Behavior Modeling and its Application on Emergency Management Parallel System for Chemical Plant

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Abstract To build an emergency management parallel system for a chemical plant, and improve the effectiveness and efficiency of emergency management, a behavior modeling method is proposed in this paper to refinedly decompose the operational procedures in a emergency response plan (ERP) into a structured description with cell activities. The proposed method is useful for the structuring of ERP documentation and the usability evaluation of the ERPs. Moreover, the proposed method is a basic technique to build a rule database and bahavior models for an artificial emergency management system.

Keywords parallel system, ACP, emergency response plan, cell activity, evaluation

I. INTRODUCTION

The ERP is a pre-developed plan or program including timely, orderly and effective emergency response and rescue activities to reduce the loss in an accident or disaster [1]. It is important for the emergency management; especially, it clarifies the responsibility assignments, the critical time points, the handling strategies and the resources preparation during the feedforward, concurrent and feedback stages [2]. However, the most existing ERP and emergency management have their drawbacks. Because not all related specialists, managers, operators, and departments are invited to develop the ERP, the accident analysis is insufficient, and the formulated ERPs are often incomplete and inefficient with ambiguous and rough descriptions. For the worse, the released ERPs are not maintained and managed effectively, which decreases the usability and effectiveness of these ERPs [3-4]. For example, some petrochemical enterprises manage their ERPs through MS Word documents on their intranet, which are difficult to be managed dynamically. This management approach of ERPs has some disadvantages, such as, keyword search among all ERPs is unavailable, and it is not convenient and intuitive for employees to learn and master these ERPs, etc.

To effectively apply the ERP to the emergency response and rescue, it is necessary to design a comprehensive ERP management system from the viewpoint of the whole lifecycle of ERPs [4]. The emergency management is a systematic engineering involved multiple disciplines, industries, and departments, and the effective emergency management should be based on the analysis, control and management of complex systems, which generally contain the engineering and social complexities [5]. However, the traditional emergency management is rarely carried out systematically from the viewpoint of complex system and generally the social complexity is neglected. To cope with this problem, a parallel system theory is proposed [6-10]. Based on the theory, an artificial system is created using agent-based modeling, and then it is possible to analyze the complex system deeply; computational experiments are executed to explore the effective operation of the emergency management mechanism, so that it is probability to comprehensively reveal the accident evolvement in production system which is not possible to perform the experiments in actual world; finally, parallel execution of the actual system and artificial system is implemented to establish a dynamic emergency management system in its whole lifecycle. The abovementioned three steps constitute the artificial system, computational experiment, and parallel execution (ACP) approach.

This paper focuses on the refined decomposition technique and its application to ERP management, which is a core technique for the construction of emergency management parallel systems. The ERP management system designed by us includes the ERP preparing, releasing, elaborating, training, emergency operations supporting, three-dimensional virtual drills & exercises and ERP evaluation functions, as is shown in Fig. 1.

In the following part of the paper, Section II introduces the closed-loop management of ERPs in their whole lifecycle; Section III describes the refined decomposition method of ERPs, by which the ERPs can be converted into cell activities; Section IV describes the evaluation techniques based on the cell activities; Section V and VI give a brief introduction about the applications of cell activities on the ERP training and the operations support; The last section concludes the paper.

