emergency response support process.

The emergency response decision-making process can be divided into four phases, namely the pre-handling phase, the program development phase, the program implementation phase, and the post-activity phase. Each one of these four phases require different rescue activities and handling approaches since they are associated with different levels of demands, complexity, uncertainty, and response time. Successful emergency response decision-making depends on a continuous, consistent, and systematic process that unifies these phases. The pre-handling phase emphasizes on the gathering of accurate emergency information, comprehensive data analysis, taking effective measures, investigating relief needs, and making emergency reports. The main focus of the program development phase is to develop a complete, executable, experts recognized, legitimate, and approved rescue program. The program implementation phase requires swiftly responding activities to the on-site need and the effective coordination with the rescue teams. The post-activity phase includes a series of activities that summaries all the activities of the calamity associated with the emergency response for future reference. These activities can include documenting emergency summary reports, rescue evaluation, cause analysis and prevention, archiving, and the like.

To effectively support the emergency response decision-making, the emergency response support process has seven sub-processes, namely the classification management, consultation management, emergency plan management, relief supplies management, human resource management, emergency financial management, and problem management. The classification management sub-process handles the emergency event classification and determines the severity level in order to better understanding the emergency as well as determining the effective rescue measures. The consultation management sub-process is employed to make full use of emergency expert knowledge, to assist the experts play an important role in the emergency response decision-making process, and to avoid mistakes in the rescue activities. The emergency plan management sub-process is responsible for the preparation of contingency plans, evaluation, storage, retrieval, use, and maintenance. The relief supplies management sub-process is used to manage and meet the demand for relief supplies in the emergency response decision-making process. The human resource management sub-process carries out the organization management and coordination, personnel assignment, monitoring and evaluation of relief activities, and on-site feedback in the emergency response process. The emergency financial management sub-process is primarily responsible for emergency financial budgeting and rescue activity cost accounting. The problem management sub-process is used to analyze and deal with various problems during emergency response decision-making process and to prevent similar problems from reoccurring.

3.2 Modeling of emergency response decision-making process based on stochastic Petri net

A Stochastic Petri Net (SPN) model is a 6-tuple, $SPN = (P, T, F, W, M_0, \lambda)$, where P is a finite set of places, T is a finite set of transitions, and F is a set of arcs where an arc connects a transition to a place or a place to a transition. W: $F \rightarrow \{1,2,\ldots\}$ is a set of weight functions,

