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Agent action diagram: Toward a model for emergency management system

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ABSTRACT

Agent-based modeling (ABM) has become a useful tool in describing microcosmic action mode of emergency management system (EMS). However, one of key challenges in multi-agent model for EMS could be how to prevent inconsistency between the simulation model established by technicians of computer simulation engineering and the conceptual model established by domain experts. In this paper, a novel multi-view modeling paradigm, agent action diagram (AAD), which has a normalized conceptual model driven architecture and combines the high-layer conceptual model and simulation model, is proposed by establishing its rule symbol system to resolve the above technology problem. Visualization representations of AADs including agent entity organization diagram, agent entity action attribute diagram, single-agent action diagram and multi-agent action diagram are presented. These different views depend on each other according to their functions and form a mutually coupled entirety, thus giving a complete description of EMS with different perspectives. Subsequently, agent model template is constructed, thus affording an automatic mechanism of transforming this graphical conceptual model to its simulation model. Finally, scenarios of emergency command for a great traffic accident and an explosion of a chemical plant are set and two case studies of EMS modeling are implemented, thus verifying feasibility and effectiveness of the proposed approach. This fact shows that the approach has more advantages in model credibility and development efficiency compared with the traditional ABM paradigm.

1. Introduction

Large public crisis events occur continuously in recent years, resulting in serious losses of human and properties and bringing great negative impacts on economic social development. Due to severe challenges, enhancing emergency management comprehensively and increasing ability of fast reaction and risk resistance to key critical incidents can reduce adverse impacts of casualties, economic loss and political crisis to the maximum extent. They have important significance to sustainable economic development and harmonious social stability.

Emergency management involves abundant industries and departments, such as military system, government departments (fire protection, public security, medical service, traffic management, communication, safety supervision and management), as well as enterprise departments and volunteers. Considering characteristics of large public crisis events like sudden occurrence, uncertainty, urgency, serious threats and society orientation, emergency command has to mobilize various resources (e.g. human power, financial and material resources), and coordinate benefits of different parties. It is one multi-layer, multi-department and trans-regional

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complicated problem.

In fact, emergency management system (EMS) is a multi-dimensional and multi-regional comprehensive, connected and coordinated system composed of interactive emergency management entities. Construction of EMS aims to coordinate entities in the system. It can not only realize vertical consistence of actions which are concerned by different layers of departments, but also maintain horizontal consistence of multiple aspects in trans-regional management and control process.

Due to the variety and destructiveness of disasters, emergency management has emerged as a world theme and attracted more and more public attention [1]. To cope with large pubic crisis events in the information era, model of EMS needs to be constructed and analyzed to explore its running mechanism. It is one scientific problem that has to be solved urgently to increase emergency management ability.

In multi-agent systems (MASs), agents coordinate their behaviors and work together to achieve a shared goal through collaboration [2]. MASs are intrinsically built as two-level systems: the “microscopic” level, where the agents are endowed with a specific behavior, and the “macroscopic” level, where the system is seen as a whole [3]. In fact, an EMS and its emergency management entities can be viewed as an MAS and its agents. Thus, in order to explore the external physical structure and internal interaction behaviors of EMS, agent-based modeling (ABM) can be used in a model for EMS.

Model driven engineering is a software development approach where the main outcome is the software specification [4–12]. In model driven engineering, this specification can be transformed directly into other necessary products, like the software or more refined versions of the specification. Model driven engineering has been applied in agent-oriented software engineering resulting into several agent oriented software engineering methodologies [12]. In the context of conceptual modeling and model-driven engineering, agents can be defined as conceptual entities that exhibit autonomy, situatedness and interactivity. Agents have been found useful in model-based development of open, distributed and heterogeneous systems [13]. The model driven architecture is a semi-formal methodology with the aim to allow systems to be conceptualized at four different layers. The architecture captures languages at some level in the hierarchy and enables generative technologies toward higher level goals such as ensuring architecture-to-implementation consistency [14].

In this study, in consideration of the characteristics of EMS, we introduce model driven engineering approach in agent-based EMS modeling and form a normalized conceptual model driven architecture with visualization representations of agent action diagrams (AADs). Our approach is completed firstly by review on research status, problem demand and research countermeasures, and subsequently by analysis of real EMS, definition of the rule symbol system for AAD, description of AAD-based modeling principle and simulation experiment with two representative case studies. The main steps include: (1) Analyze real system and give a complete understanding of the prototype system. (2) Build AADs from different perspectives of EMS, provide consistent and coherent models at different abstraction levels, and present multi-view, dynamic/static combined description for EMS. (3) Design agent model template and automatic mapping mechanism from AADs to agent entity template, and develop corresponding modeling tool for AADs. (4) Use the simulation model generated automatically, implement simulation experiment combined with specific application background, and carry through simulation results analysis.

The remainder of this paper is structured as follows. Current related work is introduced in Section 2. Problem description and research methodology are presented in Section 3. System analysis and modeling are illustrated in details in Section 4, in which the definition and principle of different views of AAD are illustrated, and agent model template is further described. In Section 5, the proposed approach is applied to two case studies to show its usefulness in modeling EMS for a great traffic accident and a chemical plant explosion. Section 6 discusses verification, validation and accreditation (VV&A), some comparisons with similar approaches and the scope of application of our approach. Section 7 summarizes the conclusion and describes some future work directions.

2. Related work

2.1. EMS analysis

In order to support EMS modeling, many researchers attach importance to EMS analysis to study the elements, organization and interactions for a specific EMS. Schaafstal et al. described emergency management within the context of naturalistic decision-making, and proposes a framework, an event-based approach to training, together with a number of team training strategies that may be applicable to emergency management [15]. Yan and He argued that an important task for government content was to solve the emergencies rapidly and effectively. According to the analysis of emergency decision-making process, they studied the relationship between the emergency information resources [16]. Sheu described the challenges of emergency logistics management, such as the timeliness of relief supply and distribution was hardly controllable in the emergency context, and resource management for emergency logistics remained challenging [17]. Ha investigated how Korea has to improve emergency managers’ disciplinary approach to ultimately contribute to the goal of effective transnational disaster management by using qualitative content analysis of government policies, college curricula, nongovernmental organizations’ emergency manager certification, and mass media coverage [18]. Yang et al. thought that safety was an emergent property and illustrated functional resonance in air traffic management with formal verification [19]. Zhou et al. proposed a new method called D-DEMATEL which combines D number theory and decision-making trial and evaluation laboratory (DEMATEL) to identify the critical success factors in emergency management [1]. From the current research results, study of taking an appropriate specification mode that represents both individual actions and multi-individual actions for EMS will be a trend.

2.2. EMS modeling

The model driven architecture is a particular case of model driven development using patterns from the Object Management Group [20]. As the most popular modeling language, Unified Modeling Language (UML) has become standard for a wide range of application domains due to its diversity and multi-view approach to represent a system. UML contains models and views that can represent various aspects (e.g., structural and behavioral) of a system in model driven architecture [21]. Xie et al. constructed a coordinating system framework of emergency management for third party logistics supplier based on UML [22]. Mescherin et al. used UML and concept maps frameworks for creating upper levels of crisis management ontology [23]. UML-based city emergency response system model [24] and typhoon emergency command system model [25] were constructed by UML diagrams description, which laid the foundation for integration development of the systems. Of course, the standard UML is not exactly an architecture description language that needs delivering elements to model the conceptual architecture of a software system, modeling explicitly the components, connectors, and their configurations [26]. Thus, some extension mechanisms for the standard UML have been proposed by some researchers. Especially, development of agent-based systems using UML including its extensions has been a hot research issue [27–31]. However, as a whole, in most cases there are only studies on designing EMS model by these notation techniques. Further and systematic research centering on development of EMS model is relatively lacking.

As far as research paradigm as concerned, ABM has been used in EMS modeling widely. Inan et al. chose disaster management as study object, and introduced an agent-based knowledge analysis method to convert disaster management plans (DISPLANs) into a collection of knowledge units that could be stored into a unified repository. They used the flood DISPLANs to illustrate and give a preliminary validation of the approach [32]. Liu et al. developed a systematic method to automatically calibrate a general agent-based emergency department model with incomplete data [33]. Shendarkar et al. proposed a novel methodology involving a Virtual Reality (VR)-based Belief, Desire, and Intention (BDI) software agent to construct crowd simulation and demonstrated the use of the same for crowd evacuation management under terrorist bomb attacks in public areas [34]. Othman et al. proposed a multi-agent-based architecture for the management of emergency supply chains, in which each zone was controlled by an agent [35]. Moallemi et al. presented an integrated emergency management system based on the Discrete-Event System Specification (DEVS) and Cell-DEVS, in which emergency management was performed by a robotic agent controlled by a DEVS model to respond to the emergency at real-time [36]. Kadri et al. developed a simulation-based decision support system to prevent and predict strain situations in emergency department systems [37]. Joo et al. presented agent-based simulation of affordance-based human behaviors in emergency evacuation, and explored a novel simulation methodology for emergency evacuation situations that incorporated the ecological concept of affordances [38].

Besides, simulation environment and platforms are also the focus of attention. Huang and Zhang described a digital emergency management platform based on GIS, and proposed the design process and basic functions of the system that could provide technical support for the area of disaster prevention and deal of YanJiao by the established YanJiao geographic information system database [39]. Brady described a simulation-based approach that allowed local county-level emergency management agencies to more quickly develop, test, and refine robust plans for an ever increasing list of potential threats. The focus of the simulation environment was on the information flow, coordination, and response of medical, police, and fire resources [40]. Unfortunately, there are few researches on automatic mechanisms of transforming the conceptual model to its simulation model for EMS.

3. Problem description and solution approach

3.1. Problem description: solution requirements

Due to the nature of emergencies, and especially large public crisis events, EMS needs decision making in stressful situations with information ambiguity and overload, and a significant level of uncertainty. In EMS, multiple members that come from different departments, which work together to minimize the negative effects of the emergency by good coordination and communication [15]. For constructing model of EMS, its microcosmic action mechanism shall be studied. In other words, internal working modes which are used by different entities in the system as well as rules and principles for interaction of these entities under complicated environmental conditions of performing emergency tasks shall be explored from perspectives of system analysis and modeling.

Exercise and training in emergency command using actual equipments will spend abundant capitals and involve relevant departments. Generally, it is difficult to test by using real population since emergency events are closely related with human safety. Moreover, tests of great traffic accidents, real explosion, poison gas diffusion and fire disasters don't meet the requirements of environmental protection and show poor operability. Considering man-in-the-loop simulation experiment, the model system is complicated with high cost and high operation difficulty. It is often difficult to further expand simulation functions. Although general modeling and simulation test methods can be used for demonstration of EMS, they have two limitations. On the one hand, modeling of specific environment like public site with dense population is facing with complicated roles and big role quantity. Besides, specific site with high role repeatability is impossible to define one client end for each scene in maneuver. If some typical roles are used as substitution, the scene is not real. On the other hand, processing functions of intelligent factors is not strong enough and description of “live” system members is not profound. It is difficult to reflect roles of random factors, thus leading to technical challenge in depicting interaction and feedback relationships of system elements in space.

For some time ABM has attracted the interest of researchers far beyond traditional computer science [41–46]. Agent is an encapsulated computational software system, which is capable of perceiving events in its environment and acting in its environment guided by perceptions and stored information [46–50]. An MAS, as a collection of agents that work together in order to meet an incommunity-shared goal, is designed to cope with a complex problem involving either distributed data, knowledge, or control by a certain interaction mechanism [51–56]. The ABM methodology relies on a population of autonomous entities called agents which behave according to rules and by interacting with other agents [57]. Agent-based models provide a natural means to describe complex systems, as agents and their properties have a convenient mapping from the entities in the real world systems [58].

The internal members of EMS run with autonomy and interaction. These information interactions include sending, accepting, and informing all kinds of command and control instruction, emergency management intelligence, situation information, and task information. EMS is so alike a distributed MAS in behaviors that we can set up mappings from its internal members, i.e., emergency management entities, to respective agents, e.g., traffic management section → traffic management agent, and public security unit command vehicle → public security unit command vehicle agent. Thus, ABM paradigm is applicable in EMS modeling.

Viewed from scientific studies, unfortunately, the traditional ABM paradigm has two prominent problems in EMS modeling. One is poor combination between the high-layer conceptual model and the simulation model. The second one is lack in developing agent-based EMS model that has a normalized conceptual model driven architecture. In applications of actual engineering, the simulation model established by technicians of computer simulation engineering is often not consistent with the conceptual model established by domain experts to some extents [59–61]. This generally needs iterative corrections [60–62]. Therefore, it is necessary for domain experts to propose a conceptual model driven simulation modeling method. Emergency command modeling field is one of fields with the most applications and the most urgent demands of ABM. Considering the actual characteristics of EMS modeling, an agent-based simulation software engineering method that introduces model driven engineering approach needs to be proposed. It has become one of model development trends.

3.2. Solution approach: research methodology

Driven by the above demands, visualization representations of AADs which meet demands of knowledge background and use habits of domain experts are proposed according to model driven architecture and ABM advocated by domain experts. Based on this description approach, an EMS modeling approach based on AAD is proposed in this work. A set of modeling specification process is presented and the modeling tool for AADs is developed. Conceptual model driven multi-agent simulation modeling separates the conceptual model and its behavioral simulation model framework for EMS, and then integrates them on model implementation, thus forming engineering mode for simulation model development centered on emergency command crews. This is to increase credibility and development efficiency of agent-based EMS model.

AAD is a graphical description approach based on conceptual agent model. It is close to characteristics described by conceptual natural language and is convenient for independent mastering and use of emergency command personnel. As the core of EMS modeling, AAD is able to make multi-perspective, dynamic/static combined and accurate ambiguity-free complete description of EMS. According to actual demands of agent-based emergency command modeling, the system is described by using different views and different perspectives. Agent entity organization diagram, agent entity action attribute diagram, single-agent action diagram and multi-agent action diagram act as different views are not independent mutually, but depend on each other according to their functions, thus forming a mutually coupled entirety. Such view relations are convenient for executable logic relation test of the model in the conceptual modeling stage.

Compared with the traditional ABM process (see Fig. 1a), the AAD-based modeling process (see Fig. 1b) mainly includes real system analysis, conceptual modeling, simulation modeling based on agent model module and operation of simulation test. Based on this multi-view modeling process, the complete description of whole EMS is realized.

In the AAD-based modeling process, forms of specific steps, implementation method of simulation model, model test, role of emergency command personnel and relationship between the simulation model and simulation control framework system are expanded and optimized according to the actual demands in EMS modeling. Specific contents are shown in Table 1.

Coupling relationships between the simulation model and its multi-agent simulation control framework system can also be compared. In the AAD-based modeling process, simulation control framework system is developed independently and is applicable to different simulation models. Such weak coupling relationship is conducive to increase model credibility and development efficiency. Moreover, advantages can be gained by using modeling languages, not only UML and other all-purpose languages, but also AADs with multi-perspective and multi-view visualization representations, with agent model template being used as an automatic mechanism of transforming the graphical conceptual model to its simulation model. Thus, AAD-based modeling for EMS can support automatic software generation, enhance software quality, and reduce development effort.

4. System analysis and modeling

4.1. Analysis of real system

To construct EMS model, the first thing is to analyze real system. From a complex objective system to its conceptual structural model, it is necessary to expand system boundaries in order to cover more real system factors. Moreover, it has to maintain the mapping relation between real system factors and conceptual model factors, so as to ensure conceptual model factors be traced back to real system factors effectively. These contents are the main body of real system. The following principles shall be followed when performing analysis of real system.

(1) Analysis with systematicness and comprehensiveness. The selected influencing factors of emergency management must be able to

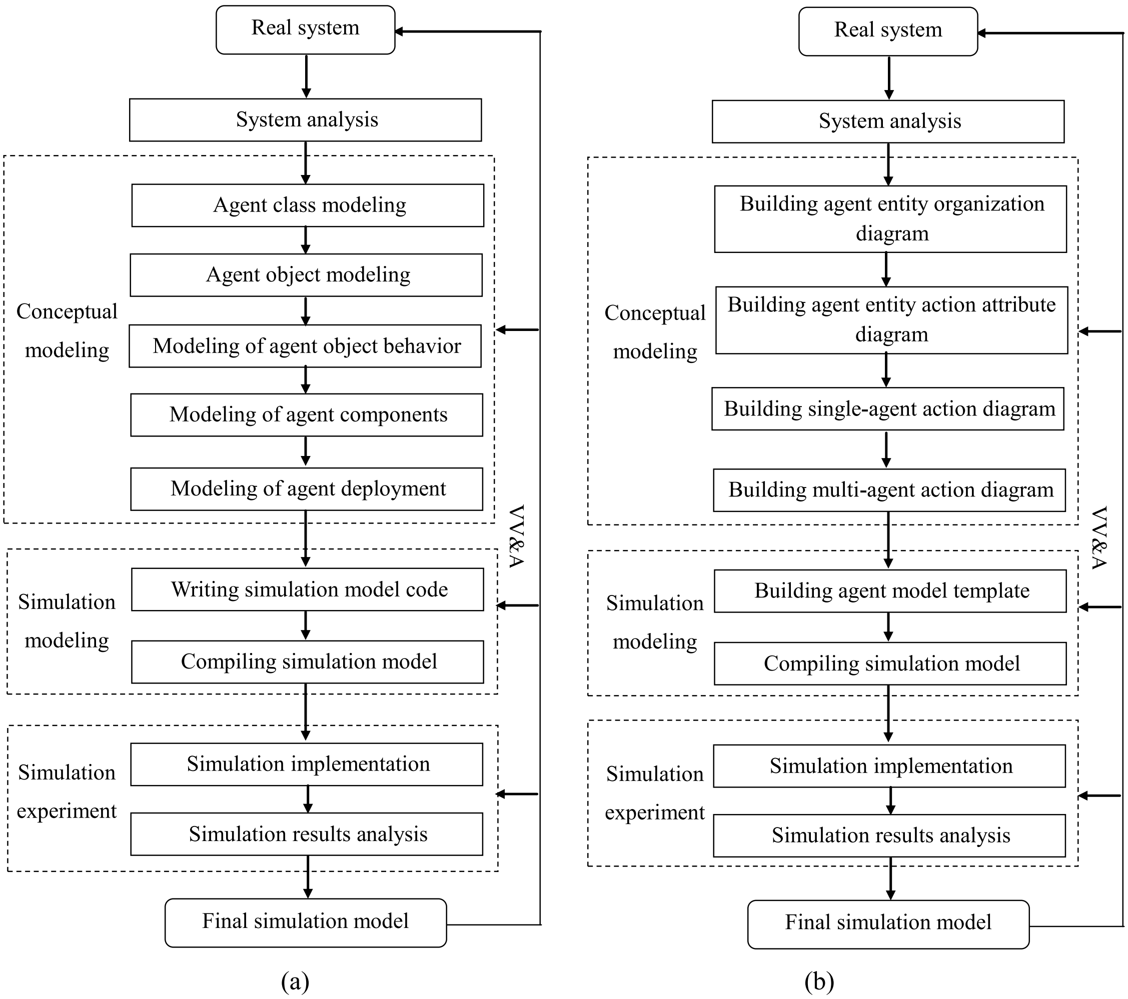


Fig. 1. Traditional ABM process (a) and AAD-based modeling process (b).

reflect structural characteristics, association characteristics and functional attributes of emergency management actions comprehensively, objectively and dynamically in order to meet the mapping relations of elements in real system and model system.