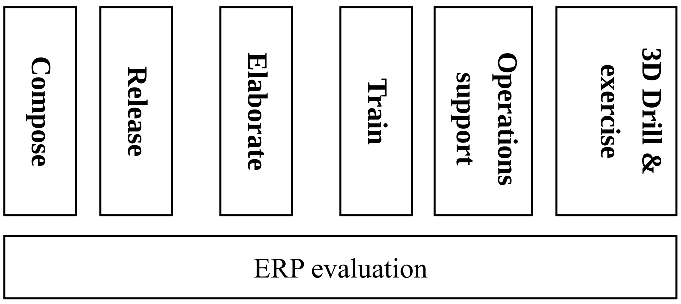

Fig 1. Structure of the emergency management parallel system

II. Closed-loop Management of ERP

The lifecycle of an ERP is shown in Fig. 2. First, in accordance with the emergency experience and the scientific method, the draft of ERP is developed and discussed by the related professionals from production workshop and management offices. Second, the draft is sequentially assessed, revised, and released formally, on the basis of the standard procedure. After the release of the ERP, plant operation specialists, expert operators and managers are gathered to perform the refined decomposition of the plan. The refined decomposition is essentially a kind of behavioral modeling for emergency handling, and it is also the foundation of the artificial systems [11]. The decomposed ERPs can easily to be employed in the ERP training, 3D virtual drill & exercise, operations support, etc. A platform for study and examination is built for the ERP training, and the examination should cover all knowledge points and operation skills of the ERPs; 3D virtual drill & exercise is a kind of special training, by which the interactive operations among operators and computers are implemented. Operational suggestion about the next manipulation or a detailed checklist for an identified emergency case is provided by the operations support during the course of the virtual drills & exercises and training. The operations supports also include the decision supports after starting an ERP. The closed-loop management of ERPs is accomplished according to the evaluation and analysis of the three processes of refined decomposition, training and practical operation.

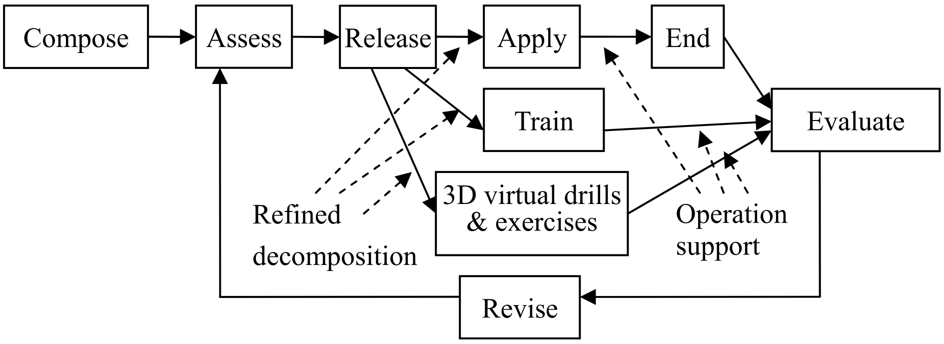

Fig. 2. Lifecycle of the ERPs

III. REFINED DECOMPOSITION OF EMERGENCY RESPONSE PLAN

It is significant to refine ERPs for improving emergency response and evaluating the usability of the ERPs. The refinement can enhance the function of the management system, the system usability and the accuracy of the evaluation and analysis. The refined decomposition has two main purposes. First, an unstructured ERP document is converted into a structured description. Second, the coarse ERPs are discomposed to detailed operational activities. The refined decomposition is carried out according to the ERP analysis or the scenario scripts of emergency drills. The refined composition should be made by a group of the professionals in the brainstorm ways. We are designing an information system platform for the refined composition.

2.1 The Base of the Refined Decomposition

Generally, for a chemical plant there are general, special, production field, and temporary ERPs [2]. The general ERP focuses on the global, general organization and coordination, which is not convenient to refined analysis. The organization, operational mechanism and the SOP (standard operation procedure) are clearly defined for other three types of ERPs, which can be refined and decomposed deeply. At present, the ERPs are usually brief procedures in many chemical plants without concrete technical details.

The desktop drills & exercises are a common pattern of emergency training. In the desktop drill, the plant operators and managers discuss and deduce the decision-making and emergency response for an imaginary accident scenario based on released ERPs and related process flow diagrams. It is helpful for these relevant staffs to remember their responsibilities and operational procedures which are written in the ERPs, and sequentially improve the decision-making and cooperation capacities. Since there is no site constraints and the production are not affected for the desktop drills & exercises, these are not only an effective training approach and the ERP evaluation, but also a necessary means of emergency training. The operational procedures can be obtained based on the desktop drills for a specific emergency scenario, but the procedures may not cover all possible situations because the desktop drills are generally simple and incomplete.