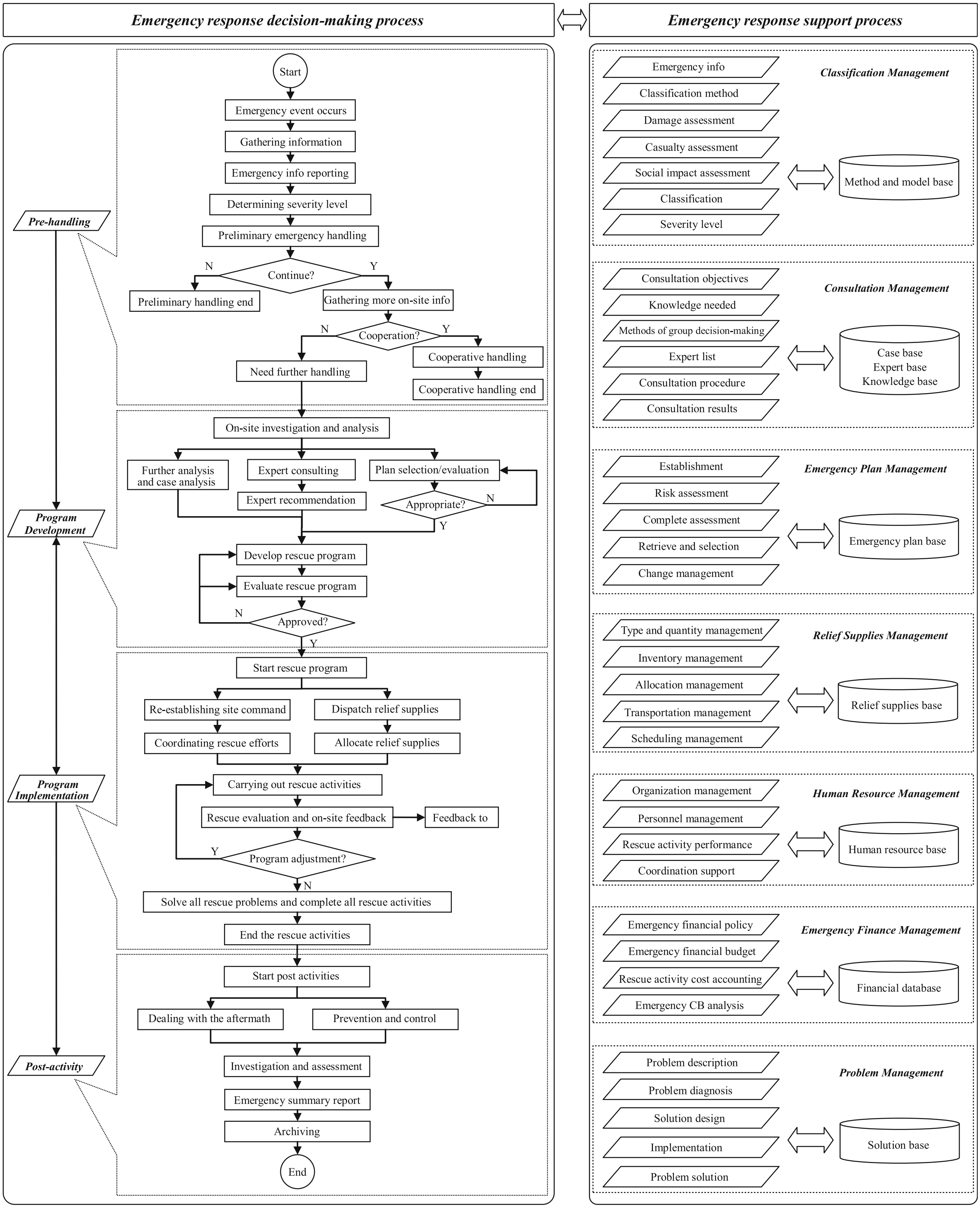

Fig. 1 Emergency response process based on e-service

M_0: $P \rightarrow \{1,2,\ldots\}$ is the initial marking, and $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_{|T|})$ is a set of average firing rates of transitions. A transition is enabled if and only if each of its input places contains at least one token. The firing of a transition removes one token from each input place and places one token in each output place. The distribution of tokens on places, called SPN marking, defines the state of the modeled process. A place *p* is presented with a circle and a transition *t* is presented by a rectangle. The nodes are connected through directed arcs. Directed arcs from *p* to *t* create input places while directed arcs from *t* to *p* create output places. Input places are a set of places that can fire a transition, while output places are a set of places that are associated with the results (outputs) from a transition. Only the static properties of a system are presented by a SPN structure and dynamic system properties result from the execution of SPN. The execution requires the use of tokens or markings (denoted by dots) associated with places. Each place contains zero or many tokens drawn as black dots. The execution of a SPN may affect the number of tokens in a place. A transition is called enabled when each of its input places has enough tokens. A transition can be fired only if it is enabled. When a transition is fired, tokens from input places are used to produce tokens in output places.

Here, we focus on the process modeling and analysis as the emergency response decision-making process is the core of the emergency response. The emergency response support process is incorporated into the process through specific activities. Figure 2 shows the SPN model of emergency response decision-making process. The SPN model integrates all emergency response decision-making activities depicted in Fig. 1 and expresses the relationships between these activities.

In the SPN model, the transitions t_k are used to represent the emergency response activities, and the places p_k represent the data processing and storage. The emergency message data in a place is a token. There are 43 places and 32 transitions in the SPN model. Only the static properties of the process are shown in the SPN model. The dynamic properties of the SPN model can be examined and verified with the user through execution which requires the use of tokens associated with places.

A token placed in p_1 indicates an initial state which occurs at the onset of the emergency event and the emergency message is in the state waiting for processing by alarm facilities. The emergency alarm is enabled indicated by transition t_1, when one token 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 the alarm facilities have monitored occurrence of the emergency message and that the emergency response decision-making process is in the state of alarmed emergency information materialized from various sources. The one token in p_2 enables transition t_2 indicating that the emergency response agency has received the emergency information and have started to process and integrate the received information. Firing t_2 produces one token in p_3, the formatted emergency report and release state which in turn enables transition t_3, decision-making activity on the formatted emergency report. Transitions t_3 and t_4, t_5, t_6, represent a conflict structure. Transitions t_3 and t_6 are a loop structure. According to the actual probabilities, firing t_3 may produce only one token in p_4, p_6, or p_8. In the initial state, one token placed in p_{10} represents this action as an information feedback place. Likewise, places, p_{20}, p_{23}, and $_{32}$, are also information feedback places. The tokens in the SPN model can represent sequential, conflict, and concurrent execution of several rescue activities. In addition, the movement of the tokens throughout the SPN model can be synchronized and prioritized according the actual probabilities. The definitions of the places, p_k and transitions, t_k are listed in Table 1.

