International Journal of Disaster Risk Reduction 27 (2018) 567–576

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Review Article

Emergency decision making for natural disasters: An overview

Lei Zhou[a], Xianhua Wu[b], Zeshui Xu[c,*], Hamido Fujita[d]

[a] School of Applied Meteorology, Nanjing University of Information Science & Technology, Nanjing, Jiangsu 210044,China
[b] Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, School of Economics and Management, Nanjing University of Information Science & Technology, Nanjing, Jiangsu 210044, China
[c] Business School, Sichuan University, Chengdu, Sichuan 610064, China
[d] Fac. of Software and Information Science, Iwate Prefectural University, 020-0193 Iwate, Japan

ARTICLE INFO

Keywords:
Natural disasters
Emergency decision making (EDM)
Decision support system

ABSTRACT

With the increasing trend of global warming, the frequent occurrences of natural disasters have brought serious challenges to the sustainable development of the society. Therefore, emergency decision making (EDM) for natural disasters plays an increasingly significant role in improving the capability to respond disasters. In this paper, we first elaborate the concept and characteristics of EDM for natural disasters and briefly expound emergency decision contents in different stages of natural disasters. Then, an overview is provided for the EDM theory and methods of natural disasters from the methodological perspective. After that, we give a detailed illustration of the construction of emergency decision support system. Finally, we summarize the main conclusions of the paper and point out the prospect of future researches.

1. Introduction

In the latest years, the frequent occurrences of destructive natural disasters in the world have caused serious damages to social construction and economic development, such as Indonesia tsunami in 2004, "5.12″ Wenchuan earthquake in 2008, freezing rain disaster in southern China in 2008, devastating 2011 earthquake in Japan, flood disaster in India in 2013 and hail disaster in Yancheng in 2016, Jiangsu. Especially in July 2016, heavy rain continues to strike the north of China, with severe flood in southern China at the same time.

Natural disasters refer to the natural processes that occur in the ecosystem, which can lead to the loss of stability of the social-economic system, and serious imbalance between supply and demand of social resources. Natural disasters can be divided into six categories: geological disasters, meteorological disasters, environmental pollution disasters, fire, marine disasters, and biological disasters [1]. At present, natural disaster research is drawing extensive attention in current society and researching fields with the characters of great varieties, high frequencies, wide coverage and big intensity.

Confronted with the stringent situation of flood relief, Comrade Xi, General Secretary of the Communist Party of China and Chairman of the People's Republic of China, addressed the issue of flood relief three times a month and put forward six requirements of "highlighting the defense focus", which provides succinct and specific instructions for disaster emergency management. As is shown above, in the face of the test of natural disasters to the bearing capacity of social and economic system, the governments of all levels, the masses and the scholars have shown great solicitudes for major issues concerning how to quickly and accurately respond to natural disasters, implementation EDM, construct emergency decision support systems, improve the capabilities of disaster prevention and emergency rescue, and provide scientific basis for disaster prevention and relief.

EDM is one of the key issues in the field of emergency management and it needs to propose a scientific and reasonable method for analyzing the effectiveness of EDM and building emergency decision support system for information sharing and cooperative service. Up to now, numerous reviews on EDM have been conducted from the perspective of unexpected disasters [2–4], but a few have been carried out in terms of EDM for natural disasters. In order to figure out the existing developments, challenges, trends of EDM for natural disasters, we try to exploit what to do and how to do it. Roughly, the first aspect concentrates on analyzing the concept and characteristics of EDM for natural disasters, whereas the second aspect focuses on the methods and systems of EDM for natural disasters.

In this paper, we further the study of EDM for natural disasters, and makes significant contributions on EDM in existing developments.

(1) The literature is structured and analyzed the EDM model types, and analyzed the detailed content and advantages and disadvantages in practical application.

* Corresponding author.
E-mail addresses: 20141262750@nuist.edu.cn (L. Zhou), wxhua_77@nuist.edu.cn (X. Wu), xuzeshui@263.com (Z. Xu).

http://dx.doi.org/10.1016/j.ijdrr.2017.09.037
Received 20 May 2017; Received in revised form 18 September 2017; Accepted 20 September 2017
Available online 22 September 2017

(2) We give a detailed illustration of the construction of emergency decision support system. Although with some foundation, there have been no systemic researches and conclusions on the system techniques for EDM for natural disasters.
(3) Through the content analysis framework, several research Resource constraints in EDM for natural disasters are identified and future research directions are proposed.

The paper is organized as follows: Section 2 systematically analyzes the concept and characteristics of EDM for natural disasters and the decision content in different stages. The theory and methods of EDM for natural disasters are summarized in Section 3. Then Section 4 elaborates the construction and development of emergency decision support systems. On this basis, challenges and possible directions are depicted in Section 5. It enriches the existing literature and further provides reference for other researchers.

2. Concept and stage analysis of EDM for natural disasters

2.1. The concept of EDM for natural disasters

Decision-making is a process of selecting the optimal scheme among numerous alternatives to achieve the objective of organizations, and EMD process can be divided into six stages: problem definition, goal setting, project design, project selection, organization implementation and feedback modification [5], as is shown in Fig. 1. In a broad sense, EDM for natural disasters refers to all kinds of prepared measures for the effective control of hazards in the event of disasters, including forecasting, monitoring, early warning and emergency planning, collection of information for emergency transferring, dispatching and rescuing, and disaster recovery after the occurrences of natural disasters [6,7]. In a narrow sense, EDM refers to the process of the timely collection of relevant information, succinct emergency objectives, the development of feasible programs, implementation, coordination and control, and dynamic adjustment according to the specific situation [8–10].