The scenario scripts including scenes, roles, tasks, processes, evaluation, etc. are designed for the three-dimensional virtual drills based on the ERPs. Although the scenario scripts contain very detailed procedures, these are just one case of many possible situations and therefore the ERP decomposition should involves situations as many as possible except for the scenario in desktop or virtual drills.

2.2 The Refined Decomposition Approach

In fact, one ERP mainly consists of three parts: 1) the organization system of emergency, in which the responsibilities of involved positions are defined according to the hierarchy of tree-like structure; 2) the emergency environmental situations, including space, time, organizing people, production technology, the external environment, etc.; 3) emergency procedures. On the basis of the above three parts, the refined decomposition of the ERPs structure the text of the plan and set the property features , so that it is convenient to do analysis and evaluation deeply and build flexible and intelligent applications. Therefore, the refined decomposition approach is as follows.

The organization system of emergency can be broken down into three parts: node, hierarchy and responsibility. Fig. 3 shows a common type of emergency response procedures, in which the contents cannot be directly used to a specific emergency. As shown in the figure, this organization system of emergency has four 4 nodes consisting of 4 positions, that is, the leader of workshop, the squad leader on duty, the operator in the control room, the first finder. The responsibilities of each position are listed. In the list, the leader of workshop is in duty bound to know the truth, direct emergency, and report to the superiors; the squad leader on duty is responsible for command and reporting; the operator in the control room is in charge of informing, reporting, execution and command; the first finder should report the accident and execute the command.

The emergency environmental situations include the time, space, organization, production systems the description of the external environment. These environmental situations are mainly used for conditional judgment of work flow. The common logics of situation judgment are OR logic, AND logic, NOT logic. OR logic needs to meet one condition at least; AND logic means that multiple conditions must be met; NOT logic can obtain the opposite to the given the conditions.

Emergency procedures consist of a group of performing actions, divided into two categories: human-machine behavior and interpersonal behavior. Human-machine behavior means that the humans operate the equipment and implement emergency measures. Interpersonal behavior refers to the information reported, issued and transmitted between the superior and subordinate, and the communication between the same levels for the tasks.

Besides starting and finishing activities, common patterns of activities include: 1) sequential pattern, in which the activities are arranged in time sequence and cannot be adjusted the order. 2) parallel pattern, starting from one time node to execute multiple actions simultaneously, without affection between each other; 3) divergence pattern, starting from one time node to execute multiple actions simultaneously, with mutual influence and dependency between each other; 4) covergence pattern, starting from the difference time nodes to execute the follow-up, single, simple activities; 5) mixture pattern, which is the mixture composed of the above patterns.

In addition to the organization system and situations analysis, time management methodology [12] converts the emergency processes into the cell activities, which is the major work in the refined decomposition. Before the conversion, a variety of the possible patterns of the incident evolvements should be listed and enriched by the collective brainstorming.