(2) Analysis with proper settings. The quantity of these selected influencing factors of emergency management must be appropriate and system setting must be scientific. The system for factor selection must be perfect, while overlapping of factors shall be reduced as much as possible. In a word, the system shall be structured properly.
(3) Analysis with clear hierarchy. The selected influencing factors shall represent evident hierarchical relations, which are conducive to ensure similar positions and role of these influencing factors at the same level in the constructed model system.
(4) Analysis with dynamic coordination. With changes of emergency management actions, the chosen influencing factors shall be increased or deleted properly. The model shall be emphasized to reflect actual situations with dynamic coordination.

Additionally, special properties of emergency management actions must be added, which can reflect the conceptual model of real system more accurately. In this study, description files of the real EMS are created according to the table template of system elements, graphic template of system structure, and description template of system actions, thus accomplishing functions of system analysis.

Main contents in file of a system action include name of action, participant of action, content of action, constraint condition of action and aftereffect of action.

4.2. Conceptual modeling

As a fundamental step in a simulation project, conceptual modeling involves the abstraction of a model from the real world system, identifying what has to be modeled and how [63]. According to analysis files of the real system, conceptual modeling of EMS is performed by using AAD approach. AADs include agent entity organization diagram, agent entity action attribute diagram, single-agent action diagram and multi-agent action diagram.

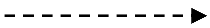
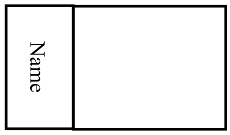
Table 1
Comparison of modeling processes.

Modeling process	Representation	Simulation model framework	Model test	Role of emergency command personnel	Relationship of model and system
Modeling process (a)	UML and other all-purpose languages	Code editing based on software model or generated automatically	Iterative corrections after simulation modeling	Participator	Strong coupling
Modeling process (b)	AADs	Automatic generation based on conceptual model	Executable test in conceptual modeling stage	Leader	Weak coupling

4.2.1. Agent entity organization diagram

Agent entity organization diagram is mainly used to reflect mapping of elements in domain problem system to agent entity in a MAS, classification of agent entity and their organizational relationships. An agent entity organization diagram includes agent entity, structural relationship and organization. The graphical representations and functions of different elements are shown in Table 2. A typical EMS modeling by using agent entity organization diagram is shown in Fig. 2.

Table 2
Elements in an agent entity organization diagram.

No.	Element		Function	Graphical representation
1	Agent entity		It reflects an agent mapped from a certain entity and is the mapping of real system elements in an MAS. Elements include name and contents of an agent.	
2	Structural relationship	Control relationship	It shows the controlling and controlled relationship between agent entities. The arrow points to the controlled agent entity.	
		Coordinated relationship	It shows the coordinated relationship between agent entities.	
		Guidance relationship	It shows the guidance and being guided relationship between agent entities.	
3	Organization		It shows the organization composed of multiple agent entities. Elements include name of organization.	

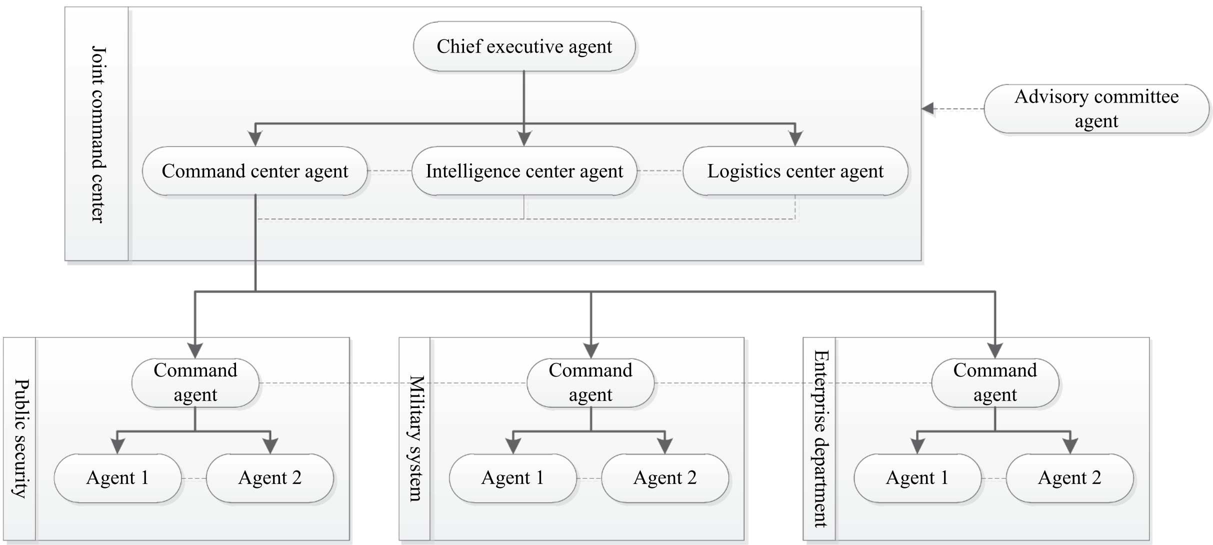
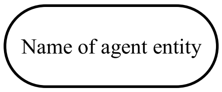
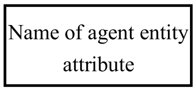
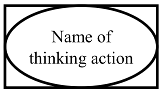
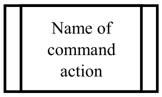
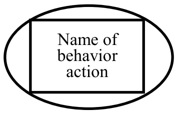
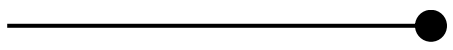
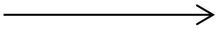


Fig. 2. Example of an agent entity organization diagram.

Table 3
Elements in an agent entity action attribute diagram.

No.	Element		Function	Graphical representation
1	Agent entity		It is corresponding to agent entities in an agent entity organization diagram.	
2	Agent entity attribute		It represents attributes of an agent entity. Attributes can be modified through some abilities.	
3	Agent entity action	Thinking action	It represents the internal decision actions of an agent entity.	
4		Command action	It represents the external command actions of an agent entity.	
5		Behavior action	It represents the behavior execution actions of an agent entity.	
6	Relationships among attributes, actions and entities		It means that a certain attribute or ability belongs to an agent entity.	
7	Influences of agent action on agent attributes		It reflects influences of ability on attributes.	

4.2.2. Agent entity action attribute diagram

Agent entity action attribute diagram describes action and attributes of single agent, and can give a detailed description of the agent entity in an agent entity organization diagram, mainly including agent entity, agent entity attributes, agent entity action, membership function between action attribute and entity, and influence relation of actions on attributes. Graphical representations and functions of different elements are shown in Table 3. A public security patrol team in EMS is modeled by using agent entity action attribute diagram, as show in Fig. 3.

4.2.3. Single-agent action diagram

Single-agent action diagram is established for different task actions of single agent, which mainly describes intelligent decision-making, state transition and task process of single agent. The action process starts from the acceptance of some tasks and end of the tasks, mainly including start, end and division of an action, single action, concurrent actions, branch, entity state, action procedure and explanatory note. Graphic representations and functions of these elements are listed in Table 4. The general structure of single-agent action diagram, which uses real-time emergency management situation as the input and results of performing emergency management task as the output, is shown in Fig. 4.

4.2.4. Multi-agent action diagram

Multi-agent action diagram is mainly used for modeling of cooperation of multiple agents to accomplish a common task. It is the connection of single-agent action diagrams, and mainly covers 13 elements, including those in a single-agent action diagram, division of action stages, and interaction between agents. Graphical representations and functions of those elements are listed in Table 5. Planning actions of EMS can be modeled using multi-agent action diagram as in Fig. 5.

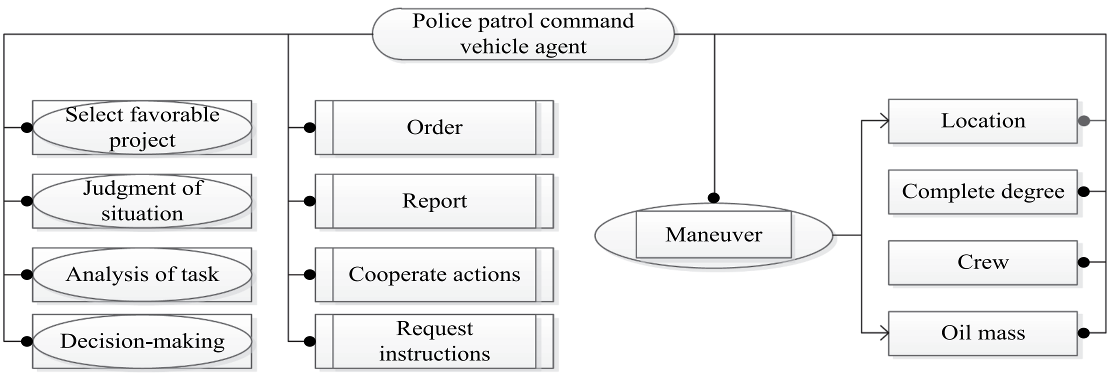
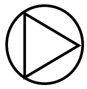
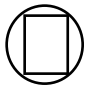
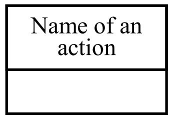
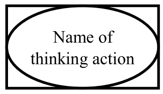
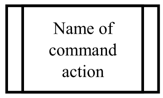
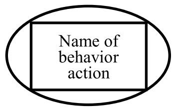
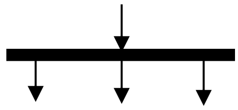
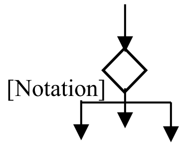
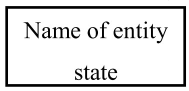
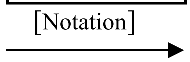
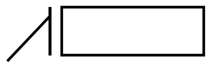


Fig. 3. Example of an agent entity action attribute diagram.

Table 4
Elements in a single-agent action diagram.

No.	Element		Function	Graphical representation
1	Start of an action		It shows the start of action of single agent.	
2	End of an action		It shows the end of action of single agent.	
3	Division of an action		It shows a certain action of single agent.	
4	Single action	Thinking action	It is the internal decision-making action of an agent entity.	
5		Command action	It is the external command behavior act of an agent entity.	
6		Behavior action	It is the behavior execution action of an agent entity.	
7	Concurrent actions		It represents the concurrent implementation of a procedure.	
8	Branch		It represents the branch judgment of a procedure.	
9	Entity state		It represents the state of an agent entity.	
10	Action procedure		It represents the precedence relationship between agent action and state.	
11	Explanatory note		It is used to explain necessary elements thoroughly.	

4.3. Simulation modeling based on agent model template

Agent model template is used to afford an automatic mechanism of transforming the AAD conceptual model to its simulation model. Agent entity organization diagram describes the organization and command relationship between agents. In transformation, the structural relationship of organization which is described by graphs is transformed into tree data structure and stored in the database of agent entity template. They provide data supports to the relationship of organization between agents. Agent entity action attribute diagram describes ability and attributes of an agent as well as influences of ability on attributes. In transformation, on the one hand, ability elements, ability attribute values, attribute elements and initial attribute data are input into the database. On the other hand, the influence relationship between ability and attribute is stored in the physical model library of an agent entity, which provides model support to physical action operation of an agent.

Single-agent action diagram describes entity actions of single agent. Relationships between elements in a single-agent action diagram and an agent model template are shown in Table 6.

Multi-agent action diagram describes entity behaviors among several agents. It is formed by combination of single-agent action diagrams and expresses emergency management actions of specific public crisis under interaction of multiple agents. Multi-agent action diagram is the further expansion of agent knowledge base. Relationships between elements in a multi-agent action diagram and an agent model template are listed in Table 7.

Thus, the system structure and interactive relationships described by AADs can be mapped into an agent entity template. The automatic mechanism can be illustrated in Fig. 6. The executable simulation program code is generated directly through the agent

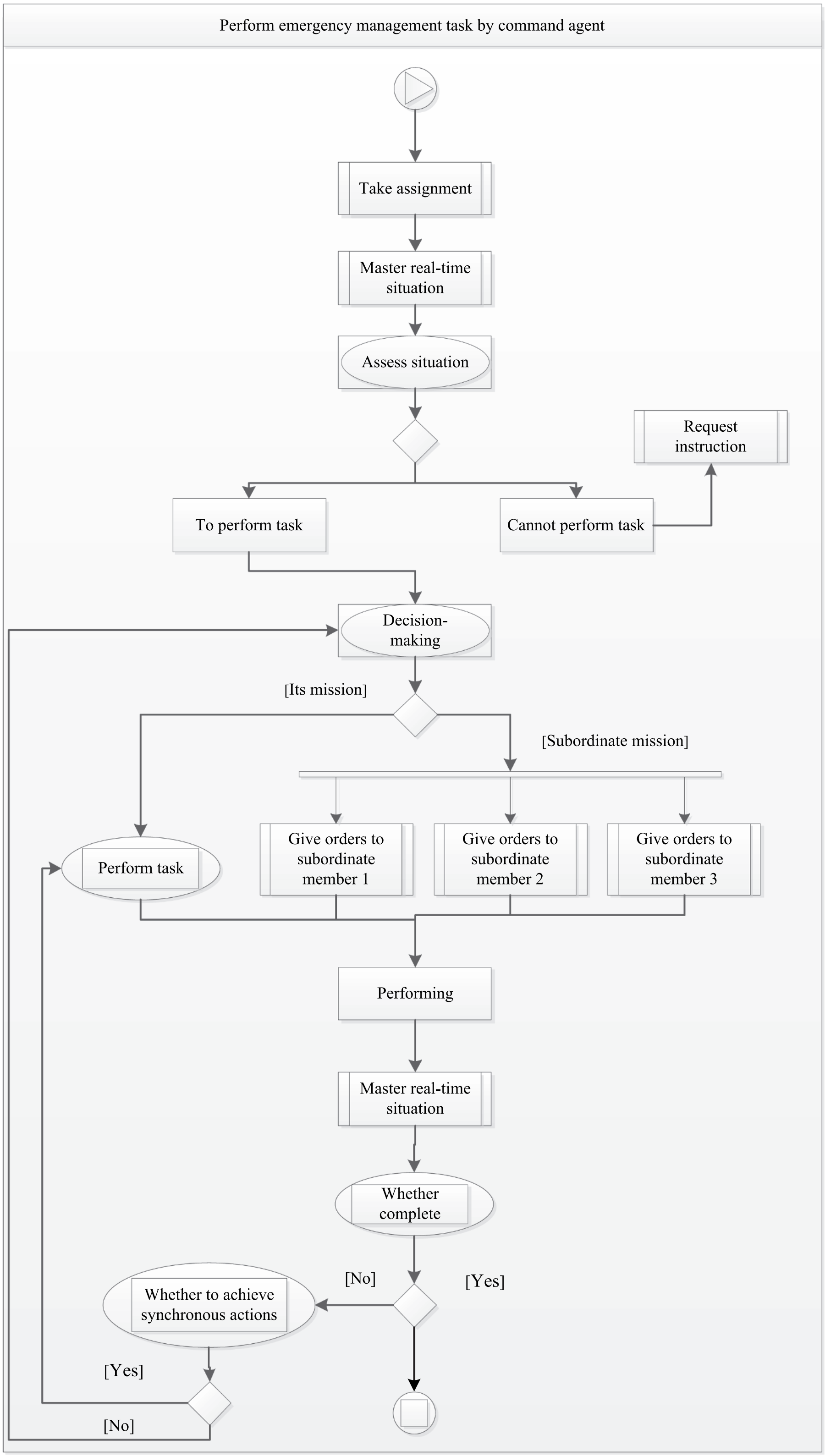


Fig. 4. Example of a single-agent action diagram.

Table 5
Elements in a multi-agent action diagram.

No.	Element	Function	Graphical representation
1 ~ 11	Same as those in Table 4	Same as those in Table 4	Same as those in Table 4
12	Interaction between agents	It represents the interactive relationships between agents.	
13	Division of action stages	It represents the division of multi-agent action stages.	[Notation]

entity template.