Under the unexpected accidents with high time pressure, high information indetermination and insufficient conditions, EDM for natural disasters exhibits the following characteristics:

From the perspective of decision subject: Multi-sectoral participation in disaster prevention and mitigation is crucial in EDM for natural disasters. Besides, decision coordination plays an essential part in EDM, which contributes to the construction of highly centralized decision core and powerful organizational executive departments.

From the perspective of decision making environment: The decision object presents great complexity in dynamic change of environment, short reaction time, information asymmetry, inadequate protection of resources, which will lead to the urgent and high demand for EDM.

From the perspective of decision objective: Great importance should be attached to humanism – the primary objective in EDM for natural disasters for the purpose of minimizing the loss of life [11]. Then other factors come second such as avoiding or reducing property losses and environmental damage, rescue time, costs and impacts among the public.

Research on Disaster Operations Management (DOM) has also been given great attention in the past decades. Rawls and Turnquist [12] define DOM as the sequence of operations damages resulting from a disaster; and to facilitate the recovery from such an event. As it can be seen, EDM is similar to DOM in considering all the actions taken to reduce the disaster impact, from the minimization of vulnerability and mitigation of risk, to the reconstruction procedures and the implementation of programs to return to normalcy. However, EDM gives more attention to the urgency of disasters, and focused on an organization with clear subject and definite goal, it pays more attention to developing communication systems to reduce the severity of damage. While DOM applies Operation Research (OR) techniques to improve the decision making process in response to the catastrophic impact of disasters [13].

2.2. Emergency decision contents in different stages for natural disasters

In terms of making timely and effective response to natural disasters, we should first understand why natural disasters occur and how emergency decision works [14], in order to reduce disaster losses. The occurrence, development and evolution of disasters are usually divided into mitigation, preparedness, response, recovery in responding natural disasters [15]. The four stages are a closed cyclic process, which runs through the latent period, formation period, stalemate period and extinction period of unexpected disasters. According to the evolution law of natural disasters, the corresponding decision contents should be formulated at different stages of disaster evolution. In the stage of disaster mitigation, the main content of EDM is disaster prevention. Effective measures can be taken such as real-time monitoring, prepared emergency plan, hunt of hidden hazard and emergency rehearsal. The emergency decision content of the disaster preparedness stage puts much emphasis on disaster identification, release of early-warning information, risk prediction and emergency support, etc. The main content of EDM in the third stage is disaster response, including environmental analysis, the determination of emergency priorities, emergency preparedness, scheme design, implementation and feedback adjustment. In the stage of disaster recovery, close attention should be paid to the development of recovery plan, post-disaster restoration and reconstruction, assessment of emergency effect and final conclusion.

Generally speaking, EDM refers to the enhancement of the prediction and prevention capabilities before disasters, the emergency rescue capability in disasters and the handling capability after disasters by optimizing the allocation of resources and making timely and effective response. The process of EDM for natural disasters includes the following steps, as is shown in Fig. 2.

The present paper retrieves the published literature by means of searching titles or keywords of EDM and natural disaster EDM in Chinese, and EDM, emergency decision support, decision support system, disaster EDM and disaster EDM in English. The literature in Chinese is based on CNKI, while Elsevier Science, Springer LINK and SCIE are used to search for literature in English. The keyword disaster EDM was searched in any place of the documents corresponding to journal articles published in English and Chinese. Conferences proceedings, book chapters, books, working papers, and these were not

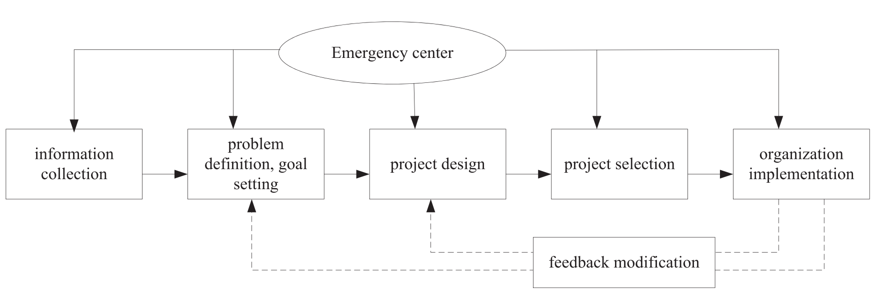

Fig. 1. General process of EDM.

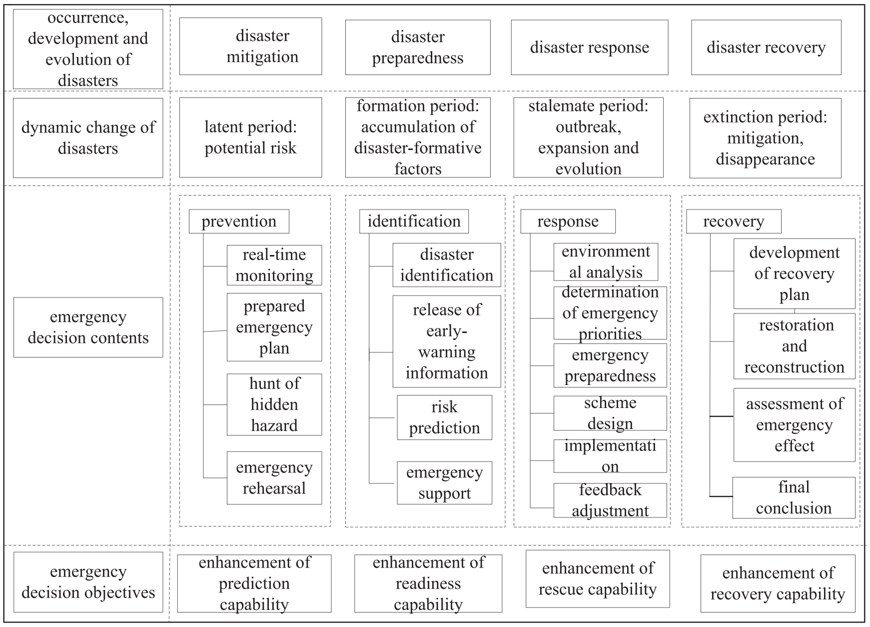

Fig. 2. Process of EDM for natural disasters.