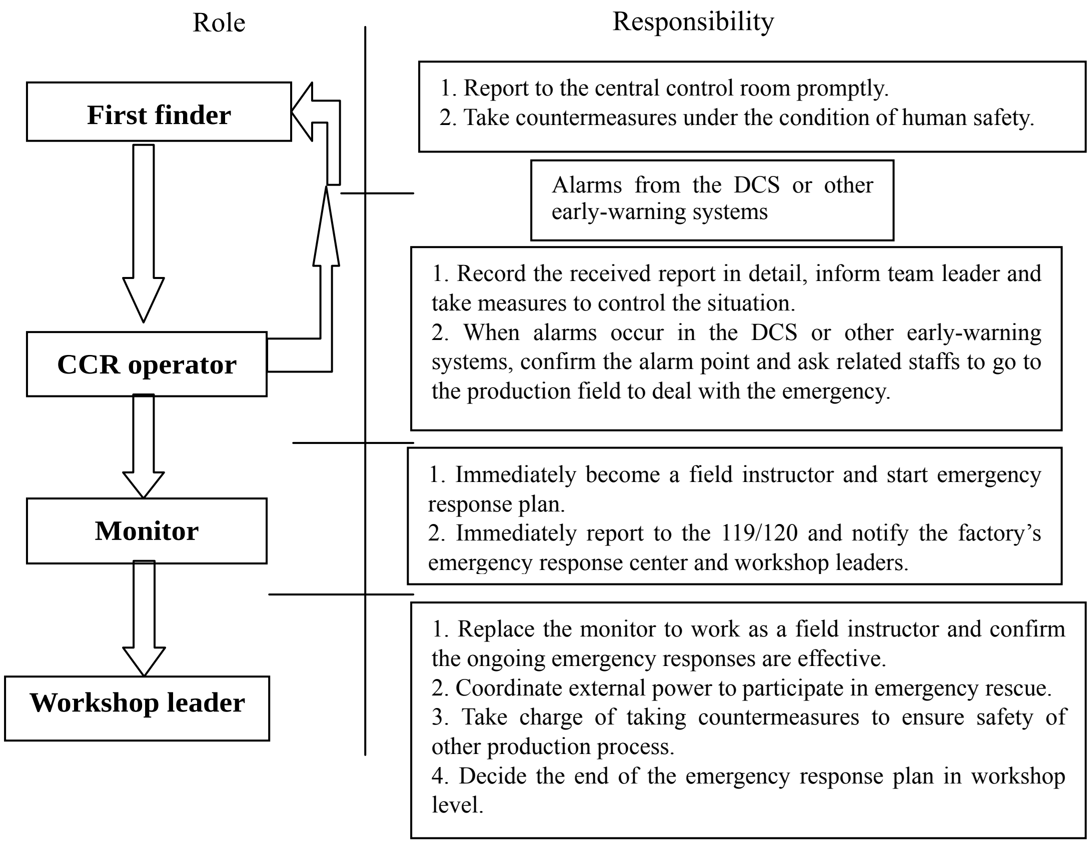

Fig. 3. General emergency response plan in workshop level

2.2.1 Cell Activities

The goal of the refined decomposition is to convert the operation procedure into the cell activities that define executor, aim, and way of one action. Each cell activity only includes one action which cannot be decomposed, e.g. open the valve to 50%. On the contrary, the detachable complex activities with multiple units contain the complex action verbs (e.g. coordinating the rescue, accident analysis) or the verbs with multiple steps (e.g. equipment shutdown, open the standby pump)

The decomposition of cell activities has 5 steps. 1) activities decomposition; 2) the arranged sequence of activities; 3) estimating activity resources; 4) estimating activity duration; 5) Drawing node network diagram of active group with the time characteristics. The principle of decomposition is that the description of human-machine behavior or interpersonal behavior is decomposed into multiple statements and each statement contains only a verb phrase. The phrase has the following requirements: 1) the only verb; 2) SVO sentence referring clearly; 3) give a clear quantitative modification for the unachievable action owing to the lack of action, measured, and other information.

An active group is composed of a group of cell activity or complex activity with the co-operation and the same target. The forcible dependency relationship is that activities of an active group must be executed strictly in accordance with predetermined sequence in order to ensure the safe and reliable operation. The selective dependency relationship means that activities of an active group can be adjusted in sequence, independently of each other, without any cross-reference relations. Some activities may have external dependencies, whose implementations depend on the completeness of external conditions.

In the process of implementation, the two activities in the mandatory dependency closely linked with each other are called the predecessor activity and successor activity. The predecessor can decide the beginning time and ending time of the successor. The two activities have four logical relationship: 1) finish to start (FS) means that the starting time of the successor depends on the completing time of the predecessor, which is the most common logical relationship; 2) Finish to finish (FF), that is, the successor cannot be finished before the predecessor; 3) start to finish (SF), which is that the ending time of the successor can be determined by the starting time of the predecessor; 4) start to start (SS), that is, the initial time of the later can be depended on the predecessor's.