3.3 Optimization of emergency response decision-making process

In this section, we propose a SVMP optimization method which can be used to analyze and optimize the emergency response process model based on the SPN. SVMP is an acronym which represents Simplification, Validity, Markov chain, and Performance.

3.3.1 Performance equivalent simplification

Performance equivalent simplification is a frequently used strategy to simplify the Petri net model. This strategy is employed to reduce the workload and highlight the focus on performance analysis [4, 58]. Thus, to simplify the emergency response decision-making process model, we utilize the following simplification techniques [7, 58]:

$$\frac{1}{\lambda} = \sum_{i=1}^{n} \frac{1}{\lambda_i} \tag{1}$$

$$\frac{1}{\lambda} = \sum_{i=1}^{n} \frac{1}{\lambda_i} - \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{1}{\lambda_i + \lambda_j} + \sum_{i=1}^{n-2} \sum_{j=i+1}^{n-1} \sum_{k=j+1}^{n} \frac{1}{\lambda_i + \lambda_j + \lambda_k} + \cdots + (-1)^{n-1} \frac{1}{\sum_{1}^{n} \lambda_i} \tag{2}$$

$$\frac{1}{\lambda} = \sum_{i=1}^{n} \frac{\alpha_i}{\lambda_i} \tag{3}$$

$$\frac{1}{\lambda} = \frac{1}{1-\alpha} \left(\frac{\alpha}{\lambda_1} + \frac{1}{\lambda_2} \right) \tag{4}$$