included in our study and we limited the period of our search to 2000–2016. As regard to disaster types, Our findings regarding in the tendencies observed in Altay and Green [16] found manmade disasters were more popular than natural ones from findings before 2006. However, Gina and Rajan [17] types of disaster show a shift that natural disasters were more popular then man-made disasters, this shift may be caused by a series of overwhelming natural disasters that have occurred since 2000, which have captured the interest of public audience (such as the earthquake in Peru in 2001, the tsunami in Indonesia in 2004, hurricane Katrina in 2005, and the Haiti earthquake in 2010). We believe that this type of study is of great value, so this paper studies only for natural disasters.

After confirming the boundaries of our investigation, we proceeded to verify that the identified papers were in compliance with our scope. Our screening process can be divided into two levels: the initial result can be quickly eliminated by examining the title, abstract and keyword of the paper, as they provide clear evidence that such papers were not related to EDM for natural disasters. We used the second and final filter to examine the paper through the first screening test. In order to do this, we read the introduction of this paper, as well as the description of the problem to determine whether the paper is included in our list. Then, we performed a forward reference search using the papers that had been already selected. We used the two-filters approach to screen those papers obtained from the forward reference search.

A total of 1358 papers are published in 2000–2016. The number of papers shows an increasing trend year by year, reaching its peak of 174 papers in 2012 but exhibiting a slight decline in 2014 and 2016. Fig. 3 shows the number of literature in 17 years. We analysis the total number, death toll and economic loss of the serious natural disasters around the world based on the EM-DAT from 2000 to 2016, we find that the total number was stable between 2000 and 2005, It began to decline between 2005 and 2010, then slowly began to rise. The death toll is in a state of ups and downs, with significant increases in 2004 and 2008. In addition, economic loss rises in fluctuation between 2000 and 2010. However, there is a downward trend between 2010 and 2016. From the above analysis, the occurrence of disaster and its influence will arouse people's attention. In addition, the theoretical research lag leads to the publication of the academic thesis.

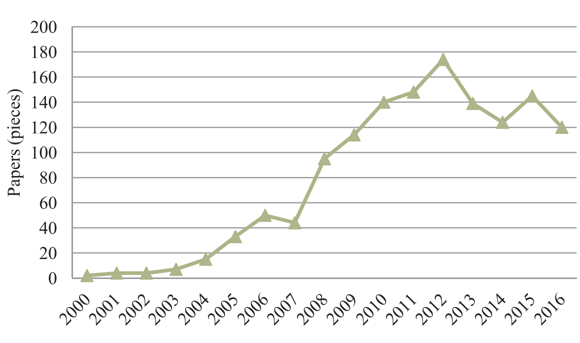

Fig. 3. The number of published papers on EDM for natural disasters in 2000–2016.

Table 1 shows the mathematical model is the most preferred methodology. Simulation, and knowledge management and group decision theory appear to maintain their participation as some of the methodologies most widely used. In emergency decision support systems, emergency decision support system based on GIS seems to be the techniques most commonly used, followed by Agent in second place, and Case-based reasoning in the third. With the development of Intelligent Technology, emergency decision support system based on combining machine learning and natural language processing also well used. In research stage, response research stage was the most widely studied, mitigation and preparedness appear respectively in the second

Table 1
Summary of our Statistics in Methodology and Emergency Decision Support systems and Research Stage in Natural Disaster EDM.

Category	Proportion (100%)
Methodology	
Mathematical model	42
Simulation	22
knowledge management	20
Group decision theory	16
Emergency decision support systems	
GIS	45
Agent	20
Case-based reasoning	19
Combining machine learning and natural language processing	16
Research Stage	
Mitigation	20
Preparedness	28
Response	47
Recovery	5

Table 2
The distribution of keywords and disciplines in disaster EDM.

Serial Numbers	Keyword Distribution	The Number of Papers	Discipline Distribution	The Number of Papers
1	Natural disasters	284	Safety science	268
2	Emergency management	251	Administrative management	235
3	Emergency logistics	183	Macroeconomic management	109
4	Decision support system	150	Computer science	83
5	Geo-information system	80	Geology	50
6	Emergency supplies	60	Meteorology	48
7	GIS	55	Physiography	38
8	Multi-objective decision	40	Geophysics	38
9	Risk management	34	Environmental Science	26
10	Prepared emergency plan	32	Mathematics	24

and third places, however, there is a lack of research in recovery stage, our findings agree with Altay and Green [16] and Galindo [17].

Seen from the keywords and discipline distributions of EDM for natural disasters, keywords are mainly centered on natural disasters, emergency management, emergency logistics, decision support system, geo-information system, emergency supplies, GIS, multi-objective decision making, risk management and prepared emergency plan, while disciplines are mainly distributed in the fields of safety science, administrative management, macroeconomic management, computer science, geology, meteorology, physiography, geophysics, environmental science and mathematics. Many researches are conducted in the field of Humanities and Social Sciences, with few carried out in the field of Natural Sciences especially in mathematics. For details, see Table 2 below. And the top 10 cited publications are summarized in Table 3.