In simulation of EMS, the simulation modeling function based on template generation of agent model is realized by using the automatic generation module in the simulation model. This module transforms the conceptual model of AADs into the agent entity template and then transforms into agent model template, i.e., executable agent entity simulation code through the agent entity template. The whole process includes two stages: generation of basic agent template object and physical model library by reading the agent entity organization diagram and agent entity action attribute diagram, as well as generation of knolwedge base and state base by reading single-agent action diagram and multi-agent action diagram.

In the first stage, the emergency management entity objects of specific public crisis and organizational relationships of different objects are generated by reading the agent entity organization diagram. Organizational relationship data are input into the agent database for later decision-making and communication actions. The external interactive function interfaces of agent objects are determined by reading the agent entity action attribute diagram and ability nodes. Attributes of agent objects are determined by reading the attribute nodes. Physical model and parameters of agent actions are determined by reading influence data of ability on attributes. Finally, an agent object which meets internal template requirements in agent standards is generated.

In the second stage, node data in the single-agent action diagram are transformed into logic action sequence of agent actions by reading the single-agent action diagram, which are further transformed into knolwedge expression and stored into the knowledge base. Types of action diagrams are stored in the state base of an agent entity. Interactive relations of multiple agents are transformed into knowledge expression and stored in the knwledge base by reading the multi-agent action diagram. Stages are divided and stored in the state base.

5. Simulation experiment and case studies

5.1. Simulation experiment

5.1.1. Modeling tool

Based on the automatic mapping mechanism from AADs to agent entity template, we design and develop a modeling tool for AADs with functions of building AADs and generating executable simulation program code automatically. This tool is implemented by Qt4.7 graphic interface library and used for AAD-based EMS modeling, as shown in Fig. 7.

In this modeling tool, File module, i.e., module (I), is used to create, save, open and delete model engineering files composed of AADs.

(II) ~ (V) represent Agent entity organization diagram module, Agent entity action attribute diagram module, Single-agent action diagram module and Multi-agent action diagram module, respectively. They are used to construct AADs and realize transformation from conceptual model to simulation model. Here, we provide more technical details on the method of transforming AADs to simulation model, as follows.

Module (II) is used to transform an agent entity organization diagram to corresponding simulation model. The first work is to establish corresponding structure objects AgentNode and AgentGroupNode for each agent entity and organization in an agent entity organization diagram. By setting the attributes of AgentNode and AgentGroupNode, such as includeHead, commandNext, commandBrother, and commandPre, a tree data structure corresponding to the agent entity organization diagram is formed. Thus, the established tree data structure representing agent entity organization structure is stored in the database of agent entity template for all agent entities to use.

Module (III) is used to transform an agent entity action attribute diagram to corresponding simulation model. The first step is to establish corresponding class with the name of the agent type inherited publicly from AgentEntityTemplate class for each agent entity in this agent entity action attribute diagram, add a constructor with AgentID as a parameter for each agent by default, and add a private AgentID attribute and its public Get method by default. Then, the next step is to convert the attributes in agent entity action attribute diagram to private class attributes according to their names and data types, and set up public Set and Get methods for each class attribute to set and get attribute values. The last step is to establish a public method for agent actions in agent entity action attribute diagram with meta-action name as the method name, and use the corresponding meta-action functions implemented on a simulation platform as function bodies.

Module (IV) is used to transform a single-agent action diagram to corresponding simulation model. Aiming at each “Entity state” element of single-agent action diagram, a new entity action state is created in the state list of the state base of the agent entity template, and the macro definition #define is presented. In a single-agent action diagram, each “Branch” element of is converted to a statement implementation with switch…{case:…;break;}, each “Concurrent actions” element is converted to create a thread function

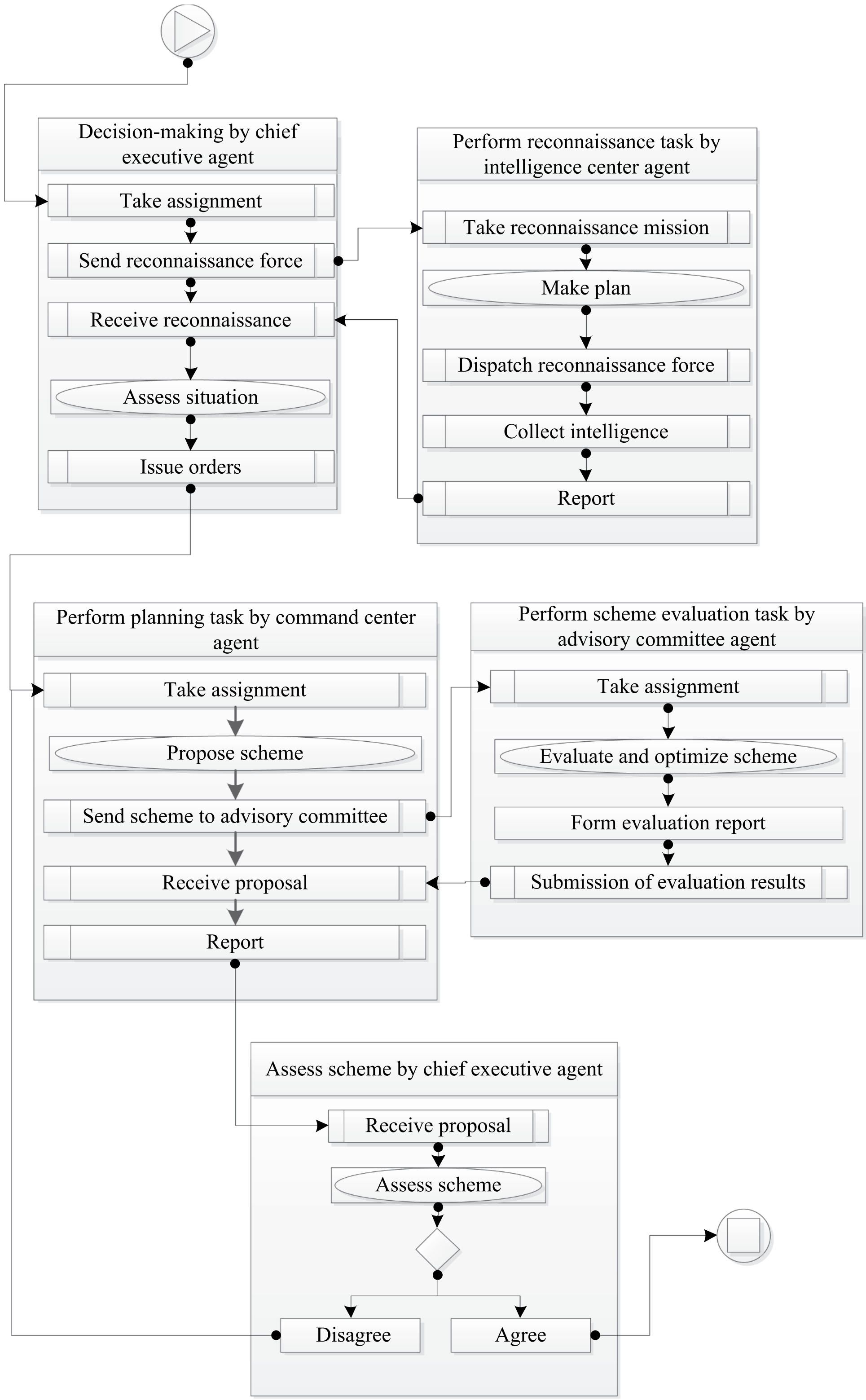


Fig. 5. Example of a multi-agent action diagram.

Table 6
Transformation from single-agent action diagram to agent model template.

No.	Elements of single-agent action diagram	Internal module transformed into agent model template
1	Division of an action	State list of state base
2	Single action	THEN expression in knowledge base
3	Entity state	IF expression in knowledge base
4	Concurrent actions	AND expression in knowledge base
5	Branch	OR expression in knowledge base

Table 7
Transformation from multi-agent action diagram to agent model template.

No.	Elements of multi-agent action diagrams	Internal module transformed into Agent entity module
1 ~ 5	Same as those in Table 6	Same as those in Table 6
6	Interaction of agents	IF-THEN expression in knowledge base
7	Division of action stages	State list of state base

CreateThread(function*), and the parallel action function to be executed is taken as a function parameter, as well as each state transition is mapped to a statement of "If … Then ….". The "Single action" elements are transformed into specific functions, and placed as function bodies in the statements of "Branch", "Concurrent actions" and state transition. Moreover, the "Action procedure" elements are transformed into the public function Function(action*) with the function pointer converted by the "Single action" as variable. Finally, the single-agent action diagram expressed by computer language is stored in the knowledge base of agent entity template for intelligent reasoning of the agent.

Module (V) is used to transform a multi-agent action diagram to corresponding simulation model. The elements identical to those in single-agent action diagram are transformed based on the same transforming method. The "Interaction between agents" element is converted into the public function Function(action*, agent*) with the function pointer converted by the "Single action" and the agent object pointer as variables. The "Division of action stages" element is used as the parent state of the "Entity state" element, and transformed into a StateGroup object. Meanwhile, the StateList attribute of the StateGroup object is established, the "Entity state" element is added to the StateList, and a StateGroup object in the state list in the state base of the agent entity template is created. Subsequently, multi-agent action diagram expressed by computer language is stored in the knowledge base of the agent entity template for multi-agent interaction and intelligent reasoning.

(VI) ~ (VIII) represent modules of Simulation model generation, Simulation implementation and Statistical analysis of simulation results, with the functions of generating executable simulation program code automatically, implementing simulation experiment and performing statistical analysis, respectively.

We compile the codes generated by this modeling tool in the development environment of Microsoft Visual Studio 2010, then generate dynamic link libraries, such as EMSGroupStruct.dll and EMSGroupStructAdmin.dll, which are embedded into "Simulation system for emergency management of great traffic accident" and "Simulation system for emergency management of chemical plant explosion" developed earlier. Thus, according to the scenarios, we can use the existing functions of these systems, such as situation display, basic physical model of vehicles and statistical analysis of simulation results, to perform simulation demonstration. The following two specific case studies are respectively presented.

5.1.2. Basic behaviors modeling and simulation implementation

In this section, we provide a further description on construction and implementation of basic behavior models of agents. In fact, AAD approach has the ability of multi-level and multi-resolution action modeling. Agent entity organization diagram can be used to describe entities that constitute the system and the organizational relationships among them, while agent entity action attribute diagram is used to describe the action capabilities of each agent. These action capabilities can be viewed as basic behavior models, which can be either indivisible meta-actions, such as "move forward" and "step backward", or action processes that can be further decomposed into meta-actions, such as "path planning" and "vehicle following". Thus, a basic behavior model can also be mapped to a single-agent action diagram, as shown in Fig. 8. Here, four basic emergency management behavior models of agents are used as examples to illustrate the principle of this method. Of course, as the connection of single-agent action diagrams, multi-agent action diagram can be used to describe combined actions. Therefore, AADs model has the ability for modeling not only the intelligent logical behaviors but also the interaction relationships of agent entities in EMS.

(1) Path planning model. The path planning model, illustrated in Fig. 9(a), starts with accepting a maneuvering task, and choosing a path planning strategy. If the shortest path strategy is to be chosen, Dijkstra's algorithm is used to calculate the path planning according to the starting point and the end point. If the shortest time strategy is to be chosen, the real-time information of road condition is obtained firstly, and the weighted sections are given according to the road condition. Then the weighted road network data are planned using Dijkstra's algorithm. After the path planning is completed, a maneuvering route is selected. In the process of maneuvering, some meta-actions, including getting real-time road condition information, maneuvering, and accepting

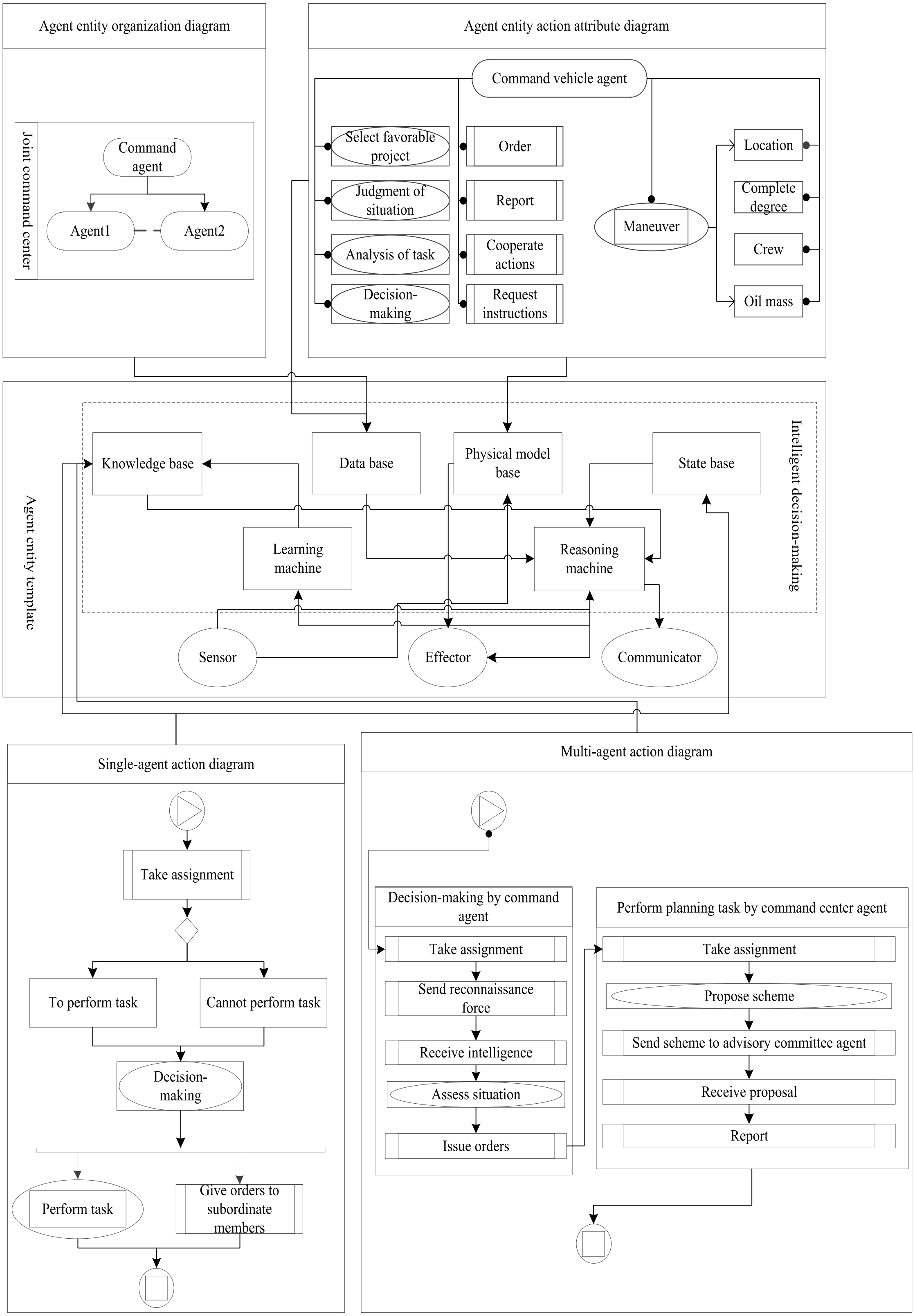


Fig. 6. Automatic mapping mechanism from AADs to agent entity template.

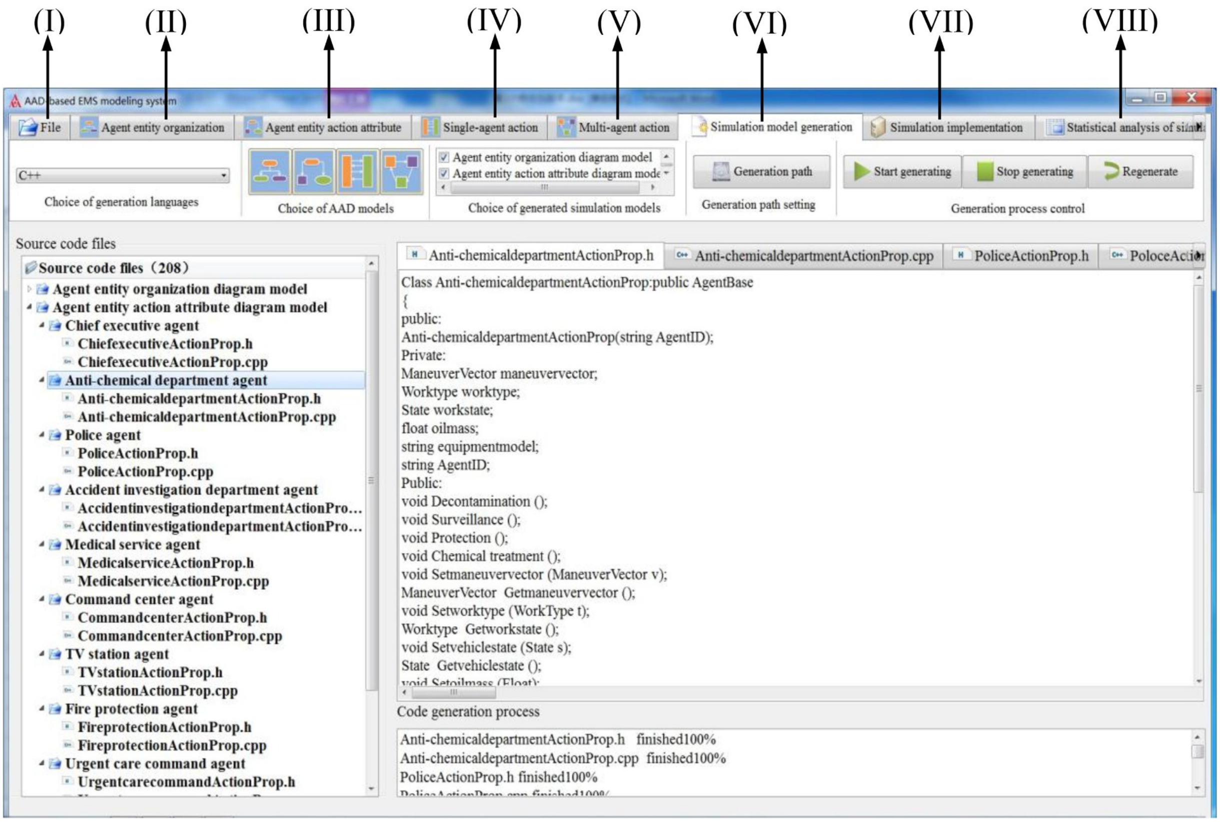


Fig. 7. Modeling tool for AADs.