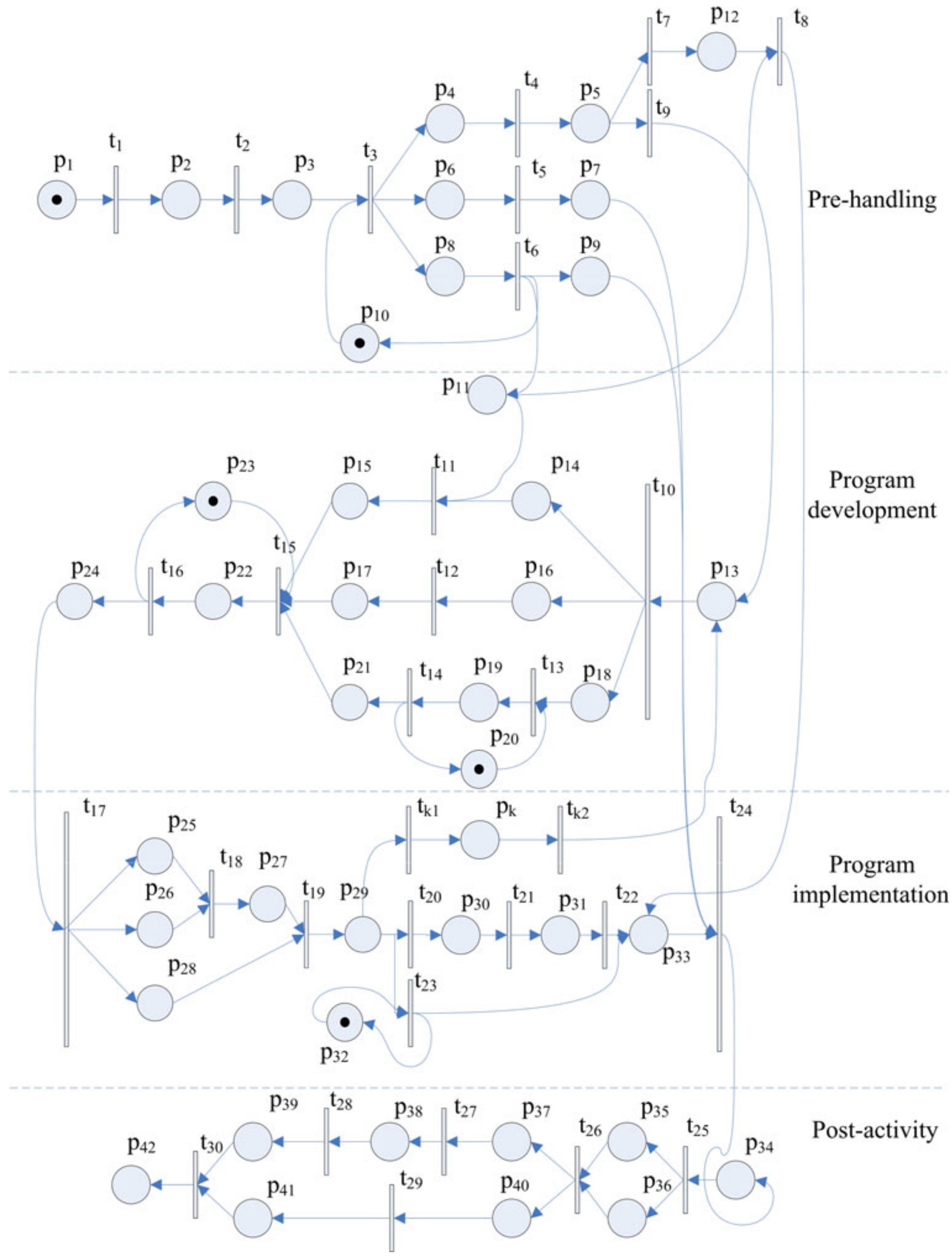

Fig. 2 The SPN model of the emergency response decision-making process

where, λ_i is time associated with transition t_i, equation (1) is the equivalent simplification formula for simplifying sequential structure. Equation (2) is the formula used to simplifying concurrent structure. Equation (3) is the equivalent simplification formula for simplifying conflict structure, where α_i is the probability of the executive transition t_i, $\sum_{i=1}^{n}\alpha_i = 1$. Equation (4) is the equivalent simplification formula for simplifying loop structure, where transition t_1 represents the entrance transition to the loop structure, transition t_2 represents the loop, and α is the occurrence probability of the transition t_1.

The characteristics of the transitions and places in the SPN model should be carefully considered in the simplification. The simplified SPN model is shown in Fig. 3.

In the simplified SPN model, t_a represents the emergency alarm, t_{c2} represents developing emergency program, t_{c3} denotes making decision on choosing the appropriate emergency plans, t_{e1} stands for problem-solving activities, t_f represents archiving assessment. p_c denotes the emergency plan, p_f stands for all emergency-related information.

Table 1 Places and transitions in the SPN model

Places	Transitions
p_1 Occurred emergency message	t_1 Emergency alarm
p_2 Emergency alarm information from various sources	t^2 Alarm reception
p_3 Formatted emergency report and release	t_3 Decision-making activity on the formatted emergency report
p_4 Emergency information to be further analyzed	t_4 Determining the severity level
p_5 Detailed information about the event	t_5 Preliminary handling
p_6 Preliminary handling information	t_6 On-site emergency decision-making
p_7 Information of ending the preliminary handling	t_7 Cooperative handling with other agencies
p_8 On-site information released	t_8 Cooperative handling end
p_9 Information about ending the on-site rescue	t_9 Handling according to normal procedures
p_{10} Emergency rescue information feedback	t_{10} Decisions regarding starting the rescue program
p_{11} On-site real-time analysis information	t_{11} Further on-site analysis
p_{12} Information regarding handling by cooperative agencies	t_{12} Carrying out expert consultation service
p_{13} Detailed information about the event	t_{13} Emergency plan evaluation and improvement
p_{14} More emergency information gathered from various sources	t_{14} Decision regarding the choice of emergency plans
p_{15} Analyzed information	t_{15} Developing rescue programs
p_{16} Information about emergency experts	t_{16} Decision regarding approving the rescue program
p_{17} Recommendation made by experts	t_{17} Start the emergency plan
p_{18} Emergency plans information	t_{18} Decision regarding relief supplies allocation
p_{19} Appropriate plan information	t_{19} Rescue implementation activities
p_{20} Request to improve the plan	t_{k1} Receiving rescue feedback
p_{21} Determining emergency plans	t_{k2} Rescue feedback handling
p_{22} Determining rescue program	t_{20} Identifying more rescue problems
p_{23} Request to improve the rescue program	t_{21} Adjusting the rescue activities
p_{24} Approved rescue program by the emergency handling committee	t_{22} Resolving rescue problems
	t_{23} Rescue progress assessment
p_{25} Information regarding rescue personnel required	t_{24} Decision regarding ending rescue activities
p_{26} Information regarding relief supplies required	t_{25} Starting post-activities
p_{27} Information regarding relief supplies allocation	t_{26} Starting archiving efforts
p_{28} Information regarding rescue activities	t_{27} Evaluating the entire rescue effort
p_{29} Rescue progress information	t_{28} Archiving
p_k On-site information feedback	t_{29} Emergency response summary preparation
p_{30} Detailed information about rescue problems	t_{30} Ending the emergency response efforts
p_{31} Information regarding rescue problem solved	
p_{32} Information feedback after rescue assessment	
p_{33} Information regarding ending rescue program implementation	
p_{34} Instruction regarding starting post-activities	
p_{35} Information regarding dealing with the aftermath	
p_{36} Instruction regarding analyzing the causes	
p_{37} Assessment information	
p_{38} Archiving information	
p_{39} Archiving completed information	
p_{40} Request about preparing emergency summary report	
p_{41} Information regarding completed report	
p_{42} Information regarding the emergency response	