2.3. Resource constraints in EDM for natural disasters

2.3.1. Critical lifeline disruption

The lifeline system is the basic system to ensure the normal operation of the society, and the basic engineering system to maintain the function of the regional economic function. It is the key engineering system for water supply, power supply, communication, transportation, gas supply and other key engineering systems. Disasters can destruct various lifeline engineering structures directly, the failure modes of lifeline system are mostly the chain reaction caused by the destruction of a lifeline and the failure of the whole network, which can lead to the paralysis of the whole system and catastrophic consequences of the collapse [28], for example, in the Wenchuan county, Sichuan province due to the strong earthquake on May 12, 2008, lifeline systems malfunction or completely failure is mainly attributed to geotechnical disasters, landslide, sink, debris and collapse are the important factors to damage the transportation and water-supply systems, which increased the rescue time window constraint. EDM for natural disasters

Table 3
Top 10 cited papers among 1358 publications.

Year	Title	Journal/ Proceedings	Research point analysis	Number of citations	Number of citations per year
2004	Emergency Logistics Planning in Natural Disasters [18]	Annals of Operations Research	Emergency planning; Natural Disasters; vehicle routing; Logistics Planning	1089	83.77
2000	Optimized resource allocation for emergency response after earthquake disasters [19]	Safety Science	Emergency response; Resource allocation; Mathematical modeling	862	50.71
2007	A dynamic logistics coordination model for evacuation and support in disaster response activities [20]	European Journal of Operational Research	Coordination model	649	64.9
2007	An emergency logistics distribution approach for quick response to urgent relief demand in disasters [21]	Transportation Research Part E: Logistics and Transportation Review	Emergency planning; Natural disasters; Vehicle routing; Logistics Planning	647	64.7
2007	Multi-objective optimal planning for designing relief delivery systems [22]	Transportation Research Part E: Logistics and Transportation Review	Natural disaster; Optimal Planning	423	42.3
2003	Preparedness for emergency response: guidelines for the emergency planning process [23]	disasters	Planning process; Emergency response; Emergency preparedness	378	27
2010	Emergency knowledge management and social media technologies: a case study of the 2010 Haitian earthquake [24]	International Journal of Information Management	Emergency management; Social Media; Knowledge management; Case Study; Natural disasters	361	51.57
2006	Interagency communication networks during emergencies: Boundary spanners in multiagency coordination [25]	The American Review of Public Administration	Social capital; Emergency communication	249	22.64
2005	Improving supply chain disaster preparedness: A decision process for secure site location [26]	International Journal of Physical Distribution & Logistics Management	Supply chain; Emergency management; Site location; Contingency planning	190	15.83
2000	A case study of coordinative decision-making in disaster management [27]	Ergonomics	Disaster management; Case study	163	9.59

deciding factors of rescue is under the restriction of critical lifeline disruption [29].

2.3.2. Data cannot be effectively fused

EDM for natural disasters is a typical interdisciplinary problem involving many disciplines, such as meteorology, geography, information science, urban planning, economics and management. Related data include meteorological data, urban waterlogging data, socio-economic data, and other sources, and the amount of data is huge. As the data come from different departments such as water conservancy, meteorology, urban management, operators and Internet, the spatial and temporal scales are not compatible with each other, and the format standards are not unified, which poses a great obstacle to the EDM for natural disasters [30]. Therefore, how to realize the integration of disaster data becomes an urgent and necessary key problem.

2.3.3. EDM with incomplete information

Any decision is a question of timing, and this is particularly prominent in EDM because of the sudden, rapid evolution of disasters. Short time emergency decision face the restriction of personnel, resources, information and other factors, therefore, decision information is discretized and incomplete [31,32]. Therefore, there is a great risk in the extraction, selection and application of the field information for EDM. How to deal with the incomplete information constraint is a difficult problem faced by EDM.

3. Theory and methods of EDM for natural disasters

In the aspects of theory and methods, literature can roughly be classified into the decision making methods based on mathematical models, the decision making methods based on situation evolution, the decision making methods based on knowledge management and the theoretical methods based on group decision making.

3.1. Decision making methods based on mathematical models

Based on the classical decision theory, the previous methods of decision analysis are mainly applied in the resource allocation for emergency and risk analysis after the outbreak of natural disasters [33]. They borrow the method of mathematical analysis or risk management, from the perspectives of emergency costs and risks. Decision making problem falls into the category of management. The present paper, viewed from management cost and benefit, studies the mathematical model of decision making problem and finds the optimal solution by making extensive use of Bayesian network, Game theory, Markoff decision and Fuzzy theory, etc.

3.1.1. Bayesian network

Bayesian network, a mathematical model based on probabilistic reasoning, is proposed to solve the problem of uncertainty and incompleteness. In terms of natural disaster analysis and emergency researches, Bayesian network has provided a solid foundation for the effective risk evaluation and emergency support system for unexpected natural disasters such as earthquakes and floods. On the basis of Bayesian network, some researchers have put forward the methods of seismic risk assessment for infrastructures and post-earthquake emergency decision support [34], and [35] proposed the models of risk analysis and assessment for dam break as a result of flood disasters. With regard to earthquakes and floods, some researchers have constructed the evolution systems of urban secondary earthquake disasters [36] and the risk analysis models of storm floods [37–39], which give a guidance of the corresponding risk evaluation and EDM.

It is admitted that Bayesian decision has achieved steady progress in EDM for natural disasters. However, the application of this method is highly limited owing to the numerous data required, the complexity of calculation and the subjective probability in processing some data.

3.1.2. Game theory

Based on the dynamic game model, some researchers have investigated the evolutionary relationships among emergency decision makers in emergency management of unexpected disasters.

Mesmer [40] adopted the utility theory and game theory to model the individual evacuation behavior and analyzed the decision making process of crowd evacuation. From the perspective of the flood relief headquarters, Ding et al. [41] inquired into EDM characteristics and objectives of urban rainstorm waterlogging, and further put forward an effective method to deal with the situation, according to Bayesian network and Game theory. The process, where the decision makers adjust emergency plan in accordance with the results of every stage and the constantly changing information, can be approximately regarded as the dynamic "game" between the subject and object of emergency management in rainstorm waterlogging, a kind of game between "rainstorm waterlogging" and "decision makers" at every stage.