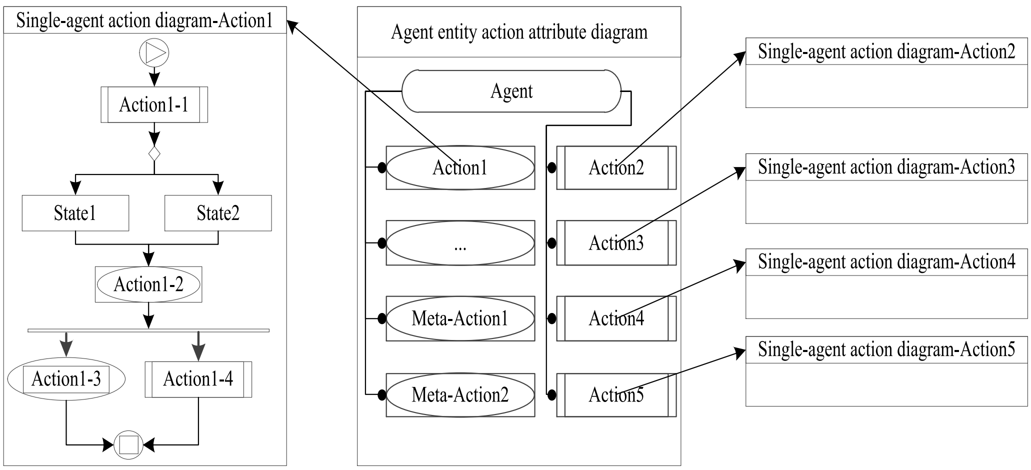
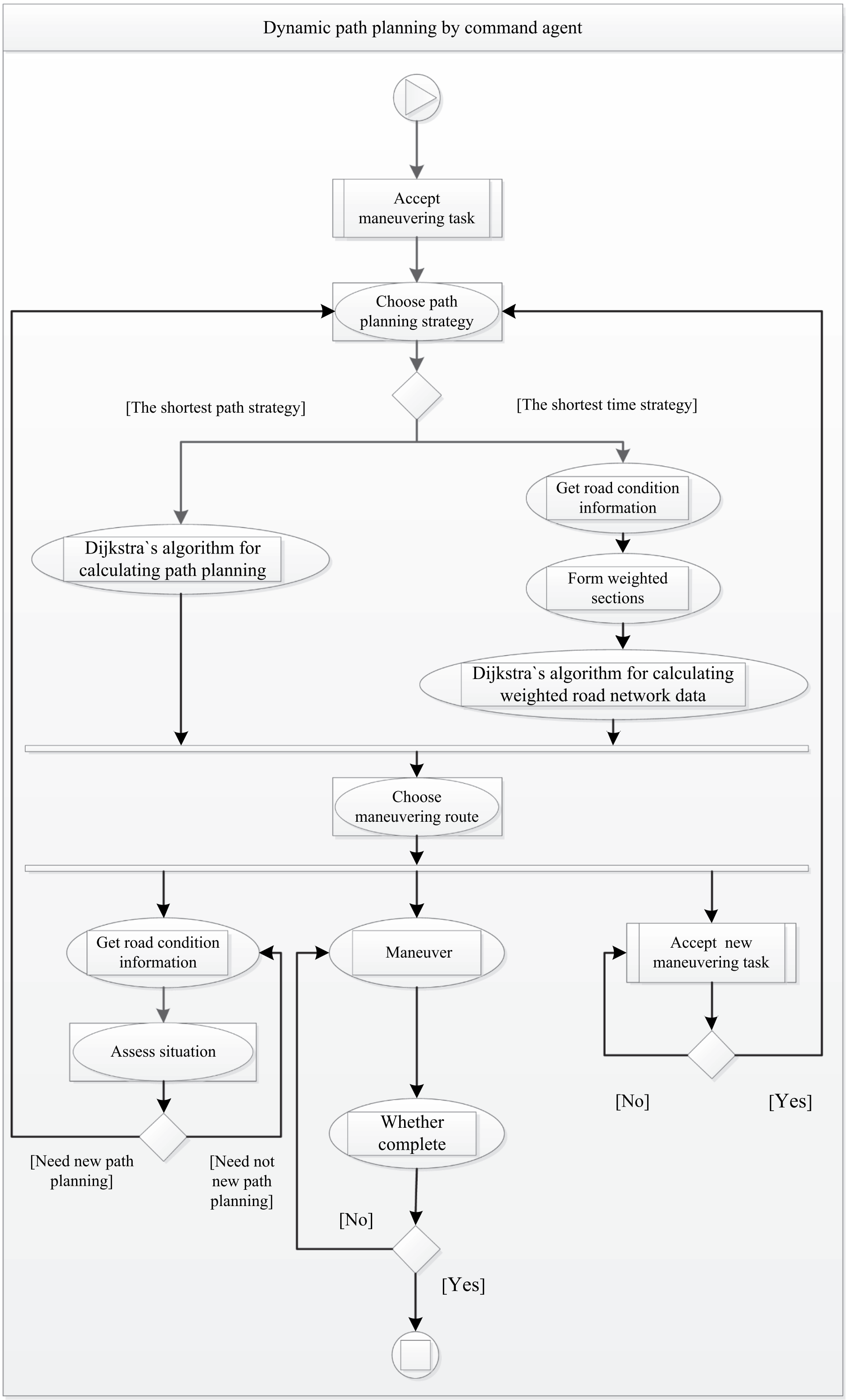


Fig. 8. Mapping process from basic behavior models to single-agent action diagrams.

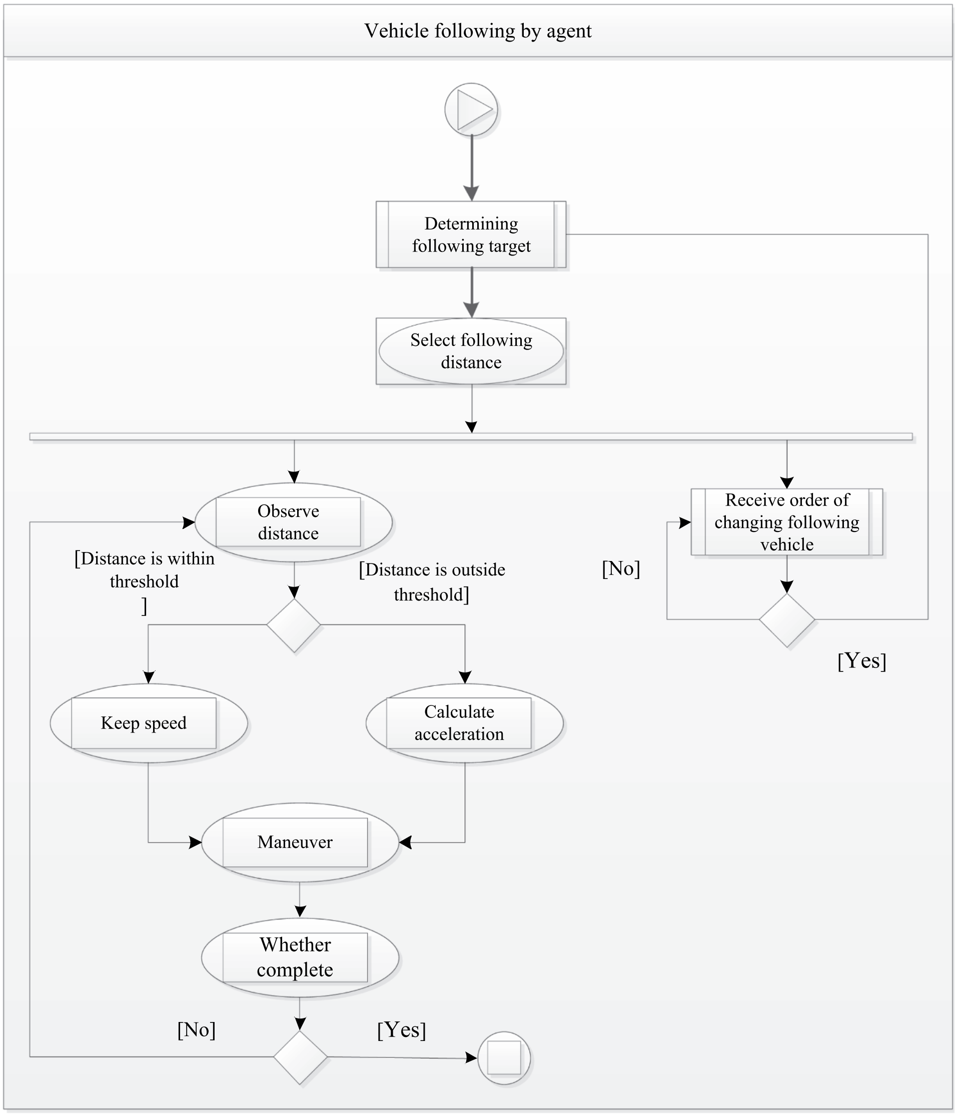
a new maneuvering task, are carried out in parallel. After obtaining road condition information, assess the situation. If the road condition changes greatly with the initial path planning, or a new maneuvering task is accepted, the path planning will be carried out again. If there is no new order or road condition change, continue to maneuver, and determine whether to reach the end point.

(2) Vehicle following model. The vehicle following model, illustrated in Fig. 9(b), starts with determining a following target. First, the following distance is selected and the meta-action is carried out on the basis of determining the following vehicle and the following distance. This process needs continuous observation on the distance. When the distance change does not exceed threshold, keep the speed, continue to maneuver, and check whether the maneuvering task is accomplished. When the distance change goes beyond threshold, the acceleration of the vehicle is calculated according to the distance, the speed and acceleration



(a)

Fig. 9. Representative basic behavior models of agents, including path planning model (a), vehicle following model (b), emergency evacuation plan model (c) and intelligent learning model (d).

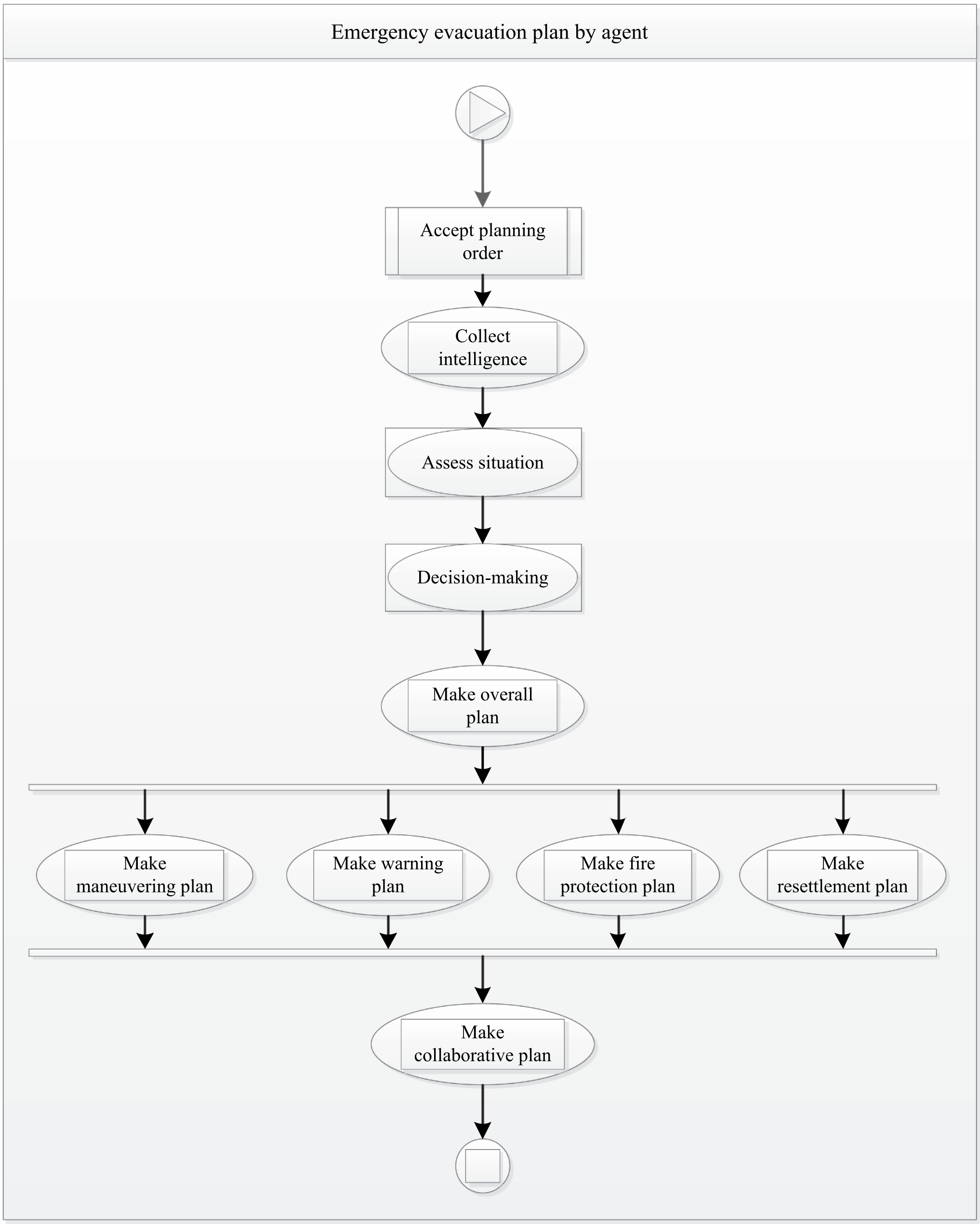


(b)

Fig. 9. (*continued*)

of the front vehicle. Of course, in the process of maneuvering, the maneuvering orders are continuously received. If an order of changing the following vehicle is received, the following target needs to be changed.

(3) Emergency evacuation plan model. The emergency evacuation plan model, illustrated in Fig. 9(c), begins with receipt of a planning order. First, relevant intelligence is collected, then dangerous situation is judged. Based on the evaluation, the decision on emergency evacuation is made, and the overall emergency evacuation plan is formulated. Subsequently, evacuation plans on maneuvering, warning, fire protection and resettlement are drawn up. After the above branch plans are completed, the collaborative plan is worked out.
(4) Intelligent learning model. The intelligent learning model, illustrated in Fig. 9(d), uses reinforcement learning. First, system state data is read, and then state situation is judged. When the execution behavior needs to be selected, the behavior is selected according to the strategy. Thus, the action is executed. At the same time, the corresponding relationship between a state and a behavior is recorded. Then, the system state data is read again. When judging the status as task completion, the state-behavior relationship records are obtained, then the learning intensity parameters are selected, and the task reward values are calculated. Finally, the strategy-behavior weight coefficients are revised to complete reinforcement learning of a task.

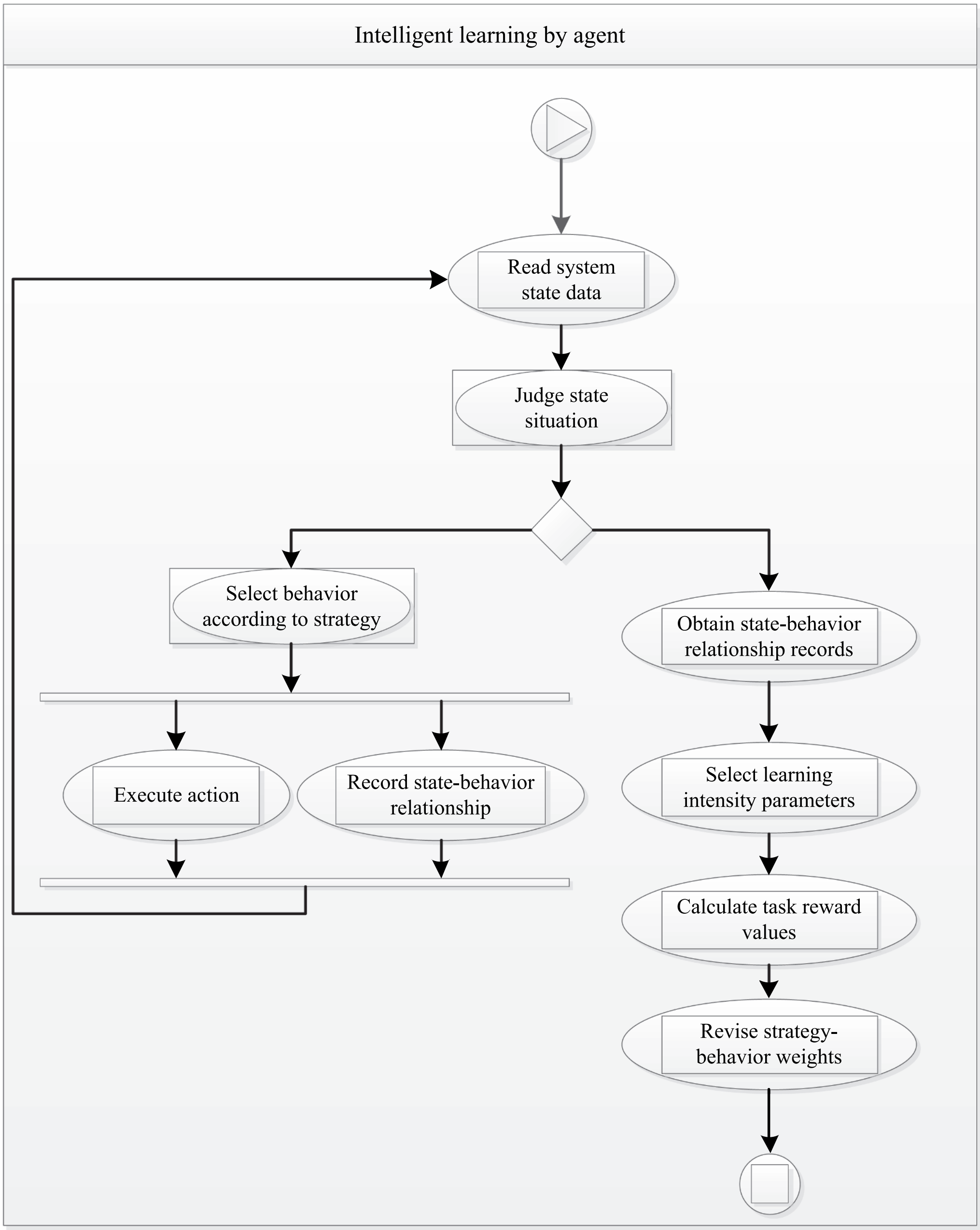


(c)

Fig. 9. (*continued*)

Note that fundamental traffic models are used to describe some basic behaviors, such as path planning, vehicle following and emergency evacuation. Some researchers have presented several traffic models that are useful to support travel decisions [64–68]. By drawing on the principles of these existing models, based on our previous practice in developing “Simulation system for emergency management of great traffic accident” and “Simulation system for emergency management of chemical plant explosion”, we give further details of some fundamental traffic models, shown in Appendix A.