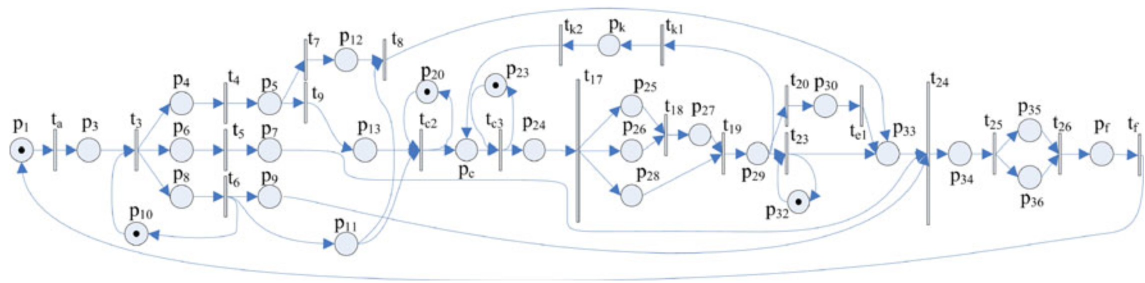

Fig. 3 The simplified SPN model

3.3.2 Validity analysis

Validity analysis is to analyze the reachability, liveness, and boundedness of the SPN model [41]. The reachability problem is to decide if a given marking M belongs to the set $M_0[\ \rangle$ or not. A Petri net is live if there is no deadlock in it. The boundedness of a Petri net can be determined by checking that $n(n = 1, 2, 3, \ldots)$ does not exist any marking on the nodes of the reachability graph [20, 56].

T_invariant can be used to analyze the validity of the SPN model. It is a necessary condition for reachability of marking M from an initial marking M_0 of a SPN that there exists a nonnegative integer vector solution of the following linear Eq. (5),

$$Ax = 0 \tag{5}$$

where $x = (x_1, x_2, \ldots, x_n)^T$ is a firing count vector and A is n $(m \times n)$ dimensional incidence matrix given by the Eq. (6). x is a T_variant of the SPN model [57].

$$A = [(p_i, t_j)] = O[(p_i, t_j)] - I[(p_i, t_j)] \tag{6}$$

The reachability graph can be constructed according to the T_invariant. According to the T_invariant and reachability graph, we can analyze the validity of the SPN model. Based on the analysis of the incidence matrix A, T_invariant, and reachability graph, we can have the following conclusions: the SPN model is characterized by reachability, no-deadlock or liveness, and boundedness.

3.3.3 Constructing isomorphic Markov chain

To evaluate the performance of the SPN model, we construct a Markov Chain (MC) which has the same performance with the SPN model. The reachable graph of an SPN model is isomorphic to a homogeneous MC. The performance indicators of the SPN model are calculated based on the probability distribution of the MC in the steady state [33, 57]. The isomorphic MC is shown in Fig. 4 which is based on the SPN model shown in Fig. 3.

The initial marking is denoted by $M_1 = (1, 10, 20, 23, 32)$, representing the tokens that are in these places, p_1, p_{10}, p_{20}, p_{23}, and p_{32}, simultaneously.

3.3.4 Service performance measures

Service performance measures are used to evaluate the service quality of emergency response decision-making process [21]. We utilize information performance, activity performance, and response time as the emergency response service quality dimensions. Information performance criterion is used to describe the amount of information processed or the integrity of information. In the model, the indicator of busy probability of the place is used as the measure of information performance criterion. Activity performance criterion is used to describe the efficiency of the rescue activities. The utilization of transition indicator represents the activity performance criterion in the model. System delay time indicator is used to measure the response time criterion.

For the MC, we can obtain the steady-state probability based on the following [13, 20]:

$$\begin{cases} PQ = 0 \\ \sum_{i=1}^{n} P(M_i) = 1 \end{cases} \tag{7}$$

where $Q = [q_{ij}], 1 \leq i,j \leq n$ represents a state transition matrix. $P = (P(M_1), P(M_2), \ldots, P(M_n))$ represents a row vector of the probability distribution of steady states. q_{ij} is defined as:

$$q_{ij} = \begin{cases} \lambda_{ij}, i \neq j \text{ and there exists an arc from } i \text{ to } j \\ -\sum_{j=1}^{k} \lambda_{ij}, \text{there are } k \text{ arcs depart from } i. \end{cases} \tag{8}$$

The busy probability of places indicator can be calculated by Eq. (9). The utilization of transitions indicator can be calculated by Eq. (10). Equation (11) is used to calculate the indicator of the system average delay time [58].