Each activity has a set of properties, including activity code, type, model, its predecessor activity and the logical relationship, its successor activity and the logical relationship, the earliest starting time, the latest starting time, the earliest ending time, the latest ending time, duration, resources required, actors, action, object, extent, direction of information flow, situations and conditions needed to start (activity with external dependence), the waiting time for meeting the conditions (activity with external dependence), the relevant process flow diagram.

After an emergency response procedure is decomposed and refined, all the cell activities are arranged according to the logical relationships and the patterns. Table I shows the logical relationship between the cell activities. Fig. 4 is the node network diagram describing the Table1, in which the earliest and the latest starting and ending times can be calculated [12]. The three-point estimates technique is utilized to predict the duration and the waiting time required by meeting the conditions. The activity resource estimate refers to the material conditions needed for each cell activity, such as tools, equipment and so on. Activities information, including actors, actions, objects, and the degree, can be obtained from the activities' description. Information flow direction contains the information transmitting between the devices and people in the human-machine behaviors, and between the subordinates and the superiors in interpersonal behaviors.

Table I

Logical relationship of cell activities

activity	A	B	C	D	E	G	H
following work	CDE	DE	G	H	H	-	-

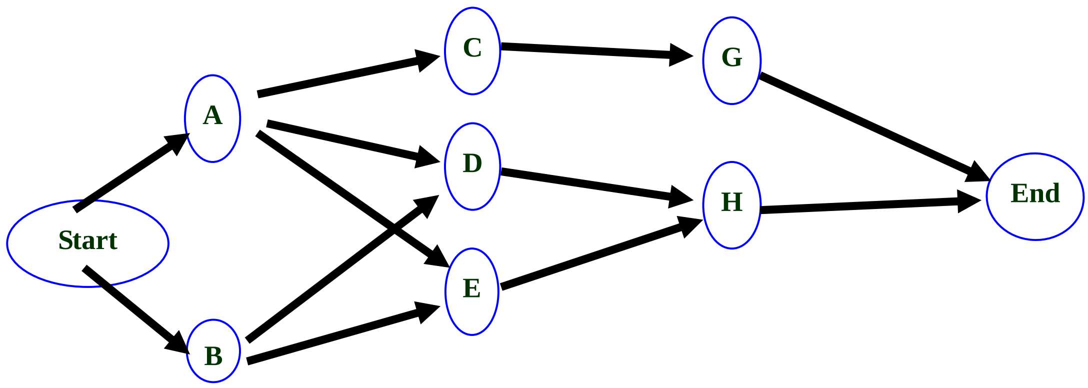

Fig. 4. Node network diagram of an activity group

Time estimate is calculated as:

$$Dmean=(P+4M+O)/6, \qquad (1)$$

where P is the most pessimistic time; O is the most optimistic time; M is the most likely time. Estimate the standard deviation σ is (PO) / 6.

After estimating the duration for each activity, the whole node network diagram can be obtained, based on the logical relationship between activities. Each node of activity is generally represented as:

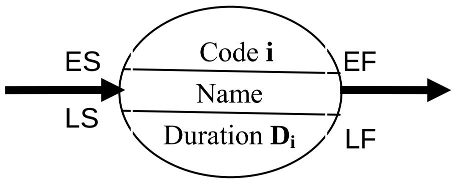

Fig. 5. Activity node

Each node represents an activity; Arrow indicates the relationship between nodes, usually from finished node to starting node. There are four parameters with time characteristics on the on both sides of node: the earliest starting (ES) time; the latest starting (LS) time; the earliest finishing (EF) time; the latest finishing (LF) time.