Simulation implementation of a basic behavior model is essentially the process of transforming a single-agent action diagram to corresponding simulation model according to the transformation rules described in Module (IV). Here, we take the path planning model as an example to discuss the transformation process, as follows.



(d)

Fig. 9. (*continued*)

(1) The actions of dynamic path planning by a command agent, such as “accept maneuvering task”, “get road condition information”, “form weighted sections”, and “maneuver”, are transformed into corresponding execution functions.
(2) The branches, such as “the shortest path strategy” or “the shortest time strategy”, are transformed into switch statements, and corresponding execution functions are established for these branches.
(3) Three thread functions are created for the concurrent actions after meta-action “choose maneuvering route”. They are used for meta-actions “get road condition information”, “maneuver”, and “accept new maneuvering task”, respectively.

The pseudo-code of the path planning model generated after transformation is as follows.

```
void PathPlanning()
{
  void AcceptManeuveringTask();
  int PlanningStrategy = ChoosePathPlanningStrategy();
  path Pathvalue;
  switch(PlanningStrategy)
{
  case 0:
  Pathvalue = DijkstraAlgorithm(RoadConditionInformation);
  break;
  case 1:
    RoadConditionInformation = GetRoadConditionInformation();
    WeightedRoadNetworkData = FormWeightedSections(RoadConditionInformation);
    Pathvalue = DijkstraAlgorithm(WeightedRoadNetworkData);
  break;
}
  path = ChooseManeuveringRoute(Pathvalue);
  CreateThread1(fun1);
  CreateThread2(fun2);
  CreateThread3(fun3);
}
void fun1()
{
    while(true)
{
    RoadConditionInformation = GetRoadConditionInformation();
    situation = AssessSituation(RoadConditionInformation)
    switch(situation)
{
  case 0:
  continue();
  break;
  case 1:
      go to ChoosePathPlanningStrategy();
  break;
}
}
}
void fun2()
{
    while(true)
{
      Pos = Maneuver();
      switch(WhetherComplete(Pos))
{
    case 0:
    continue();
    break;
    case 1:
    go to end;
    break;
}
}
}
void fun3()
{
      while(true)
{
    Pos = Maneuver();
    switch(AcceptNewManeuveringTask())
    {
  case 0:
  continue();
  break;
  case 1:
  go to ChoosePathPlanningStrategy();
  break;
    }
  }
}
```

5.2. Case study 1: simulation for emergency management of a great traffic accident

5.2.1. Case scenario

A great traffic accident has the characteristics of complexity and suddenness with serious traffic jam and major casualty events. Timely and flexible emergency management actions play important role in processing crisis. When a great traffic accident occurs, the decision maker of EMS has to face a choice in a short period of time: take action centered on situation or centered on plan? The former is an emergency management action mode to make decisions and perform tasks based on the development of situation awareness, which means dynamic planning and acting, i.e., managing multiple goals and determining activities required to satisfy the active goals. Compared with the former, the latter is a more traditional and simpler action mode, which only requires planning and acting in light of the prior plan. In order to evaluate the effectiveness of the two schemes, the decision maker may use simulation experiment.

Here, we apply AAD-based modeling for EMS of great traffic accident. Based on statistics and analysis of collected manoeuvre data from the civil-military integration system, we can set scenario as following: due to sudden heavy fog, there's a great traffic accident of 16 vehicles close to Dujiakan toll station of Beijing-Hong Kong-Macao Highway to Beijing, which caused 5 deaths and 21 injuries of different degrees. After receiving the report, the government set up an emergency management headquarter for public crisis. This emergency management headquarter was composed of chief executive, regional administration office, public security, fire protection, publicity, sanitation and traffic department. The public security, fire protection, hospital and emergency center obey unified command, while TV station, highway management company, telecommunication enterprises, internet enterprises and insurance company were coordinated positively for disposition.

The evacuation and casualty treatment plan can be described as following. After the accident, people stayed at the scene of the accident would be evacuated to Changxindian Trade Union service station. The specific route would be from the exit of Dujiakan toll station to Dujiakanan Road. Casualties in the accident would be treated urgently on the spot and divided into light casualties and heavy casualties. Light casualties would be sent to Changcheng Hospital on Dujiakanxi Road for treatment, while serious casualties would be rushed to Changxindian Hospital by ambulance along Jingzhou Road for rescue. In the process of maneuvering, the police cars would be used to afford traffic control.

We further specify the simulation conditions in this case scenario. Terrain environment: a suburban plain with a highway and its toll station. Simulation platform: "Simulation system for emergency management of great traffic accident" that has been developed earlier by the authors of this paper. Model granularity: single vehicle (platform) that means platform-level simulation [46]. Simulation end condition: the traffic accident has been controlled in time, as well as traffic has been restored and unblocked.

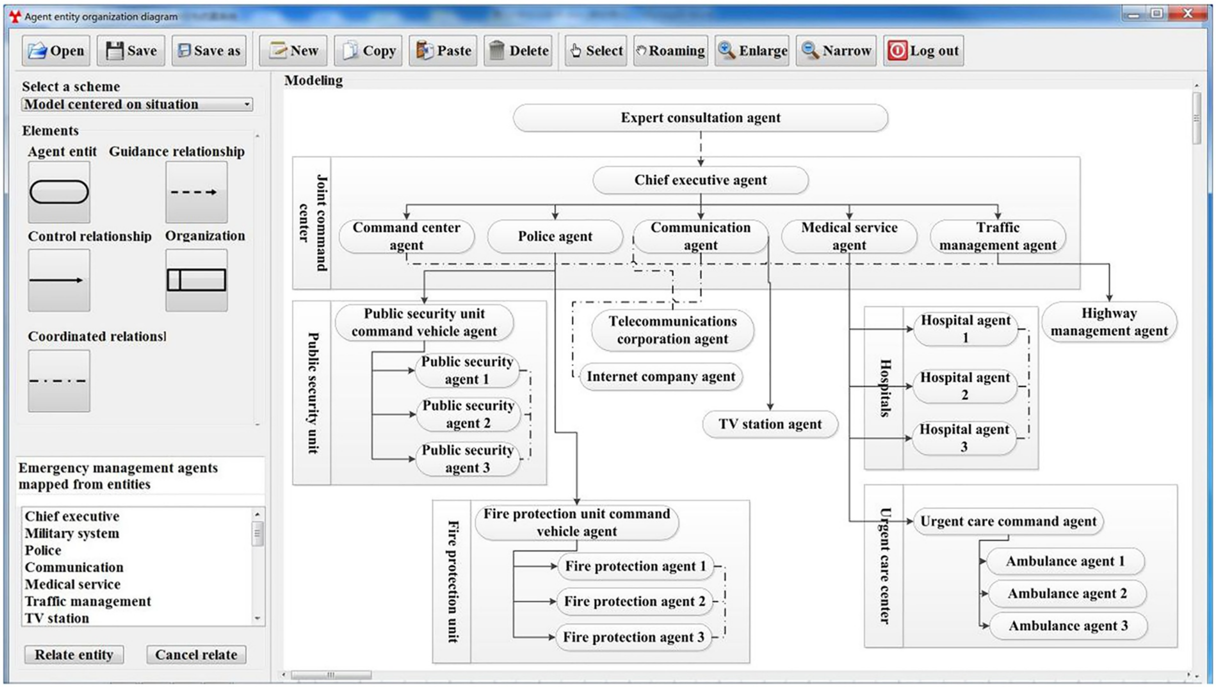
5.2.2. Design and operation of simulation system

Main functions of modules in the AAD model for public crisis emergency management are to present multi-perspective and multi-view visualization representations for EMS through human-computer interaction. Besides, the simulation model is generated automatically by agent model template.

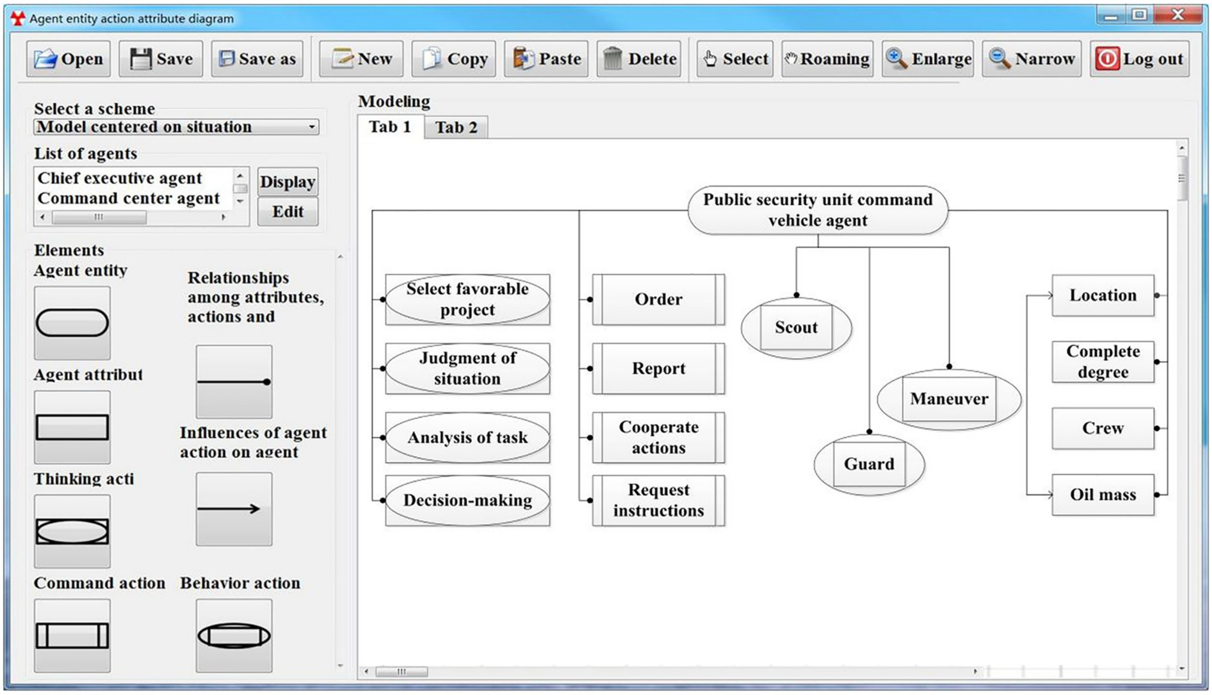
In the designed simulation system of EMS, two new schemes of "AAD model of action centered on situation" and "AAD model of action centered on plan" can be constructed. Depending on this simulation system, agent entity organization diagram, agent entity action attribute diagram, single-agent action diagram and multi-agent action diagram can be constructed by using graphical elements. They are shown in Fig. 10(a), Fig. 10(b), Fig. 10(c) and Fig. 10(d) respectively. Note that the constructed agent entity organization diagrams in the two schemes are same, since the organizations of EMS in defferent schemes are same. The same is ture of the agent entity action attribute diagrams. Since action centered on situation and action centered on plan are different in state transition driven mode and interaction strategy of agent entities, single-agent action diagrams in the two schemes are different. Because of the same reason, multi-agent action diagrams in the two schemes are also different. Here, we only show the constructed single-agent action diagram and multi-agent action diagram in the scheme of "AAD model of action centered on situation", since action centered on plan is coordinated only by the prior plan, and is simpler than that centered on situation. Of course, the principles of constructing these two kinds of models for different schemes are consistent.

The simulation starts through Simulation implementation module. The implementation process can be checked by the situation map as illustrated in Fig. 11. Fig. 11 presents the dynamic and real-time situation information during emergency management simulation based on AAD. According to scenario setting, the entities (vehicles) in this real EMS enter the area of Dujiakan toll station of Beijing-Hong Kong-Macao Highway, and participate in dealing with related emergency management affairs. In this simulation, the entities (vehicles) have been mapped into respective agents. The conceptual model of AADs has been transformed into computer simulation execution code. By implementing the simulation, one observes multi-agent interaction behaviors and can analyze the organizational behaviors of EMS. By this system, one can find out easily a certain emergency management agent entity's real-time state information, which gives an approach to explore the running mechanism of EMS.

Note that the basic actions of agent entities in the system, such as path planning, scout, situation assessment and report, have been implemented as meta-actions in the simulation platform "Simulation system for emergency management of great traffic accident". In the agent entity action attribute diagram, these meta-actions are combined, and the capabilities required to achieve these meta-actions are given to the corresponding agent entities. According to the system organization formed by the agent entity organization diagram, the single-agent action diagram and multi-agent action diagram call these combined meta-actions to perform corresponding emergency management tasks. In other words, our approach is mainly used to describe the intelligent logical behaviors and interaction relationships for agent entities in EMS by AADs. Specifically, by AAD-based modeling, simulation behavior model codes are generated and compiled as the dynamic link libraries used in the simulation platform. These dynamic link libraries are used as

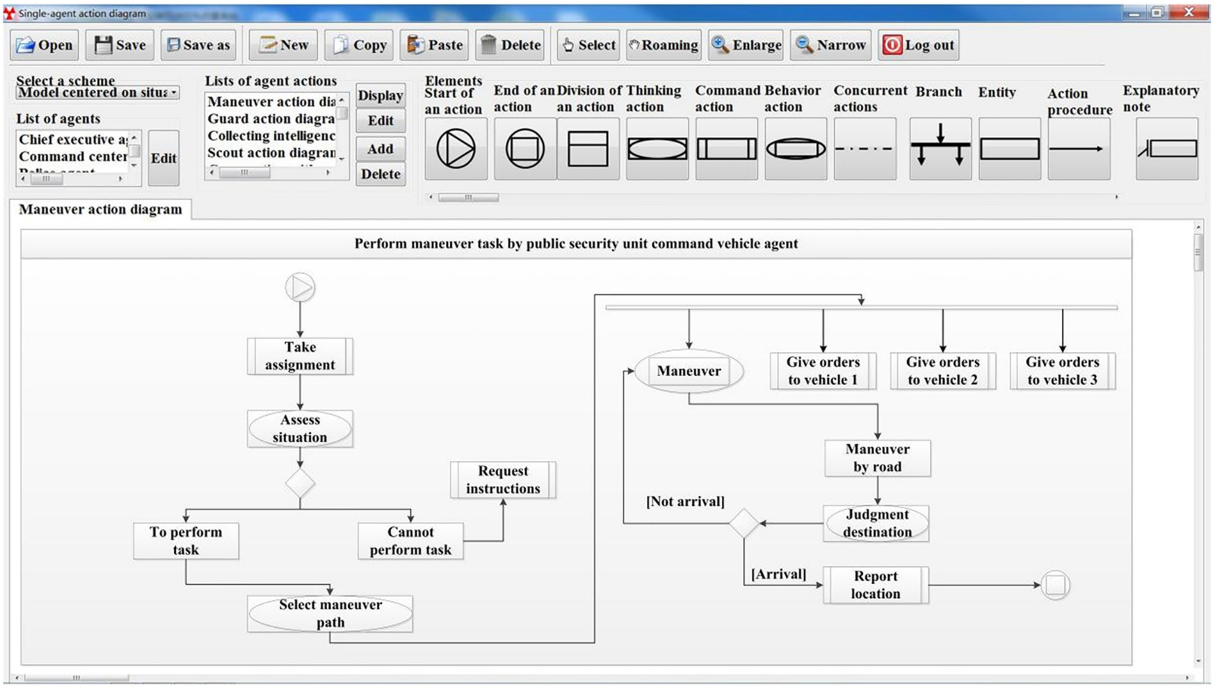


(a)