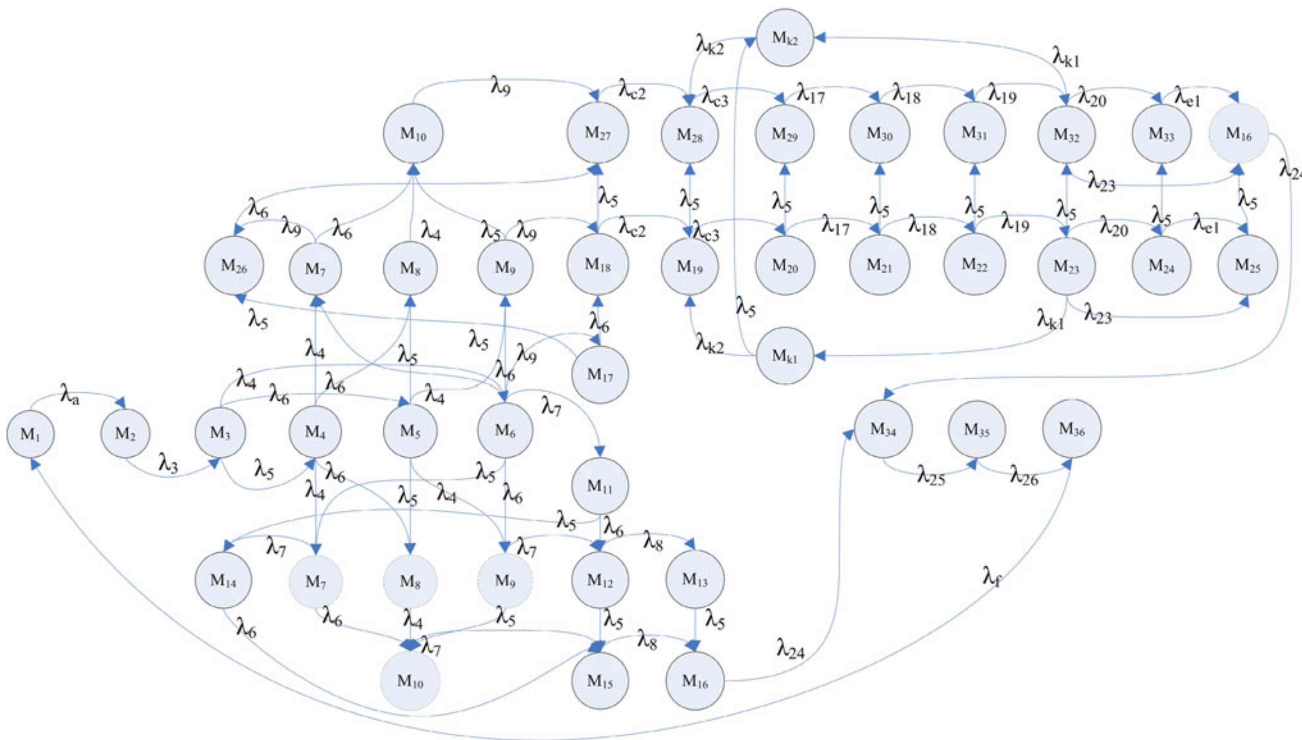

Fig. 4 The isomorphic Markov chain equivalent to the SPN model

$$P[M(p)=i]=\sum_{j} P[M_j], M_j \in [M_0\rangle, M_j(p)=i \tag{9}$$

$$U(t)=\sum_{M\in E} P[M] \tag{10}$$

$$T=\frac{\bar{N}_i}{R(t,p)}=\frac{\sum_{j} j\times P[M(p_i)=j]}{W(t,p)\times U(t)\times \lambda} \tag{11}$$

4 Case study

To validate the proposed model, we applied the process to the 512 Wenchuan Earthquake in Sichuan Province, China. This section presents the application of the models and solution methodology developed in the previous sections to evaluate the emergency response decision-making process. We collected information about 512 Wenchuan Earthquake from various sources and made a recommended rescue schedule for the 72-h period after the earthquake. Some information related to emergency response activities are listed in Table 2.