In view of the practical applications, more factors should be involved in EDM, such as diverse game relations between the subjects or the subject and object in the multi-stage, multi-objective and multi-sectoral EDM, and more complex dynamic game models, etc., which are all important contents for future researches.

3.1.3. Markov decision

The dynamic process of making uncertain decisions and generating emergency response plan indicates a kind of problems about random sequential decision in the light of different stages of emergency situation development and evolution. Since many sectors, departments and persons are involved in the emergency response, the researchers have applied Markov decision process to EDM.

Kozin et al. [42] proposed a method to discretize the damage degree of infrastructures, like urban lifelines, into a system state whose transition probability is defined as the function of system state, rescue resources and the geographical and structural characteristics of urban lifelines, and the return value, on the basis of the spatial economics and economic returns defined by the system state, refers to the optimal strategy for rescue resource allocation by using Markov decision.

With the aid of Markov decision, Zuo et al. [43] forecasted the dynamic development of unexpected disasters, discussed the relationship between disaster prediction and decision, established the application model of multi-sectoral and multi-decision plan, and further effectively solved the problem of emergency response of unexpected disasters.

The process of Markov decision can be used for the modeling of complex systems. The evolution behavior of the system is not only related to the structure of the model, but also affected by the uncertain problem-solving strategy. In the process of EDM for natural disasters, the flexibility of Markov decision will be improved if uncertain factors are taken into consideration such as time and resource constraints.

3.1.4. Fuzzy theory

At present, fuzzy theory in natural disaster EDM mainly includes TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) and fuzzy optimization models. Wang [44] applied fuzzy mathematics theory in hydrology and water resources system and fuzzy optimization scheduling of reservoirs. Chen et al. [45] suggested an intelligent decision making model of fuzzy optimization neutral network on the basis of genetic algorithm, which contributes to the intelligent decision making on the optimal plan for detention areas in Songhua River. As for the optimization of emergency plan for flood control, Fu [46] proposed a method of EDM on the basis of fuzzy approximation.

The methods adopted above indicate that the decision-making methods based on mathematical models is helpful in decision modeling and evaluation. Moreover, it has been widely used in modeling, forecasting, risking assessment and decision optimization. However, owing to the difficulty in modeling, the methods show its inefficiency in solving the complicated problems.

3.2. Decision making methods based on situational evolution

When unexpected disasters occur, the decision makers in emergency management are often confronted with complex and ever-changing situations. Situational evolution is regarded as the effective emergency decision and the modes of emergency management. In case of emergency management of unexpected disasters, the situation is a dynamic evolutionary process, including the past, present and future. In the light of system dynamics, Simonovic [47] built an evacuation model of victims in the process of flood disasters. The model simulates the evacuation behaviors of victims in emergency situation by computer simulation. Chang [48] investigated the problem of emergency logistics in flood disasters with uncertain conditions, which provides a decision-making tool for governments in terms of emergency material dispatch. On the basis of situational planning, Platt [49] conducted a case study to discuss the decision response at different stages of Turkey earthquake.

The decision-making methods based on situational evolution rely on the accumulation of previous knowledge and experience. Nevertheless, the decision makers often lack relevant experience and knowledge in dealing with unexpected events, especially those that have never occurred. The application of situational evolution is highly limited in handling the situations above.

3.3. Decision-making methods based on knowledge management

In the field of natural disaster emergency decision, it is one of the hot issues for the researchers to solve the problems of monitoring, data analysis and resource allocation in decision support by using knowledge management, so as to establish the knowledge model and system. The current researches are mainly concentrated on the implementation and organization of knowledge management for natural disaster emergency decision, as well as the development of knowledge management software and tools.

In terms of emergency decision, the realization of the accurate emergency decision is achieved by knowledge management and the author's purpose is reflected in the business process. Generally speaking, the classification is based on some keywords, such as “know-what”, “know-why”, “know-how” and “know-who” [50,51]. Some researchers have proposed a modest expansion on this basis. For example, Wen [52] put forward “know-conditions” and “know-decision” of emergency decision, which are situation conditions of knowledge and types of knowledge decision. Wu et al. [53] added “know-contexts” and “know-decision” on this basis and proposed an emergency decision-making model of knowledge supply from the perspective of emergency decision. Taking the typhoon disaster as an example, they have carried out a knowledge-oriented analysis. Besides, some researchers apply the model of knowledge management to natural disasters. Richter [54] pioneered the application of the model to typhoon disasters, which yields fruitful results that the essential knowledge for the decision makers is the key to improve the efficiency of emergency decision. Hernandez et al. [55] advocated the use of advanced knowledge model to filter numerous raw information with aim to support emergency decision making. The model has been successfully put into practice in the flood emergency decision in Spain.

Since a great variety of knowledge management tools are available, the core issue lies in how to employ these tools to support decision making. Furthermore, the key points of the future application of knowledge management in disaster emergency decision-making process are reflected in how to establish a system to support knowledge management, increase capital investment in knowledge management, adapt to the ever-changing environment and place the focus on the prevention, mitigation and recovery of disasters.

3.4. Theoretical methods based on group decision-making

Owing to the diversity of participants and the heterogeneity of representative interests, it is essential to realize group decision-making with multi-objectives, multi-interests and multi-agents in the process of emergency decision for natural disasters. Tang et al. [56] provided the targeted strategy adjustment on the basis of the similarity of evaluation opinions and further established the model and algorithm steps of intuitionistic fuzzy group decision-making according to the similarity adjustment. Slattery et al. [57] proposed an eight-step training model of emergency decision to improve the leadership in disaster management. Besides, a comprehensive and effective communication tool was suggested to support group decision-making by Kapucu et al. [58]. In the light of risk elimination in large group decision-making, Chen [59] constructed the coordination mechanism of emergency decision for natural disasters.