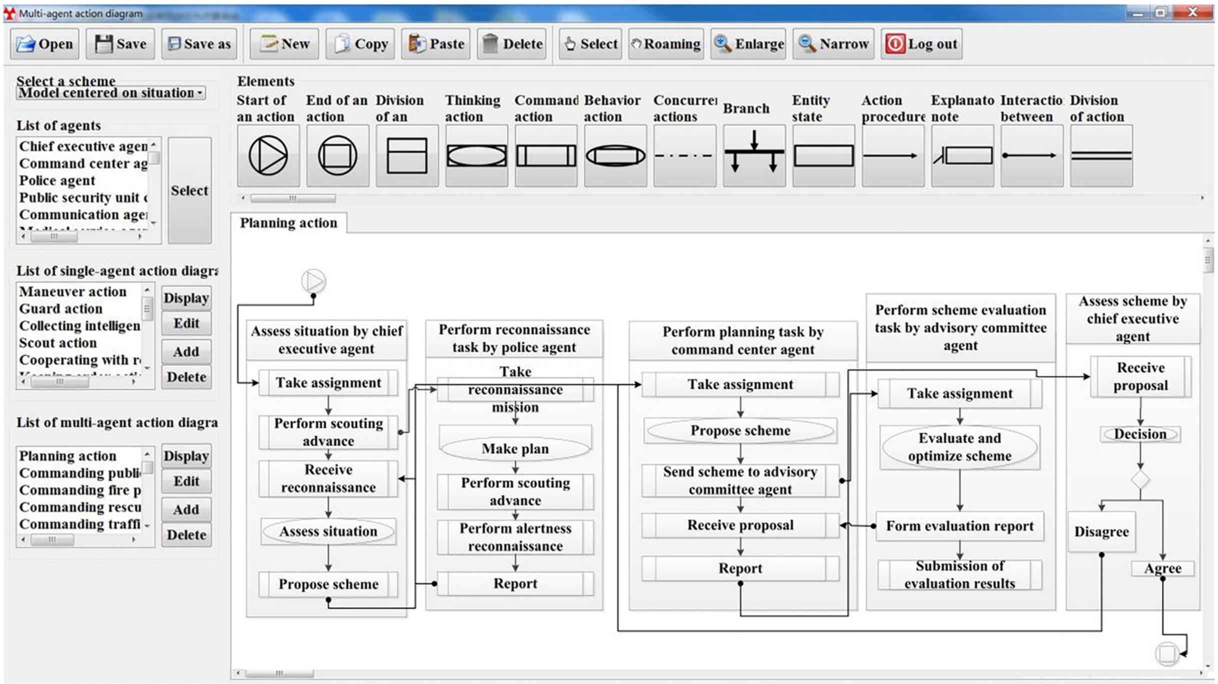


(b)

Fig. 10. Interfaces of constructing AADs including agent entity organization diagram (a), agent entity action attribute diagram (b), single-agent action diagram(c) and multi-agent action diagram (d).



(c)



(d)

Fig. 10. (*continued*)

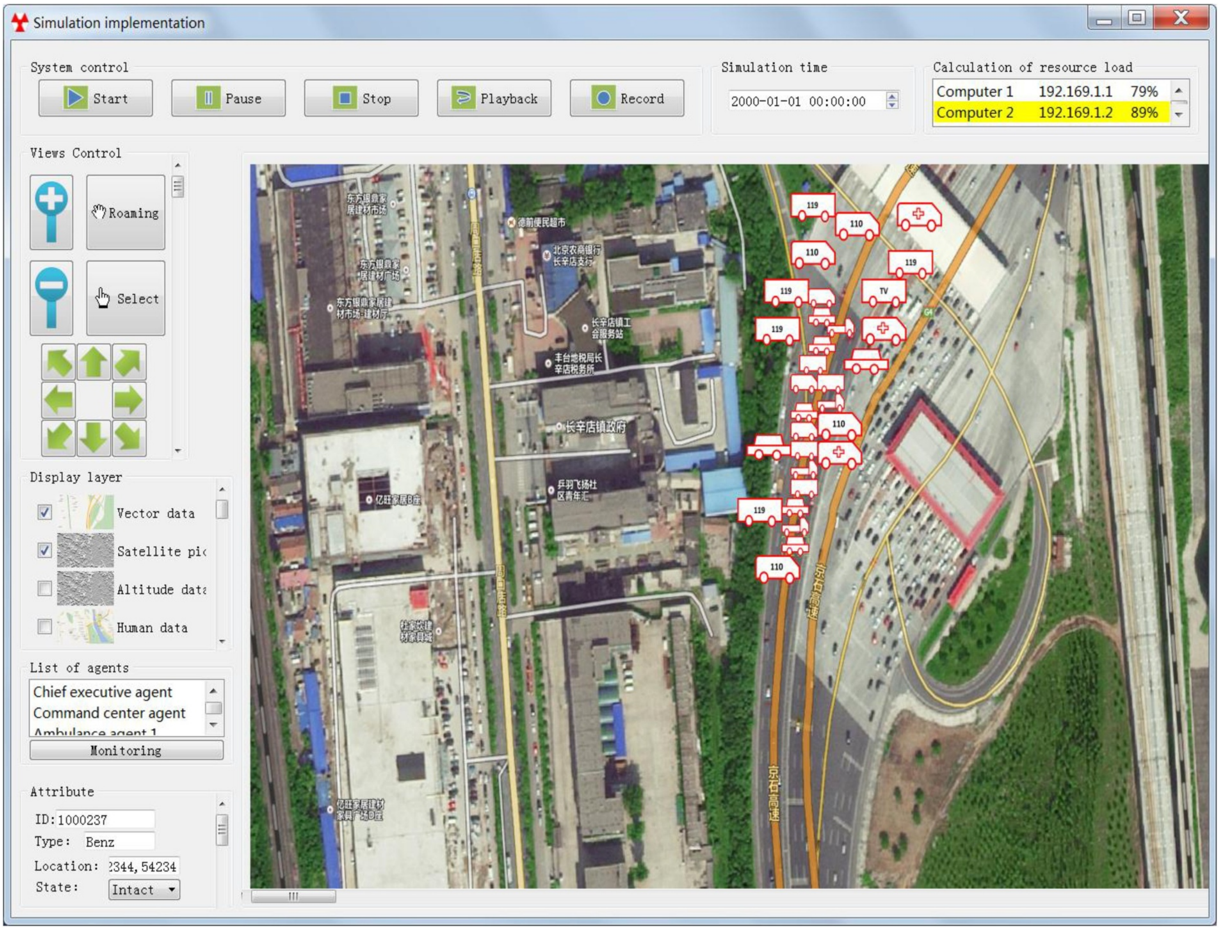


Fig. 11. Simulation implementation.

behavior models and put into behavior libraries of the simulation platform. Thus, the agent entities are driven to execute meta-actions, e.g., path planning, to realize emergency management simulation.

5.2.3. Simulation results

According to scienario setting of public crisis, two schemes of "AAD model of action centered on situation" and "AAD model of action centered on plan" are simulated. The comprehensive statistical data of simulation results after 100 simultaions are shown in Fig. 12.

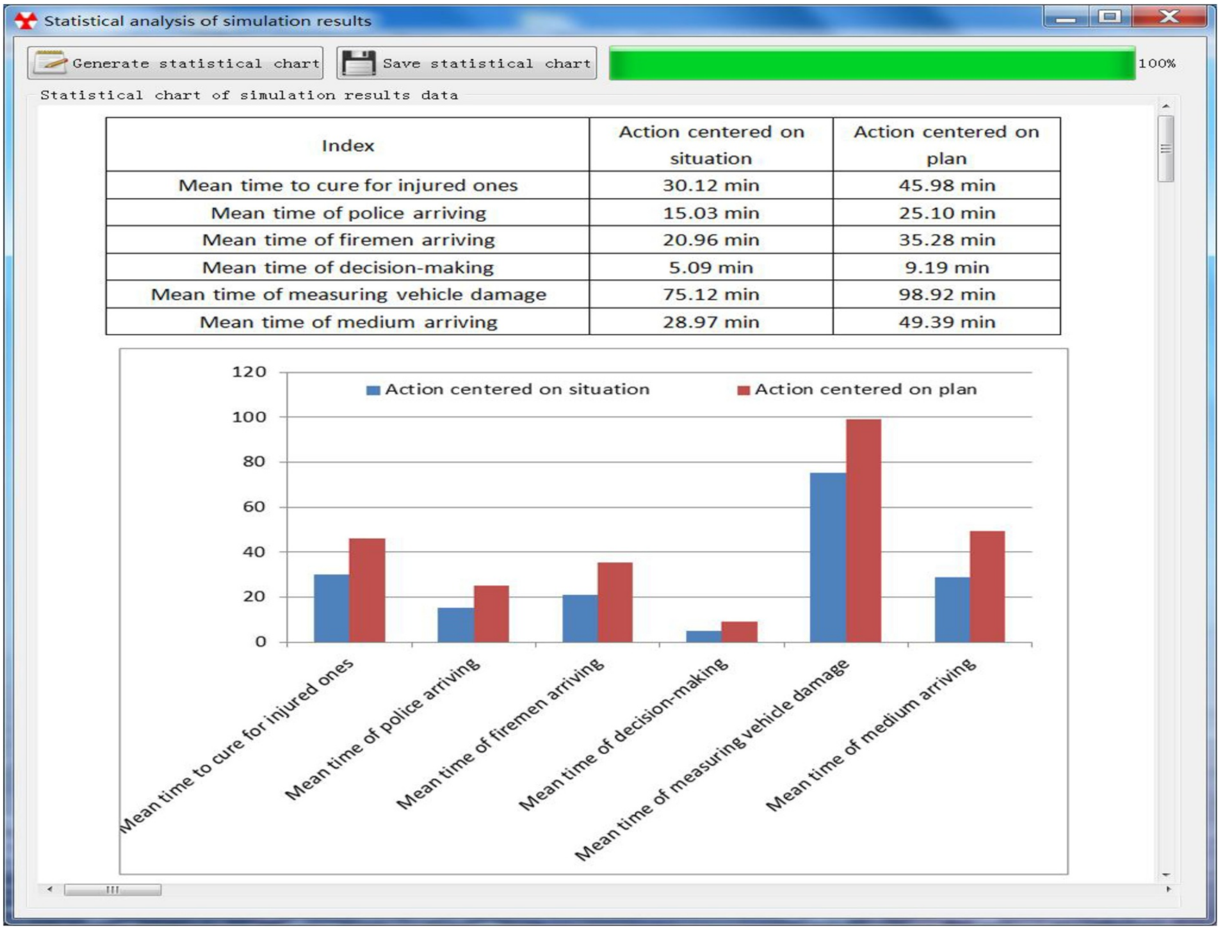
Based on the simulation results, the synchronous action mode centered on situation is superior to the action mode centered on plan in term of timeliness of actions of agents in EMS. By playback of these simulation processes, this is mainly attributed to higher flexibility, higher initiative, quicker response and more timely processing of synchronous action mode centered on situation upon emergency conditions. These results disclose the operation mechanism of EMS to some extent.

5.3. Case study 2: simulation for emergency management of an explosion of a chemical plant

5.3.1. Case scenario

Chemical plant explosion is a serious crisis event because it causes inevitably many poisoned injuries and deaths, significant financial loss, and wide-range environmental pollution. Only by adopting timly and effective emergency management measures can we reduce the loss of life and property. The treatment of a chemical plant explosion accident is especially inseparable from the anti-chemical department. In order to evaluate the role of this department in EMS, we perform AAD-based simulation experiment.

In this case study, we set scenario by collected historical real-world data from reported news: because of leakage of combustible material in oil tank farm of Beijing DF chemical plant, the rapid diffusion of combustible gases formed by a combustible material. A burning explosion occurred in a fire source, causing leak of a large number of combustible and toxic chemicals such as naphtha and ethylene. 9 people died and 39 were injured in the accident. After receiving the report, the Beijing municipal government set up a public crisis emergency management headquarters in the seat of the government of Tongzhou District. It was composed of chief executive, municipal government office, public security, fire prevention, health, publicity, accident investigation and anti-chemical



Index	Action centered on situation	Action centered on plan
Mean time to cure for injured ones	30.12 min	45.98 min
Mean time of police arriving	15.03 min	25.10 min
Mean time of firemen arriving	20.96 min	35.28 min
Mean time of decision-making	5.09 min	9.19 min
Mean time of measuring vehicle damage	75.12 min	98.92 min
Mean time of medium arriving	28.97 min	49.39 min

Fig. 12. Statistical analysis of simulation results.

department, to conduct unified command of public security, fire protection, hospitals and emergency centers. Joint crisis disposal of EMS also included works in coordinating TV stations, telecommunication enterprises, internet enterprises, insurance companies and other units. Emergency management activities consisted of: (1) rescue of the injured persons; (2) martial law blockade and evacuation of people at the scene of the accident; (3) assessment and analysis of environmental pollution and toxic and harmful substances, as well as further effective measures; (4) control of the relevant individual responsible for the liability for accidents; (5) social notification of progress in accident management through the media; (6) coordination with insurance companies on settlement of claims for the plant and personnel; and (7) investigation on accident cause.

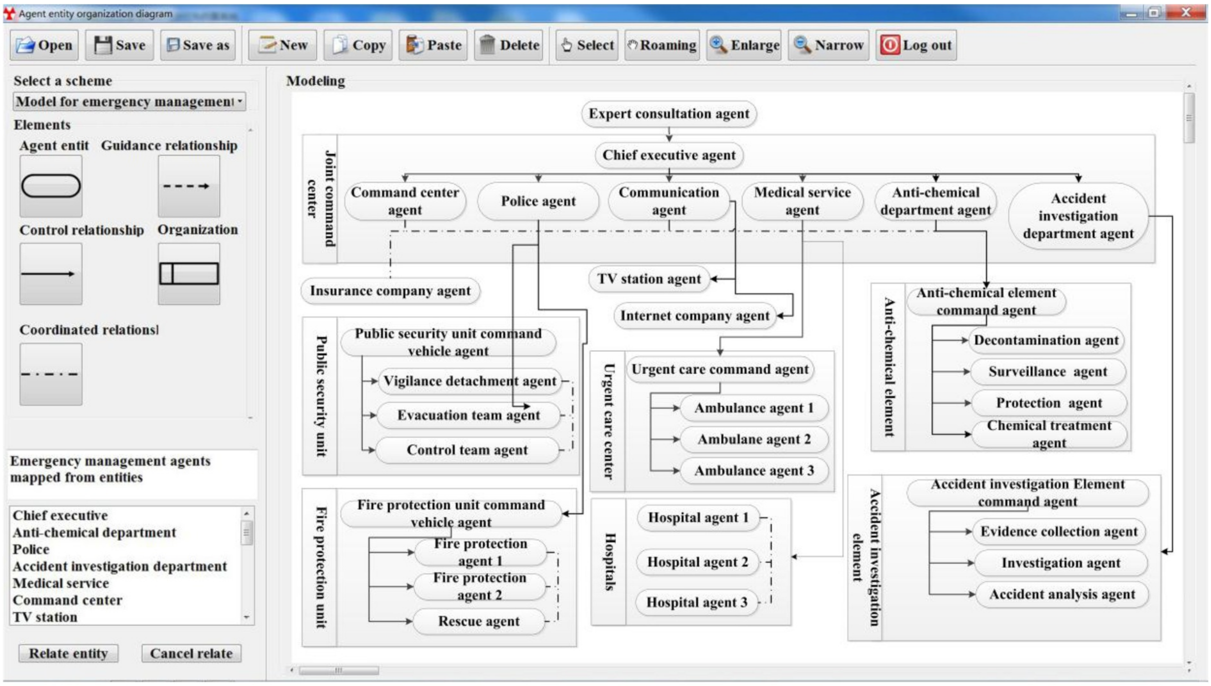
The evacuation and casualty treatment plan can be described as following. After the explosion, more than 2500 residents in the vicinity of DF chemical plant would be evacuated in batches from residential areas to Nanguan School, and temporary settlements would be set up in the school. People injured in the explosion would be transferred by ambulance to Luhe Hospital along the main road for emergency treatment. Other specialized hospitals would send experts for consultation.

The simulation conditions can be further specified. Terrain environment: an urban residential land with many roads and buildings. Simulation platform: "Simulation system for emergency management of chemical plant explosion" developed by us. Model granularity: single vehicle (platform). Simulation end condition: the explosion accident and diffusion of toxic substances have been controlled.

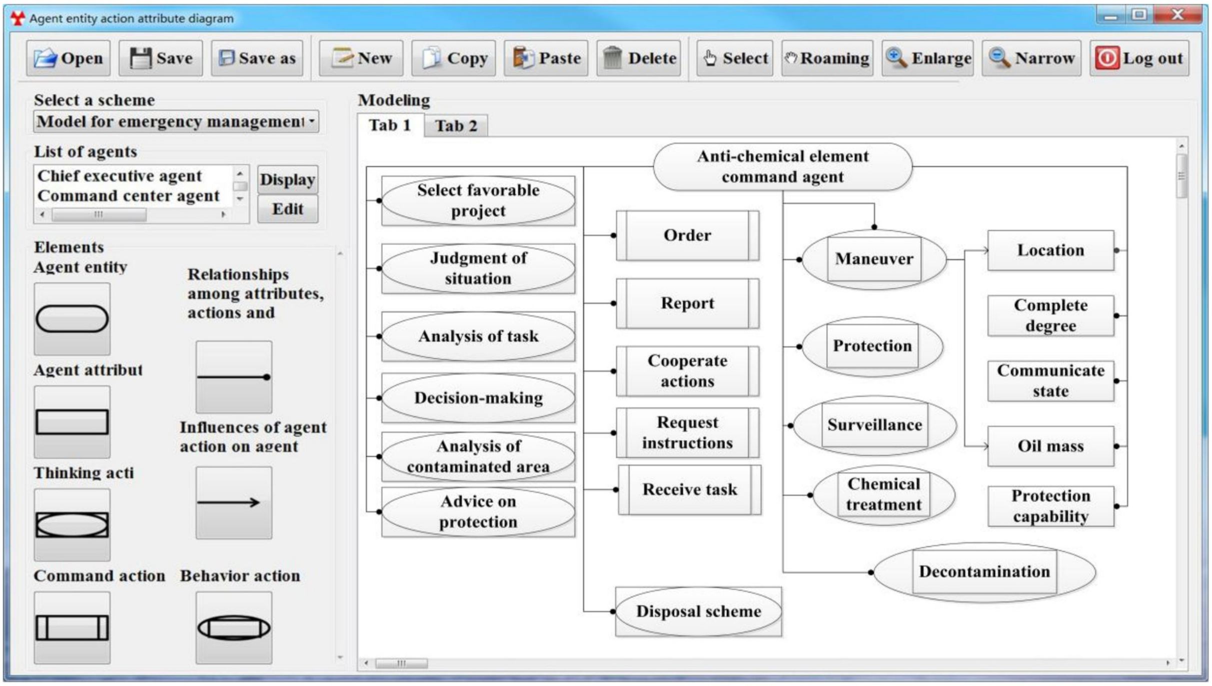
5.3.2. Design and operation of simulation system

Similarly, we construct the AAD-based conceptual model for EMS of chemical plant explosion, by the proposed multi-view modeling paradigm, as shown in Fig. 13.