In general, 72 h after the earthquake is known as the best rescue period. In order to facilitate the theoretical analysis, in this paper we assume that the average time for the rescue program implementation is 72 h. Some transitions are initialized at zero such as alarm-like activities as these transitions consumed a very small amount of time in the Wenchuan Earthquake. In order to facilitate the subsequent analysis, we assumed that the time of these transitions were based on the exponential distribution with $\lambda = 10$, such as $\lambda_a = 10$. Some transitions are the major emergency response decision-making activities, such as on-site handling and resolving the rescue problems. The time for these transitions consumed were calculated and are in Table 2, with $\lambda_5 = 0.5$. Some transitions are rescue activities, such as program development. The time these transitions consume were based on literature, experience, and assumptions, such as $\lambda_4 = 1$.

The steady state probabilities are calculated based on the steady-state probability Eq. (7). Then, the busy probabilities of places can be obtained according to Eq. (9). The results are shown in Table 3.

In Table 3, the busy probability of the places p_{20}, p_{23}, and p_{32}, is 1 and the busy probability of the place p_{10} is almost 1. This indicates that these places have been busy processing emergency information. In fact, these places are the necessary feedback nodes in the emergency response

Table 2 Some emergency response activities regarding Wenchuan Earthquake

Time	Activities	Type
15:00	Earthquake	Alarm
17:00	The helicopters and emergency rescue is being organized and deployed to Wenchuan	On-site pre-handling
16:00	Disaster information reported to Beijing, and start related emergency plans	Information report/release Program development
20:00–22:00	Two transport aircrafts from Beijing arrived in Chengdu	Resource scheduling
20:00–20:10	Armed police entered Wenchuan	Program implementation
1:10	Earthquake site investigation, aircrafts returned	Information release
2:30–3:00	Chongqing fire brigade rushed to the earthquake zone	Resource scheduling
3:00–4:30	Border police rushed to the disaster area	Resource scheduling
4:00–5:40	Mianzhu disaster relief teams arrived in Yunnan	Resource scheduling
6:00–7:30	Chongqing medical teams arrived in Deyang	Resource scheduling
7:00–9:00	Henan emergency fire brigade rescue team left	Resource scheduling
7:00	Armed police rescued more than 1,800 wounded and transferred more than 30,000 people	Program implementation
7:30	Road collapsed	Identify problems
8:00–8:50	Troops of Jinan Military Region departure by special air planes	Resource scheduling
8:20	Troops of Jinan Military Region went to Wenchuan by train	Resource scheduling
9:00	Troops of Jinan Military Region went to Wenchuan by aircrafts because of road collapsed	Solving problem
12:00	A military team arrived in Sichuan on foot	Solving problem
13:00	Altitude aerial photography purpose aircrafts returned as tasks cancelled due to raining	Identifying problems
15:00–18:00	Yunnan Zhaotong assembled a group of rescue teams, and arrived in the area	Resource Scheduling
17:00	Rescue teams can not continue to move forward because of the road collapsed	Identify problems
17:00	Armed police rescued more than 4130 wounded and transferred more than 30,000 people	Program implementation
23:15	Rescue teams in Sichuan walking to Wenchuan	Solving problem
9:00	Armed police opened the road from Malcolm to Lixian	Solving problem
9:20	Rescue teams in Sichuan walking to Maoxian	Solving problem
12:20	More than 100 paratroopers arrived in Maoxian	Solving problem
13:35–13:50	Three air planes delivered the food, tents and equipment to Wenchuan	Resource Scheduling
14:30–16:20	A medical rescue team from Beijing arrived in Sichuan	Resource Scheduling
15:00	Airborne returned the disaster situation of Maoxian	Information release
15:45–16:00	6 rescue teams from Nanjing starting to take off	Resource scheduling
16:00–16:10	Dropped five tons of relief supplies	Resource scheduling
22:00	317 State Road from Chengdu to Wenchuan opened	Solving problem
2:38–2:55	Air Force dispatched a military aircraft	Resource scheduling
6:10	Water lines reopened	Solving problem
12:00	Highway opened up access from Mianyang to Beichuan	Solving problem

decision-making process. In addition, the busy probabilities of these places, p_7, p_9, p_{35}, and p_{36}, are always high. This indicates that the information in the places cannot be processed in a timely manner which resulted in information accumulation. Based on this analysis, we can conclude that real-time data acquisition and analysis facilities should be deployed in the feedback nodes, and rational division of labor and effective use of information systems should be taken care of in these busy places in order to improve the efficiency and quality of emergency information processing.

The utilization of transitions was obtained using Eq. (10). The results are shown in Table 4.