IV. Application on ERP Evaluation

Activity group decomposed from ERP is used as operational rules for the operator Agent in the artificial system. It also can be used for ERP evaluation, such as the Monte Carlo simulation on the ERP's execution time, usability evaluation of the ERP based on the node network of activity group and complexity evaluation of the ERP based on the structure of activity group.

3.1 Evaluation of the ERP execution time

Based on the Monte Carlo simulation approach, input data are randomly defined according to the probability distribution of cell activity's execution duration and trigger condition waiting time, and then the execution time and its probability distribution of the entire ERP is calculated. The evolvement probability of the branch activity group should be defined in the case of the activity group with external dependences.

3.2 Usability evaluation of the ERP

The critical activity chain(s) is/are recognized based on the node network graph of an activity group. The delay of any activity in the chain may cause the delay of the emergency response as a whole and worse may result to an unpredicted heavy accident. Based on node network graph and activity sequence bar chart, the application conflict of resource, such as human, tool or material can be found, for example, the same executor is assigned more than two tasks at the same time. Efficiency of resource application can also be computed. The advantages and disadvantages of several ERPs for the same accident are obtained based on the evaluation.

3.3 Complexity evaluation of ERP

3.3.1 Network analysis method

The general structure complexity of an ERP is estimated by the density ρ of the node network graph of an activity group, ρ is defined as:

$$\rho = \frac{2L}{N(N-1)} \quad , \qquad (2)$$

where L is the number of the arrow lines in the network graph, N is the number of nodes. The node density ρ implies the relation tightness among the activity nodes, and it shows the difference between the actual distribution graph and a complete graph.

The out-centrality of the activity node network graph is defined as:

$$C(V_i) = \frac{x_{i+}}{\sum_{i=1}^{N} x_{i+}} \quad , \qquad (3)$$

where x_{i+} is the out degree. The centrality shows the importance of an activity node from the structure viewpoint. The node with a large out-centrality is followed by many sequential activities, and the activity denoted by such node should be specially monitored by the managers. The activity node with large in-centrality connects with the execution results of several precedence activities, and the workshop managers should specially confirm these results.

3.3.2 Graph entropy based evaluation method

Graph entropy is defined according to the concept of entropy in informatics, and based on graph entropy the ERP's procedure complexity is estimated according to the graphical structure of activity group network. The entropy H is calculated by:

$$H = -\sum_{i=1}^{h} p_i \log_2 p_i \quad , \qquad (4)$$

where h means the number of divided group, p_i denotes the probability of every group's occurrence. The more the uncertainty of a variable, the more the information is needed to make it clear, that means the entropy is larger. If a system runs in order, its entropy is small, and vice versa, if a system is disordered, its entropy is large.

The graph entropy includes first and second order entropy. The first order entropy is calculated according to the number of inputs and outputs (IOs) of every node. The nodes with the same number of IOs are one group, and the total first order graph entropy is the summation of all groups' 1st order entropy. The second order entropy of a node is calculated according to the neighbor nodes. The nodes around with the same node are one group, and the total 2nd order graph entropy is the summation of all groups' 2nd order entropy [13-16]. The more the activities with the same number of IOs, the smaller the 1st order entropy is. The 1st order entropy reflects the unirregularity of the ERP activity group in logical structure. The more the nodes connecting with the same precedence and successor nodes, the smaller the 2nd order entropy is. The 2nd order entropy shows the procedure complexity of the ERP.

V. Application on Emergency Response Training

The refined decomposition of ERPs can be used for the training of emergency response. There are three types of training based on the activity group: 1). Activities are employed to demonstrate operational procedures. 2). Responsibility assignment matrix (RAM) for the activity group is useful for emergency response drills and exercises. 3). the prerequisite conditions of activities and their logical relations are listed clearly.

Table II. RAM of an ERP

Role / Activity	Indoor operator	Outdoor operator	Indoor assistant operator	Outdoor assistant operator
A	Execute	Inform	Inform	Inform
B	Report	Execute	Inform	Inform
C	Conduct	Inform	Inform	Execute

VI. Application on emergency response support

Activity groups can also be used to support the desktop drills and the actual emergency response. Such support is implemented based on the detailed information of every activity, for example, if the prerequisite conditions, roles and current situations are known, the system will supply the possible operational suggestion; if the current activity is clear, the system will show the next activity; the system can also supply an operational checklist, etc.