AAD-based simulation implementation for EMS of chemical plant explosion is shown in Fig. 14. In this simulation system, we can observe dynamic and real-time actions of the agents mapped from the entities (vehicles) in EMS. In vicinity of the explosion site, different emergency management tasks such as guard, command, rescue and accident investigation are performed by these agents. Of course, anti-chemical element can be put into use, which affords some salvation measures including anti-chemical surveillance, decontamination, protection and chemical treatment. Thus, we can investigate the effect of anti-chemical department more specifically.

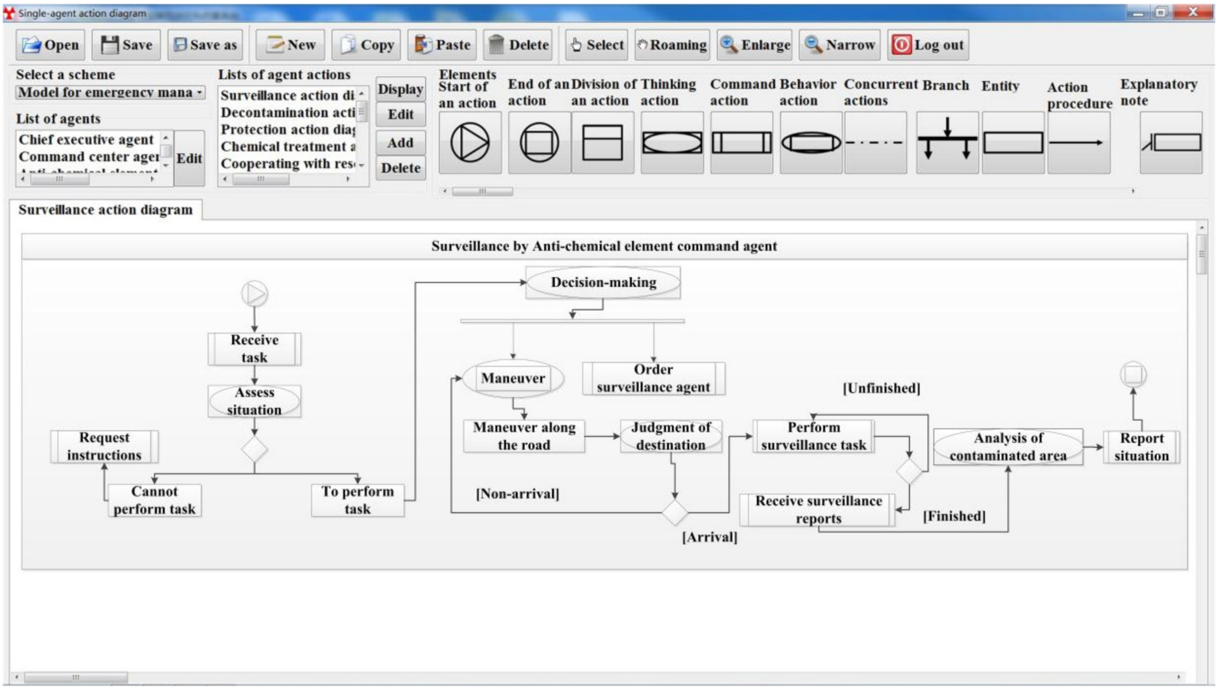


(a)



(b)

Fig. 13. Interfaces of constructing AADs including agent entity organization diagram (a), agent entity action attribute diagram (b), single-agent action diagram(c) and multi-agent action diagram (d).



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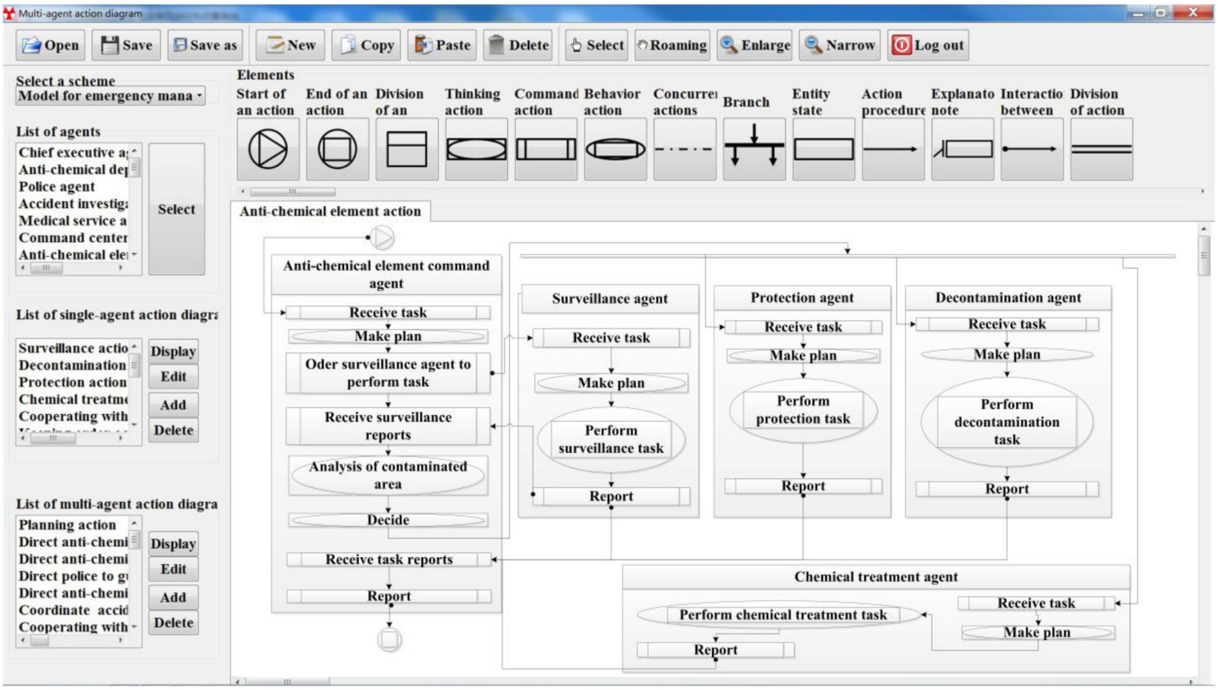


(d)

Fig. 13. (*continued*)

5.3.3. Simulation results

Similarly, we illustrate the comprehensive statistical data derived from 100 times simultaion results, as in Fig. 15. From Fig. 15, we can see that the efficiency of emergency management by cooperation with anti-chemical department is higher. This fully indicates the importance of anti-chemical department in emergency management of chemical plant explosion. In orther words, if we add anti-chemical department to EMS in time and coordinate the operation of different emergency management entities, human casualties,

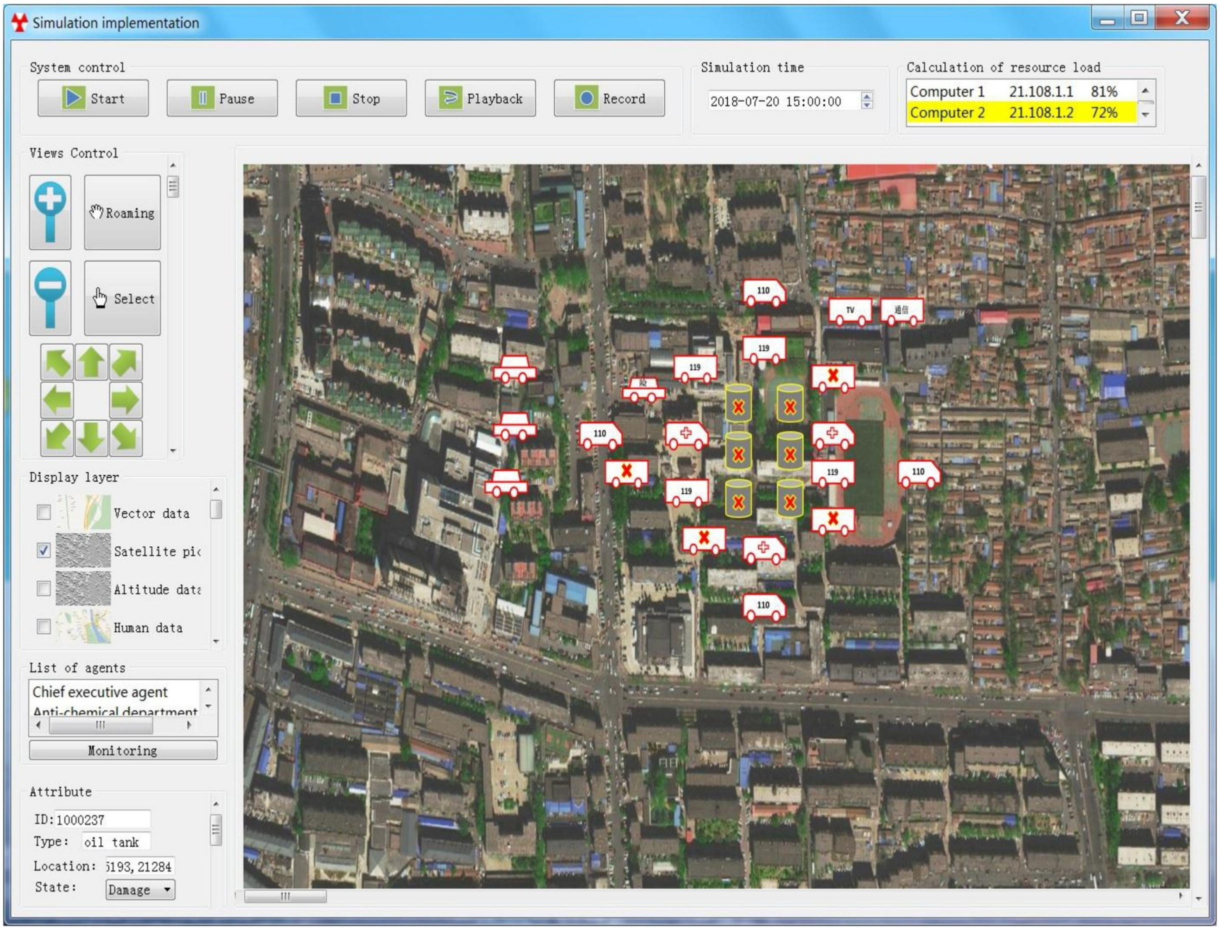


Fig. 14. Simulation implementation.

financial loss and toxic substances can be controlled more effectively.

6. Discussions

6.1. VV&A

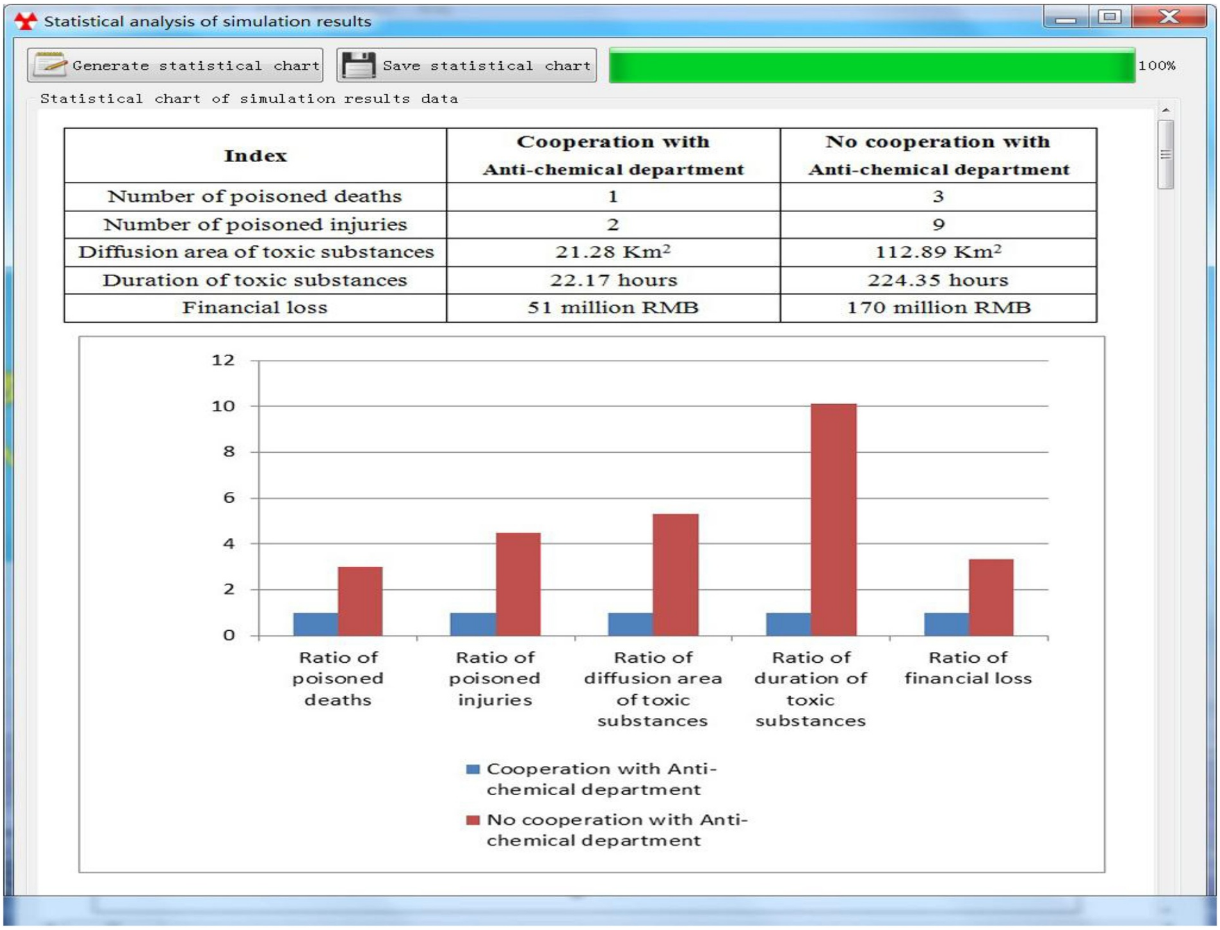
We carry through VV&A for the AAD-based simulation models to analyze these results. As for the conceptual models, we check whether attributes description and interactions, e.g., the entities and their behaviors are consistent with real emergency management situation. As for the program models, emphases are put in data to verify their correctness, dependability and performance [46].

By the evaluation, the simulation results basically coincide with actual emergency management data, indicating high credibility of the results. Moreover, the conceptual models of EMS described by AADs build a bridge between the real world EMS and the simulation system, thus emergency command personnel and software engineers can design the model and implement the simulation system with more convenience. The AAD models depict appropriately interactions of different elements in EMS, reflect reasonably not only the corresponding operation functions of agent entities but also the simulation results of multi-agent interaction running. This is a procedure of verifying each other. In a word, the simulation experiments prove validity of the method and results of AAD-based modeling.

6.2. Comparisons with similar approaches

6.2.1. Comparison with UML modeling form

In terms of modeling forms, as earlier described, UML is presently being recognized as a satisfactory medium to support ABM, mainly because it is an extensible language providing built-in mechanisms to introduce new elements for specific domains [28]. UML has gained popularity due to its multi-view support. In UML, the structural diagrams represent the static aspect of a software, whereas behavioral diagrams are used to represent the dynamic aspects of an under development software. The structural type contains class, object, deployment, component, composite structural, package, and profiling diagrams. In contrast, the behavioral type includes



Index	Cooperation with Anti-chemical department	No cooperation with Anti-chemical department
Number of poisoned deaths	1	3
Number of poisoned injuries	2	9
Diffusion area of toxic substances	21.28 Km^2	112.89 Km^2
Duration of toxic substances	22.17 hours	224.35 hours
Financial loss	51 million RMB	170 million RMB

Fig. 15. Statistical analysis of simulation results.

sequence, state chart, activity, use case, communication, timing, and interaction diagram [21].

In fact, the multi-view modeling form of UML has been absorbed in our approach. As structural diagrams, agent entity organization diagram and agent entity action attribute diagram represent the structure organization of EMS and the individual attributes of emergency management entities respectively. As behavioral diagrams, single-agent action diagram and multi-agent action diagram represent the behaviors of individuals and EMS respectively. Thus, by these four associated ADDs, we can present the specification, visualization and documentation requirements for EMS completely with different perspectives. Of course, one key characteristic of EMS is time sensitivity. For example, in a great traffic accident, an emergency management headquarter should take out the action plan as soon as possible based on simulation demonstration. For UML, its multi-view form contains a large amount of modeling work and thus leads more difficulty in EMS modeling. Therefore, it is to some extent difficult to meet the requirements of emergency modeling. In contrast with UML, our approach fits very well with a timely and complex problem of EMS by the four-diagram modeling process, i.e., it can provide higher efficiency and more convenience of modeling for EMS.