In Table 4, the utilizations of transitions, such as t_5, t_{19}, and t_{26}, are relatively higher which confirms the above conclusion from another point of view that on-site

Table 3 Busy probabilities of places

Place	Busy probability	Place	Busy probability
$P[M(p_1)=1]$	0.0062	$P[M(p_{26})=1]$	0.0061
$P[M(p_3)=1]$	0.0062	$P[M(p_{27})=1]$	0.1530
$P[M(p_4)=1]$	0.0617	$P[M(p_{28})=1]$	0.1592
$P[M(p_5)=1]$	0.0003	$P[M(p_{29})=1]$	0.0001
$P[M(p_6)=1]$	0.1231	$P[M(p_{30})=1]$	0.0123
$P[M(p_7)=1]$	0.2362	$P[M(p_{33})=1]$	0.0554
$P[M(p_8)=1]$	0.0560	$P[M(p_{34})=1]$	0.0056
$P[M(p_9)=1]$	0.3033	$P[M(p_{35})=1]$	0.5612
$P[M(p_{10})=1]$	0.9440	$P[M(p_{36})=1]$	0.5612
$P[M(p_{11})=1]$	0.0471	$P[M(p_f)=1]$	0.0617
$P[M(p_{12})=1]$	0.0500	$P[M(p_k)=1]$	0.0001
$P[M(p_{13})=1]$	0.0074	$P[M(p_{20})=1]$	1
$P[M(p_c)=1]$	0.0122	$P[M(p_{23})=1]$	1
$P[M(p_{24})=1]$	0.0006	$P[M(p_{32})=1]$	1
$P[M(p_{25})=1]$	0.0061		

emergency handling, program implementation, and rehabilitation treatment are relatively time-consuming, and therefore, improving these links can effectively improve rescue efficiency. Also this indicates that these emergency response activities are time-consuming. These emergency response activities include preliminary handling, rescue implementation activities, and archiving work. It can be concluded that the ability of the emergency pre-handling needs to be enhanced, the emergency management and assessment of the implementation activities needs to be strengthened, and the IT means to improve the level of information archiving needs to be considered.

The system average delay time was calculated based on Eq. (11). The system average delay time was 40.4244 h. As we assumed earlier that the average time for rescue program implementation is 72 h, we can conclude that the efficiency of the emergency response activities should have been enhanced.

5 Conclusions

In this paper, we proposed a method to model and optimize the emergency response decision-making process based on stochastic Petri nets from e-service perspective. To validate the proposed method, we applied the approach to evaluate the 512 Wenchuan Earthquake in China. The results illustrated that the proposed method was able to find the problems that existed in the emergency response process and provided some suggestions for improvement.

In addition, IT service management was also incorporated into the design of the proposed method that was developed for the emergency response process. In order to integrate the IT service management, the emergency response process was divided into the service-providing process and service-supporting process. Emergency response decision-making process was service-providing process, and emergency response support process was service-supporting process. Emergency response decision-making process was the core of emergency response process. A modeling method to model the emergency response process based on stochastic Petri nets was proposed. A service performance model was developed for measuring and evaluating the service performance of emergency response process. There were three service performance indicators in the service performance model. A SVMP method was proposed to analyze and optimize the service performance of emergency response decision-making process.

This work can be further extended. It would be appropriate to apply our methodology to other emergency cases to enhance the emergency response decision-making process. Another extension would be to develop an emergency response decision support systems based on the process models in e-services [44].

Table 4 Utilizations of transitions

Transition	Utilization	Transition	Utilization	Transition	Utilization
$U(t_a)$	0.0062	$U(t_{c2})$	0.0059	$U(t_{24})$	0.0056
$U(t_3)$	0.0062	$U(t_{c3})$	0.0123	$U(t_{25})$	0.0056
$U(t_4)$	0.0617	$U(t_{17})$	0.0006	$U(t_{26})$	0.5612
$U(t_5)$	0.1231	$U(t_{18})$	0.0061	$U(t_f)$	0.0617
$U(t_6)$	0.0560	$U(t_{19})$	0.1530	$U(t_{k1})$	0.0001
$U(t_7)$	0.0003	$U(t_{20})$	0.0001	$U(t_{k2})$	0.0001
$U(t_8)$	0.0265	$U(t_{e1})$	0.0123		
$U(t_9)$	0.0003	$U(t_{23})$	0.0001		

Acknowledgments This research was supported by National Natural Science Foundation of China under the grant 70971004 and 70971005, National Social Science Foundation of China under the grant 11AZD096. We also like to thank the anonymous reviewers for their insightful comments that helped us improve the quality of the paper.

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