The investigation of group decision-making process can improve the decision quality. However, how to establish an appropriate coordination mechanism and achieve the consistency of group decision- making, has always been the key and difficult points of group decision-making.

Response operations considering facility pre-positioning, resource allocation, relief distribution and casualty transportation, and a great many papers have studied this disaster phase. From the detail research methods corresponding to content of emergency decision-making, we find that mathematical models solve the problem of uncertainty and incompleteness mainly in response stage. Situational research focuses on the development of models that help process and analyze input data for the response phase. Since a great variety of knowledge management tools are available, the core issue lies in how to employ these tools to support decision making, it mainly in mitigation, and the group decision-making Mainly in the response phase.

4. Construction and development of emergency decision support system for natural disasters

In the process of EDM, it is of great theoretical and practical significance to improve the rapid response to natural disasters by taking effective information science so as to provide the efficient, intelligent and intuitive and visual information support, and assist the decision makers to make decisions quickly. At present, one of the hot issues in this field is the establishment of Decision support system (DSS), which is a human-computer interaction system, which uses various data, information, knowledge, especially model technology to assist decision makers at all levels to solve structural and semi institutional decision-making problems, model management is the core of decision support system [60,61]. In recent years, the development of DSS with the integration of new technologies, contributed to its further research on in different directions. In view of the method and model building of emergency decision, some researchers have brought computer technology, GIS technology and Agent to the decision field and constructed the corresponding emergency decision support system, which contributes to the efficiency promotion of aided emergency decision.

4.1. Emergency decision support system based on GIS

The developed countries attach tremendous importance to the use of technical means like GIS to carry out emergency decision for natural disasters, such as the United States, Japan, Australia and other countries in Europe. The 1960s witnesses the maturity of emergency decision for natural disasters. With international standards, there have been three influential emergency management systems, Emergency Management System (EMS) in the United States, Intelligent Management System for Major Emergencies of EUREKA and “Emergency Response System” in Japan (DRS). In addition, Korea has developed a real-time monitoring system for disaster emergency management in 2013 [62]. Generally speaking, GIS is mainly applied in

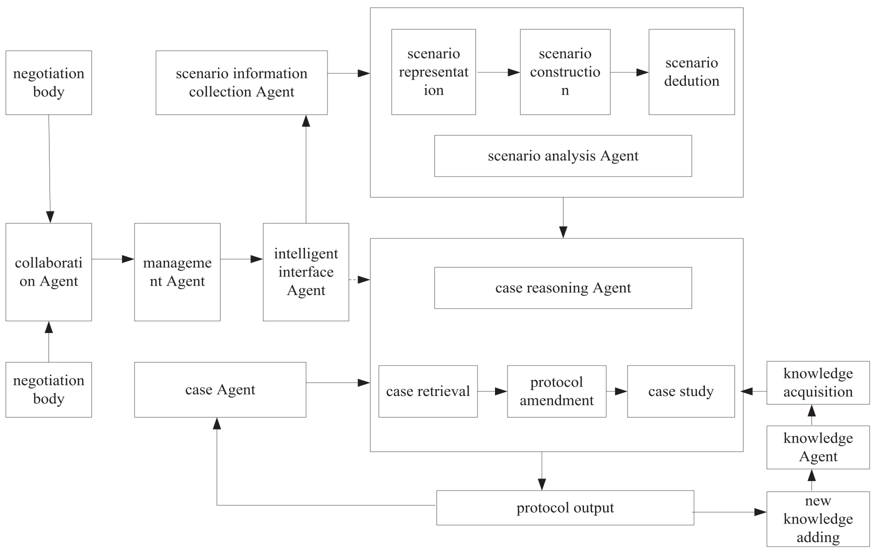

Fig. 4. The structure of emergency decision-supporting system based on multi-agent negotiation.

earthquake or flood disasters.

Since the 1990s, GIS has been employed in emergency decision for earthquakes. At the early stage, developed countries such as Japan and American use GIS in the statistics for natural disasters and the design for thematic map. For example, researchers in Kobe University have carried out an in-depth analysis of disaster statistics and causes based on GIS in Osaka-Kobe Earthquake in 1995. Owing to the requirements for earthquake prediction and relief, the spatial decision support system and intelligent spatial decision support system will be increasingly applied in earthquake prediction and emergency decision [63,64]. There are many function modules in domestic information management systems for earthquake prediction and disaster relief such as collecting meteorological information, disaster forecast, emergency response, dynamic track of disasters, assistant decision, emergency command and data management [65]. Quite a few scholars at home and abroad have carried out the design and research of emergency decision support system for earthquakes. Wei [66] established a model which can evaluate the earthquake risk, assess the vulnerability of infrastructures, estimate the losses of life and property and improve the rescue management. Based on the model, a simulation system is developed for earthquake prediction and emergency decision. Song [67] has examined the emergency decision system for earthquake prevention and mitigation in Shanghai, and set up an emergency decision system through GIS, with an aim to improve the quality of earthquake prevention. Emergency decision for earthquakes includes disaster relief, mitigation of secondary earthquake disasters, medical care, social security and communication recovery [68]. With the help of GIS, Kun [69] has carried out the investigation about earthquake information, the distribution analysis of earthquakes, earthquake prediction, the quick report of earthquakes, disaster evaluation, simulate of secondary disasters and prepared emergency plan, which achieve a good result.