VII. Conclusions

As an important technique to build an emergency management parallel system, a refined decomposition method for ERPs is proposed, and the applications on ERP evaluation, emergency response training and emergency response support are introduced. In future, this method will be used to construct the rule database of operator Agent in the artificial system, and it is useful for artificial system construction, computational experiment execution, and dynamic emergency management.

Reference

[1] A. Chen, N. Chen, H. Ni, et al., *Modern emergency management theory and method*. Beijing：Science Press, 2009.

[2] Y. Jiao, Y. Xiong, *Handbook of emergency response to production safety accident in chemical plant*. Beijing: Chinese Labor and Social Security Press, 2008.

[3] D. Xu, “Problems and their countermeasures in the constitution and application of enterprise emergency rescue plans,” *Science and Technology Innovation Herald*, vol. 13, pp. 246-246, 2010.

[4] S. Wu, “Emergency management in whole life cycle,” *Modern Occupational Safety*, vol. 3, pp. 47-51, 2011.

[5] F. Cui, C. Cheng, F. Wang, X. Liu, L. Li, Y. Zou, L. He, “Design of parallel management information system based on service-oriented architecture,” *Computers and Applied Chemistry*, Vol. 27, No. 9, pp. 1171-1176, 2010.

[6] F. Wang, “Computational Theory and Methods for Complex Systems,” *China Basic Science*, Vol. 6, No. 41, pp. 3-10, 2004.

[7] F. Wang. “Artificial Societies, Computational Experiments, and Parallel Systems: An Investigation on Computational Theory of Complex Social-Economic Systems,” *Complex Systems and Complexity Science*, Vol. 1, No. 4, pp. 25-35, 2004.

[8] F. Wang, “Parallel System Methods for Management and Control of Complex Systems,” *Control and Decision*, Vol. 19, No. 5, pp. 485-489, 2004.

[9] F. Wang, “Computational Experiments for Behavior Analysis and Decision Evaluation of Complex Systems,” *Journal of System Simulation*, Vol. 16, No. 5, pp. 893-897, 2004.

[10] F. Wang, “Parallel Control and Management for Intelligent Transportation Systems: Concepts, Architectures, and Applications,” *IEEE Transactions on Intelligent Transportation Systems*, Vol. 11, No. 3, pp. 630-638, 2010.

[11] Liu, X., M. Noda, and H. Nishitani, “Evaluation of plant alarm systems by behavior simulation using a virtual subject,” *Computers & Chemical Engineering*, Vol. 34, No. 3, pp. 374-386, 2010.

[12] Project Management Institute, *A guide to the project management body of knowledge (PMBOK Guide)*, 4th edition. Y. Wang, B. Zhang. Beijing: Electronic Industrial Press, 2009.

[13] Y. Zhang, B. Wu, Z. Li, et al. “Operation Complexity Measure of Emergency Failure Operation Procedure in Spaceflight,” *Journal of Astronautics*, Vol. 30, No. 3, pp. 1225-1230, 2009.

[14] W. Wei, C. Cheng, “The complexity evaluation of chemical emergency response plans based on Graphical Entropy,” *Journal of Safety Science and Technology*, Vol. 7, No. 2, pp. 67-72, 2011.

[15] A. Mowshowitz, “Entropy and the complexity of graphs: I. an index of the relative complexity of a graph,” *Bulletin of Mathematical Biophysics*, Vol. 30, pp. 175-204, 1968.

[16] J. Park, W. Jung, J. Ha, “Development of the step complexity measure for emergency operating procedures using entropy concepts,” *Reliability Engineering and System Safety*, Vol. 71, No. 2, pp. 115-130, 2001.