More impotantly, consistency problems arise due to multiple views and diagrams in UML and due to the iterative nature of the software system development [21]. Generally, the more views and diagrams, the more difficult it is to manage models consistency. Thus, by our approach, the tasks of analyzing and monitoring different views and diagrams will be smaller than ones for UML modeling. In addition, as Williams stressed, close collaboration between modeller and domain expert is required to ensure a solid foundation of the real-world system. Development of the domain model is an iterative process, where the various views of the system are refined until they meet the abstracted view of the real-world system for the purposes of the simulation project [56]. In AAD-based modeling for EMS, emergency command personnel can play a role of leader and dominate the whole process of modeling, since our approach presents an automatic mechanism of transforming the graphical conceptual model to its simulation model. This is also an advantage for preventing inconsistency between models.

Furthermore, in EMS modeling, UML is mainly used in conceptual modeling by its corresponding diagrams to describe the physical structure of EMS, agent's and multi-agent behaviors. There is a great requirement in a type of correct transformation, i.e., model-to-code. In other words, code needs to be generated automatically from the UML diagrams [21]. Note that our approach is an integrated process. From system analysis, conceptual modeling and simulation modeling to simulation experiment, construction of complete conceptual model and automatic generation of executable model are combined. Because of the designed agent model templete and the accordingly developped modeling tool for AADs, it makes the modeling process more automated and efficient.

6.2.2. Comparison with agent-based knowledge analysis framework

In terms of modeling methodology, Beydoun and Inan et al. have made important progress in disaster management modeling from knowledge analysis and knowledge management perspective [13, 32, 69–73]. For instance, Beydoun et al. presented a generic product metamodel for any MASs methodology. In this context, "product metamodel" is synonymous with "modelling language specification" [69]. Besides, Beydoun et al. introduced a relatively generic agent-oriented metamodel to support modeling language development [70], adopted a model-based security approach to identify security requirements during the early stages of MAS development [13], presented software engineering requirements for ontology-based development for MAS and examined an existing methodology for ontology-based MASs [71]. The development process of the metamodel aims at completeness and consistency of outcome, and extends a metamodeling process that was used in software engineering of complex systems [13, 69]. The process iteratively reconciles and validates individual concepts and their relations. The disaster management metamodel (DMM) therefore represents a complete picture of disaster management, but the level of rigour and detail is left for the users of DMM to apply. Thus, Inan and Beydoun et al. presented agent-based knowledge analysis framework in disaster management. They addressed the challenge of how to convert existing disaster management knowledge into layers of abstraction to enable a unified point of access, and advocated the use of a knowledge repository based on a common Meta Object Facility (MOF) modelling framework, the Object Management Group, and a DMM [32]. Although the above researches are only for disaster management, they are of great value to other fields in emergency management.

However, there are substantial differences between the agent-based knowledge analysis framework in disaster management and our approach in this paper.

(1) Different research goals. The work done by Inan and Beydoun contributes to development of a knowledge transfer analysis framework to unify access to DISPLANs through a unified repository [32, 72]. The aim of their work is to develop a systematic disaster management knowledge transfer process [32, 72, 73], while the goal of our approach is to propose AAD-based model for EMS to resolve the technology problem in preventing inconsistency between the simulation model established by technicians of computer simulation engineering and the conceptual model established by domain experts.
(2) Different research methodologies. The aforementioned analysis framework is developed following design science research methodology in information system [32, 72, 73]. In the development, agent-based models are used to code the DISPLANs to enable their transfer into a repository. The MOF metamodeling framework is then used to create a repository that is ready for storing the content of agent-based models [73]. Their work finally forms agent-based knowledge analysis framework in disaster management. In contrast, our approach applies the principle of model driven engineering in agent-based modeling, thus forming a normalized conceptual model driven architecture with AAD representations for EMS. Our work actually presents AAD-based modeling approach in emergency management.
(3) Different research procedures. The aforementioned analysis framework consists of three stages. Stage 1: The input is customized by seven agent-based models (i.e., goal models, role models, organizational models, interaction models, environmental models, agent models, and scenario models) that are tightly coupled with the MOF. This process results in the customized agent-based models of DISPLAN knowledge templates. Stage 2: The customized agent-based models from Stage 1 are used to analyze the DISPLAN template based on the specific local resources and circumstances. Stage 3: This is the knowledge transformation process. In this stage, the agent-based models of DISPLAN produced in the second stage are transferred to the annotated DMM-based repository [32, 72, 73]. In contrast, our approach first involves system analysis, follwed by conceptual modeling, simulation modeling and simulation experiment. By building agent entity organization diagram, agent entity action attribute diagram, single-agent action diagram and multi-agent action diagram, the conceptual model of EMS is constructed. Subsequently, by presenting agent model template and modeling tool for AADs, the AAD conceptual model is transformed to its simulation model and corresponding executable simulation program code automatically.
(4) Different representation forms. In the aforementioned analysis framework, a DISPLAN template describes the structure of every DISPLAN. It also has knowledge that is common to all plans. The template is in a semi-structured format [32, 72]. In this framework, the agent-based model template and the customized model of the DISPLAN knowledge template can be represented as a table form, which includes some structured elements, or be described as a form of diagram, which is similar to use case diagram in UML. For example, as for Role model, the structured elements in a table form include Role ID, Name, Description, Responsibilities and Constraints, while those in Agent model include Agent type, Name, Description, Activities and Environment considerations. In contrast, our approach provides graphical modeling description for EMS by establishing its rule symbol system and forming visualization representations of AADs. This representation form is completely different from the previous one.

6.3. Scope of application

It is impossible that one conceptual model is useful for all applications. Therefore, it is necessary to further define the scope of application of our approach. The definition will be helpful to make our approach be more specific with more availability.

On the one hand, our work focuses on the organizational level of EMS, in which platform-level entities (vehicles) are mapped into corresponding agents. When the number of entities needing to be modeled and simulated is quite large, we have to establish an aggregation mechanism for those entities that are less important and less concerned. Thus, the aggregated entiey agents can be used in AAD-based modeling. For example, after decision-making we think that evidence collection agent, investigation agent and accident analysis agent can be aggregated as an accident investigation element command agent, which is an aggregation-level agent in AAD model and acts as an accident investigation element.

On the other hand, our approach is conditional on its application to different domains in emergency management. Although it is a general EMS modeling process, and actually we have presented two case studies, which verify its feasibility and effectiveness, there is a condition in extending it to other EMS applications. In the above case studies, note that the codes generated automatically are respectively embedded into the systems developed earlier by us. In other words, some functions in a certain simulation system such as situation display and statistical analysis of simulation results should be implemented. Based on the work, our approach can be extended to this new model and be used to explore the running mechanism of this new EMS.

7. Conclusion and future work

The comprehensive analysis and understanding of complex intelligent system, e.g. EMS, is extremely difficult without the assistance of appropriate modeling. One kernel in constructing a model for EMS is a multi-layer, multi-dimensional, hypothetical, complete representation of the real world. For some time ABM paradigm has become increasingly important to be aware of the potential applications in computer simulation science. ABM, as a useful tool to explore complex intelligent systems, can be applied to describe real microcosmic action mode of EMS by representing agents interaction behaviors.

In this study, though improving the traditional ABM paradigm, we discuss the need and graphical modeling description for EMS demonstration by proposing a novel abstraction process of the real world EMS to an AAD-based visualization model, in which components and individual behavior can be expediently identified, documented and illustrated. Further, agent model template is constructed to present an automatic mechanism of transforming this visualization conceptual model to its simulation model. Validity of AAD-based EMS modeling results is verified by two case studies. The research results provide a new approach for developing models of emergency management simulation. Compared with the traditional ABM paradigm, our approach has some advantages: (1) constructing a multi-view conceptual model of EMS by proposing AAD modeling method, thus giving a visualization tool to describe the objectives, inputs, outputs, contents, assumptions and simplifications of the EMS model; (2) advancing the development process of the EMS model by introducing model driven engineering approach in AAD-based modeling, thus forming a means of providing consistent and coherent models at different abstraction levels; and (3) establishing agent model template by designing an automatic mapping mechanism from AADs to agent entity template, thus building a bridge to link the technique by increasing the abstraction level in simulation model specifications and the technique by automating the derivation of simulation code.

Our approach will be perfected in future researches. First, key attentions will be paid to display the nonlinear relationships of different agent entities in EMS more scientifically and accurately by AAD representations. Especially, representations of uncertainty and probabilistic characteristics because of human decision-making and action will be further deepened and expanded in the future. Current representation forms such as concurrent actions, branch and entity state will be extended to support more functions. Second, issue on environment modeling will be taken into account. In current version, this area mainly centers on relatively simple environmental settings such as road and building modeling. In the next revision, we are considering what to do in more complex environment modeling. Third, the computer simulation systems for EMS will be improved centering on function expansion in order to meet more requirements of public crisis analysis and decision-making, and to provide better service for demonstrating its applicability to complex and applied emergency management problems.

Acknowledgments

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Appendix A. Fundamental traffic models

A.1. Road network model and algorithm

The road network model is the basis of path planning. The road network representation consists of static and dynamic components. The static components represent the topology of the road network [64]. Since a road network can be expressed as a combination of two basic elements, node (V) and arc (E), the road network model is implemented with an Arc-Node model to represent the topological relationship of the actual road network. Its core idea is to replace an actual curve road with continuous small straight lines. We give the formal definition for the road network model as following:

$$R = (V, E), V = \{x|x \in N\},\ E = \{M\},\ M = \{\langle x, y\rangle|A(x, y). ..(x, y \in V)\}$$

where R is the road network, N is the node set of the road network, M is the directed road section set of the road network, x and y are respectively the starting point and end point of the road section, and $A(x, y)$ is the attribute set of the road section, which can be expressed as distance, time and so on [65].

Thus, an actual road network is viewed as a topological structure with broken-line roads. The principle of the topological model and algorithm implementation can be simply described as: according to the characteristics of a road network, an Arc-Node model is generated from the given road network and is used to represent its topological structure. The generation process can be basically divided into two steps.

(1) Enrich and preprocess data for the given road network by transforming actual curve roads to corresponding broken-line roads.
(2) Generate the Arc-Node data structure to represent the topological structure of this broken-line road network by these network data.

A.2. Path planning model and algorithm

Due to some unpredictable factors, the entities (vehicles) in real EMS are often delayed to reach rescued sites. The fact may affect rescue effectiveness, and result in unnecessary casualties or economic losses. It needs efficient path planning to provide traffic predictions and travel guidance. This means not only off-line inputs, i.e., the road network representation historical data, and real-time inputs, i.e., the road network data loaded by surveillance system control, but also prediction and guidance generation based on the road condition [64]. Therefore, we carry out dynamic path planning for these entities (vehicles) based on the weighted road network data. Our algorithm is mainly designed to support short-term travel decisions, since emergency management behaviors have unique characteristics on fast reaction and risk resistance to key critical incidents. Of course, it is important to note that short-term decisions are conditional on long-term travel and mobility decisions such as vehicle ownership and residential and work locations [66]. The algorithm is as follows:

(1) According to the hierarchical analysis model of road attributes, give the static weight of a road network. First, the hierarchical model of influencing factors of road traffic is established, as shown in Fig. A.1. Second, the weight coefficients of each influencing factor are determined by analytic hierarchy process [67], and the road is evaluated according to the influencing factors to form data structure $G(V, \omega E)$ of this weighted road network, where $\omega = \omega_1 \times \sum_{i=1}^{3} (P_{1i} \times \omega_{1i}) + \omega_2 \times \sum_{i=1}^{3} (P_{2i} \times \omega_{2i})$.
(2) Obtain the real-time information of the road condition, and use correction coefficients to modify the weights of the road network to form a new data structure $G(V, \alpha\omega E)$ of the weighted road network, which α represents the traffic jam parameter, and $\alpha \in [0, 1]$.
(3) Carry out path planning and determine the maneuvering route. Based on the generated weighted road network data, the overall path planning approach to find the shortest path in an elliptical restricted search area is used. Specifically, focusing on the starting point S and the end point D, an ellipse is drawn. The length of its long axis is $\mu_0|SD|$, where $|SD|$ is the Euclidean distance from S to D, and μ_0 is a statistical parameter related to urban road network information. According to statistics of collected data, we know that μ_0 for Beijing road network is 1.417 [65]. Thus, the elliptical restricted search area is constructed, and Dijkstra's algorithm is used to calculate the shortest path in the search area. Therefore, the shortest path can be found between the nodes in the elliptical region. In other words, once we input the starting point S and the end point D, as well as load the road network data, by this process we can output the shortest path between S and D.
(4) Obtain the real time road network information in the process of maneuvering, determine whether the change of traffic jam parameter α exceeds threshold value δ, and adjust the local route when $|\frac{d\alpha}{dt}| \geq \delta$ holds.

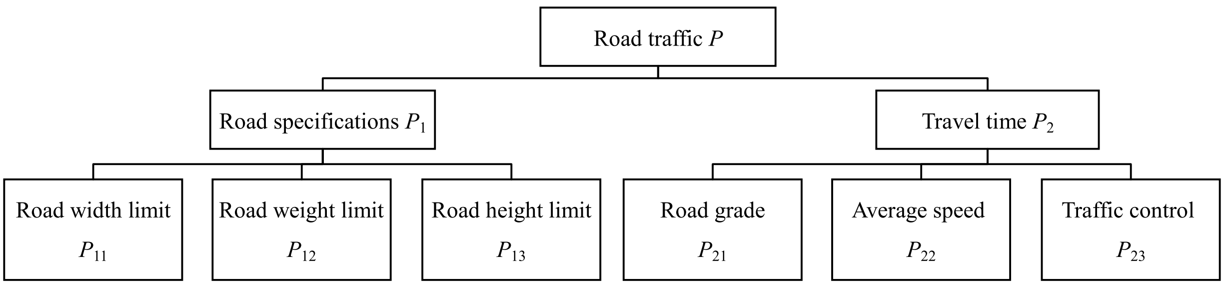

Fig. A.1. Hierarchical model of influencing factors of road traffic.

A.3. Obstacle avoidance model and algorithm

In the process of maneuvering, the entities (vehicles) in real EMS may encounter some obstacles, such as a poisoning area and buildings, and need to achieve obstacle avoidance by skirting them. According to the characteristics of these actual obstacles, we abstract them as round obstacles and square obstacles during developing our simulation systems. The models of skirting a round obstacle and square obstacles can be illustrated by Fig. A.2(a) and Fig. A.2(b).

As shown in Fig. A.2(a), when route SD intersects this round obstacle, it is necessary to re-plan the path, i.e., insert some nodes between point S and point D, so that the path can bypass this obstacle. The algorithm is as follows:

(1) Define the radius of this round obstacle as r, and draw a circle by taking point O as its center and $2r$ as its radius. Then, intersections A and B with line segment SD are obtained, and these two points are inserted into the list.
(2) Find out intersection P of tangents AP and BP. Thus, the new path can be obtained, i.e., S-A-P-B-D.
(3) As shown in Fig. A.2(b), the quadratic parabola method is mainly used to plan the process of passing through square obstacles [68]. The algorithm is as follows:

(1) Obtain the current positions of entity (vehicle) *a, b*, and the center point of channel *O*. Then, make two quadratic parabolas passing through *a* and *b* by taking *O* as origin, the horizontal line and vertical line of the channel as coordinate axes, respectively.
(2) When two points are known, the coefficient of a quadratic parabola can be obtained. Thus, we can obtain the two parabolic equations above.
(3) Calculate the tangent directions of *a* and *b* on the corresponding parabolic equations, in which the two entities pass through the square obstacles, respectively.

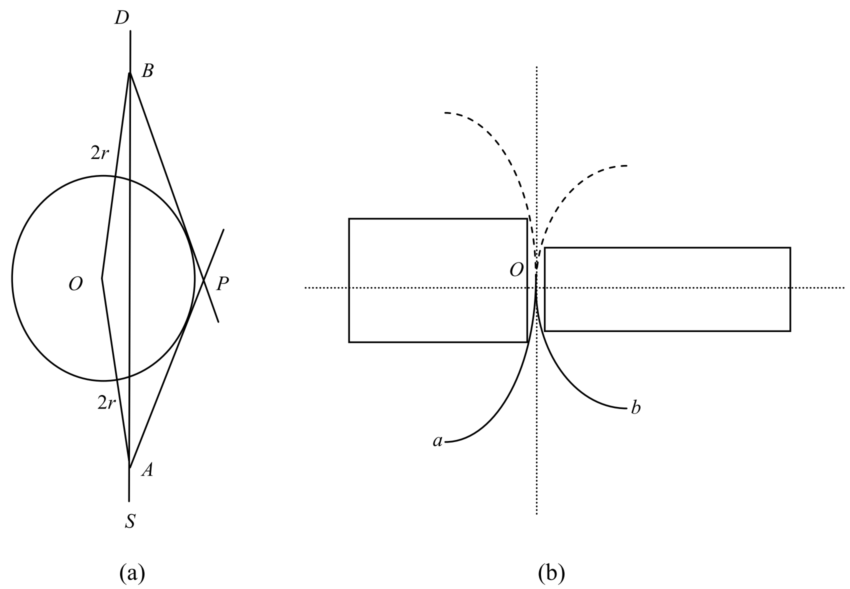

Fig. A.2. Models of skirting a round obstacle (a) and square obstacles (b).

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