GIS has been brought into practice for floods since the 1970s, with initial researches carried out in the EU and America. Researches concerning flood control in China are conducted from the middle of 1980s. China has achieved initial results in the establishment of the model base of emergency decision support system for flood control, especially for the Yangtze River [70], the Yellow River [71] and the Huai River [72]. At the beginning of the 21st century, the command system for the state flood control and drought relief provides an integrated framework of data, application and portal. Besides, a real-time monitoring system for water resources has been built to fulfill functions of disaster visualization, flood prediction, flood simulation and emergency decision [73]. So far many scholars both at home and abroad have undertaken the analysis of the support system for flood emergency decision. Chen [74], in the light of GIS, has designed an emergency decision support system for urban flood disasters and realized the flood simulation, flood visualization, risk evaluation, emergency evacuation and optimal layout of relief supplies based on 3D space model. Combining GIS with hydrological model, Xu et al. [75] employ the digital elevation model to simulate the flood area and further construct an emergency decision system for small towns. Through the establishment of spatial database of small towns, the system fulfills its functions in terms of flood submerging range, real-time dynamic demonstration, prediction of flood disasters and losses, quick evaluation of flood disasters. Furthermore, human-computer interaction can assist us with inundation analysis and emergency command and rescue in flood control, which meets the requirements of flood control decision for spatial information. In view of Web GIS, a visualization model proposed by Abdalla [76], has achieved flood forecast and visualization in different situations and has been applied in flood emergency management in Don Valley of Toronto in Canada.

4.2. Emergency decision support system based on Agent

Without a unifying concept, Agent, also called intelligent body or subject, generally refers to the intelligent computer entity [77]. Based on the decision support of Multi-Agent organization, Molina [78] described the computer system which can implement the flood emergency decision. Besides, Moser employs Multi-Agent to construct a multi-disaster emergency decision system [79]. Cuena [80] illustrated the structure of Multi-Agent system and points out the types of Agent in the flood emergency decision, including problem detection Agent, reservoir management Agent, civil protection Agent. According to Multi-Agent negotiation, Gong [81] proposed an emergency decision support system by adopting Agent technology which develops from artificial intelligence theory. Combined with situational analysis and case-based reasoning, as shown in Fig. 4, Gong also establishes the functional structure, system structure and Multi-Agent negotiation mechanism of the emergency decision support system. The system makes up for the defects of the traditional decision system which only depends on the technologies of model and data processing, and provides a new theoretical framework for future researches. Throughout the whole EDM process, the mutual cooperation of the various types of Agents is achieved, and the users do not need to participate in the decision-making task decomposition and scheduling, as well as the information exchange between users and the collaboration of the knowledge-based system and the mission system, which can greatly improve the intellectualization of the decision-making system.

4.3. Other related emergency decision support systems

Besides, other decision support systems with potential relations to natural disaster EDM include the case-based reasoning (CBR) decision support system and the decision support system for combining machine learning and natural language processing.

Through accumulation of previous experience, CBR is an important empirical-based problem solving in the field of artificial intelligence, it directly uses matching and correction function to reduce the difficulty of knowledge acquisition, especially in complicated decision-making environment. The iterative strategy is suitable for the dynamic evolution of the natural disaster EDM. Based on the database of the 181 potential debris flows in Taiwan, accurate debris flow prediction models were built to prevent debris flow using CBR in the decision support server by Kung et al. [82]. Tong et al. [83] built a new framework and program of grassland fires disaster emergency spatial decision support system based on CBR, which can be used in the prevention and rescue work of the grassland fire, moreover, the system can learn new knowledge by itself.

Another decision support system is combining machine learning and natural language processing. When a natural disaster occurs, large amounts of data will be generated by social media. Therefore, social networks play a fundamental role in the development of decision support systems that could help EDM. Some scholars have presented decision support systems for natural disaster EDM based on machine learning and natural language processing to effectively extract and organize knowledge from online social media data. Fersini et al. [84] proposed a novel decision support system based on natural language processing to address earthquake early warning signals from a real Twitter dataset. Avvenuti et al. [85] described the design, implementation and deployment of a decision support system for the detection and the damage assessment of earthquakes in Italy, data mining and natural language processing techniques were employed to select meaningful and comprehensive sets of tweets to exploits the messages shared in real-time.

5. Conclusion and outlook

In view of the rich literature mentioned above, the present paper holds that emergency decision for natural disasters is mainly based on methods of mathematical model, situational evolution, knowledge management and group decision and two emergency decision support systems are employed in the light of GIS and Agent, respectively. Despite the continued progress in the emergency decision method and emergency decision support system, research gaps still exist in the following aspects. We will present a summary on some of the current challenges and predict some possible directions of EDM for natural disasters as well as possible opportunities and trends in the coming years.

5.1. Current EDM challenges for natural disasters

EDM needs to be made according to the concrete situation. Currently, technical and non-technical challenges exist in each phase of EDM processing for natural disasters. Due to the focus of this review, we shall concentrate on some of the challenges which might be related to uncertain circumstances and methods. Some other challenges, such as the development of decision making systems are referred to in the section.

5.1.1. Challenges raised by basic characteristics of EDM for natural disasters

Major challenges are caused by the commonly acknowledged characteristics of EDM for natural disasters. For instance, the group members must rapidly make decisions under the high time pressure, high information indetermination and insufficient conditions. In this section, we focus on challenges caused by the characteristics.

Firstly, the group decision-making experts participating in EDM involve many fields and with different levels, which decides the complexity of personnel making up of decision-making group and there will be cognitive conflict and interest conflict among different members [86]. In such emergencies, it is difficult to form the decision scheme with high consistency, therefore, the coordination mechanism is suggested to propose for emergency decision conflict eliminating. Secondly, external environmental pressure makes the decision emergency plan to be achieved in very short time, uncertainty, incomplete cognition and limited information, and also the environment is dynamic, how to effectively predict information according to the existing information is the key to the EDM. In addition, the emergency decision-making objectives in different stages of the disaster are changing, there is only a clear target to find the direction of EDM for natural disasters.

5.1.2. Challenges caused by limitation methods of EDM for natural disasters

From the introduction above, we know that the EDM methods for natural disasters are based on mathematical models, situation evolution, knowledge management and group decision making, these methods have been widely used but have some drawbacks and limitations.

The application of mathematical models is highly limited owing to the numerous data required, the complexity of calculation and the subjective probability in processing some data; Situational evolution methods rely on the accumulation of previous knowledge and experience, however, the unexpected events are highly limited in relevant experience; knowledge management is mainly concentrated on the implementation and organization of knowledge management for natural disaster emergency decision, as well as the development of knowledge management software and tools, the core issue lies in how to employ these tools to support EDM for natural disasters; group decision making lacks an appropriate coordination mechanism to achieve the consistency. All of these methods restrict the development of EDM to a certain extent, and we have to be creative and to strive to practice, continue to develop these methods.

The methods of EDM for natural disasters have significant meanings to elevate the public crisis management capability and decision-making level. Finally, the purpose of reducing disaster risk is achieved. Up to now, a lot of innovative approaches have being developed, including mathematical model, situational evolution, knowledge management and group decision, however, the usefulness of each approach in reducing risk has not been effectively validated, on the one hand, there is no uniform standard for measuring the risk of disaster, on the other hand, the researchers pay attention to the probation of the method in EDM for natural disasters, but not consider the practicability of the method. For example, in Ref. [34], the study develops a methodology for using Bayesian networks to perform seismic infrastructure hazard assessment and provide decision support. This represents a novel approach to assessing and responding to seismic risk that draws upon and integrates knowledge from a range of disciplines, but it does not elaborate on how this method could reduce risk, that is why the usefulness of these methods has not been verified. In the long term this "shoot-out" will make it easier to see which approaches are best.

5.1.3. Challenges related to development and application of decision support systems

Decision support systems have the typical characteristics of complex software system and the intelligent spatial decision support system, the emergency decision support system which is based on GIS assistant decision-making of geo-hazards emergency response, and the emergency decision support system where Agent displays the results to the user and the user only needs to submit the task to the Agent on behalf of the user. They have greatly facilitated EDM for natural disasters. There is room for improvement in combine the intelligent decision support system with expert system to solve the qualitative analysis problems easily, in addition, the suitable technical framework should be constructed to provide the essential building blocks for creating an application, which makes more implementation specifically by layering an application framework on top of it.

5.2. Possible directions and opportunities of EDM for natural disasters

It us urgent to propose a scientific and reasonable method for analyzing the effectiveness of EDM and building decision support system, EDM for natural disasters is taken into account by two separated strategies. The first one is to extend the existing methods of EDM for natural disasters and intelligent decision support systems related to GIS and Agent techniques to the EDM applications. In this case, more attention should be paid to the implementation of the existing methods and systems, such as solving decision-making methods with incomplete information, and the usefulness of these methods in risk reduction. The second is developing completely new techniques to deal with EDM for natural disasters problems. Both strategies will continue in the near future. In this sense, we list some possible directions and opportunities of EDM for natural disasters as follows:

5.2.1. EDM under incomplete information provides additional flexibility

How to carry out effective emergency decision provides a new avenue for future researches owing to the urgent decision-making time, limitations of evaluation methods, a high level of uncertainty in decision information, bounded rationality of decision makers, insufficient existing cases and incomplete prepared plans. Ren et al. [87] proposed a method to deal with the EDM by utilizing the hesitant fuzzy elements to represent the fuzziness of the objects and the hesitant thought of the experts, and introduced the negative exponential function into the prospect theory so as to portray the psychological behaviors of the experts. The concept of hesitant fuzzy set (HFS) [88] can be used in EDM for natural disasters due to that people are usually hesitant and irresolute for one to make a decision in the timeliness of emergency response and unknown information in emergency situations. Of course, there are other ways to be explored.

5.2.2. The fusion of big data which enriches the EDM for natural disasters

The fusion of big data will enrich the natural disaster emergency decision science. Natural disasters include the data of geology, flood and meteorology, disaster data and social statistical data. In addition, the four "V" of big data characterize natural disasters, which are Volume, Variety, Velocity and Value. At present, the data are unable to meet the need of governments for emergency decision in disasters, owing to the ambiguous demarcation, inconsistent standards and incompatibility [31]. Against the background of big data for natural disasters, one of the important contents of natural disaster emergency decision lies in the way to describe the data with different sources, data mapping and fusion, feature extraction and classification, quick and accurate access to valuable information and intelligent decision in emergency response. Among the contents mentioned above, it will be beneficial for future researchers to study those aspects concerning the ontology construction of data, data fusion, Data dimensionality reduction, disaster identification, social and economic effect of disasters and the generation and evaluation of emergency decision.

5.2.3. Considering the actual situation of disaster chain to extend the EDM processing

The theory of disaster chain will be more in conformity with the natural disaster emergency decision-making practice. Owing to the relevance between disasters, the phenomenon that the occurrence of natural disasters give rise to a series of secondary disasters [89], will lead to a more serious disaster with the accumulative effect, greatly exceeding the impact of one disaster. Therefore, these aspects are worth further investigation in terms of disaster-formative environments, disaster-formative factors, and disaster-affected bodies of the disaster chain, the complex interaction between time and space, and practical site selection, emergency evacuation, dispatch of emergency supplies and the establishment of emergency decision support system after mature consideration of the disaster chain.

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