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Agent-based Discrete Event Simulation Modeling for Disaster Responses

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Abstract

We develop a comprehensive simulation model for civilian emergency/disaster responses. In order to incorporate the detailed interactions among various responders and victims, we integrate the agent-based modeling ideas into the discrete-event simulation framework and hybrid several components such as GIS.

Keywords
Emergency response, agent-based simulation, discrete event simulation, geographical information system, rule-based system

1. Introduction
An interdisciplinary team at University of Pittsburgh has developed the Dynamic Discrete Disaster Simulation System (D^4S^2), a comprehensive decision support system to simulate the large-scale disaster responses. This project incorporates principles and approaches from industrial engineering, information sciences and emergency medicine into a framework to assist decision makers in planning and managing responses to catastrophic events. Specifically, the architecture integrates an agent-based simulation model, a geographical information system (GIS), data bases, a rule based system for responders and optimization modules to create a hybrid system of agent-based and discrete simulation components. A number of innovative strategies have also been incorporated to reduce computational demands, so that the simulations can be completed in real-time on a standard PC platform. Although the system is built mainly for emergency response management, the architecture has broad applications in military operations, global supply chain management and financial portfolio management.

This project was motivated by the lack of rational, comprehensive decision support systems for disaster response management. Catastrophic events such as the terrorist attacks of September 11, 2001, hurricane Katrina and the tsunami in the Indian Ocean have reminded us of the difficulties in preparing for and responding to man-made and natural disasters. Because the time, location, and scale of the events are impossible to predict, it is increasing clear that pre-event planning and preparedness are imperative in order to limit the damage to human lives and property and restore the affected communities to a semblance of normal operations. We envision sophisticated, realism-based decision support systems as an efficient approach for three aspects of disaster management:

- Assisting key decision makers in developing and improving emergency response policies.
- Training emergency personnel on how to respond by simulating various disaster scenarios.
- Assisting disaster management team in making response decisions in real-time.

The overall objective is to provide a circumstance-independent laboratory for testing how the type and scale of the event, situational state and command decisions affect responders' efficiency and effectiveness in dealing with complex, evolving disasters.

2. System Overview

D^4S^2 is a specialized architecture designed for decision makers. Examples of the system decision makers are public safety service officials (EMS, fire and police), regional incident commanders/managers, city planners and federal officials. Figure 1 shows the basic structure of D^4S^2.

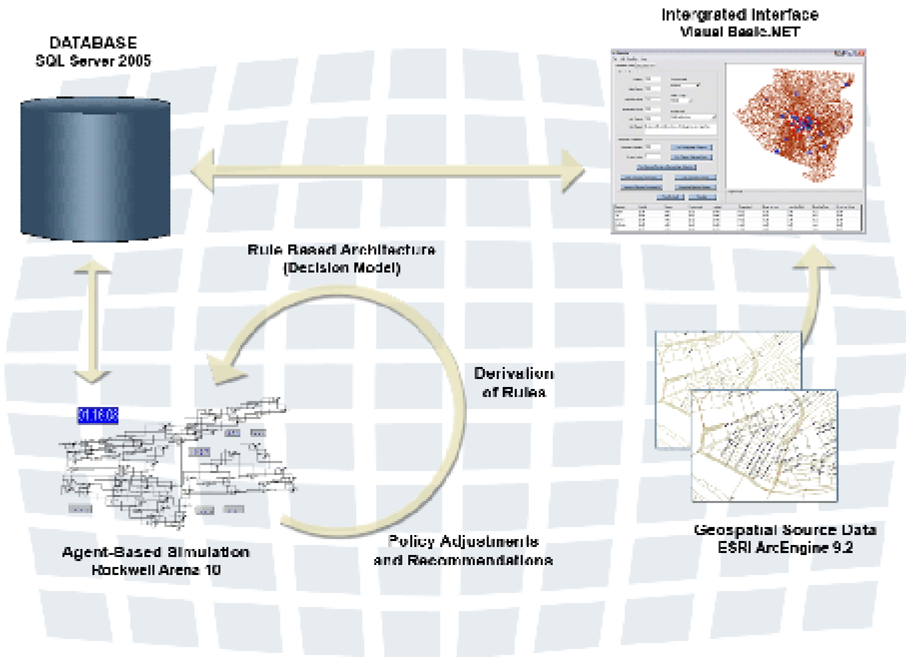

Figure 1: D^4S^2 system framework

The system components are integrated seamlessly on one platform. VB.NET servers as the core structure of the system due to its advantages in integration and interoperability. The key components are GIS, simulation, rule-based system, and interfaces, all of which communicate through a well-designed relational database. The individual components and their interactions will be introduced in details in the following.

2.1 Geographical Information System (GIS)

The geographical information system contains geographically referenced metadata about geography, assets and environment [1]. The geographic data describe the infrastructure such as roads, waterways and topography of the area. The information about emergency response resources such as fire, police and EMS units can be stored in the geo-database and associated with the infrastructure. Real-time environmental data such as weather and hydrology are also part of the system. Different types of information are constructed on different layers. Normally a GIS system contains dozens to hundreds of layers. When used with the simulation model, the GIS system can feed rich data to the simulator and make the simulation more realistic and robust. Keeping the geographic-related data in the independent GIS system can simplify the system deployment process. As long as an area has adequate GIS data, the disaster simulation system can be quickly implemented for that area. The GIS interface is shown in Figure 2. ESRI ArcGIS 9.1 is used in this project to integrate with the simulation. The GIS system can also provide the point-to-point routes. This feature helps route the emergency responders in the simulator.

2.2 Simulation

The simulation model is a key component in the system. It uses discrete event simulation (DES) as the main construct and models the emergency response system as a transportation network. The current implementation uses Rockwell Arena. Important street intersections are chosen as network nodes and the roads connecting the intersections are arcs. The response vehicles are the entities moving along the network and performing various response tasks. The entities are built in different layers, for example, cars on the roads, trains on the railways, boats in the rivers, and helicopters in the air. A number of strategies have been incorporated to reduce computational effort without sacrificing accuracy. For example, counters are extensively used to model other objects instead of actual entities to reduce computational efforts. Some examples of the objects built in counters are victims, hospitals and regular vehicles.

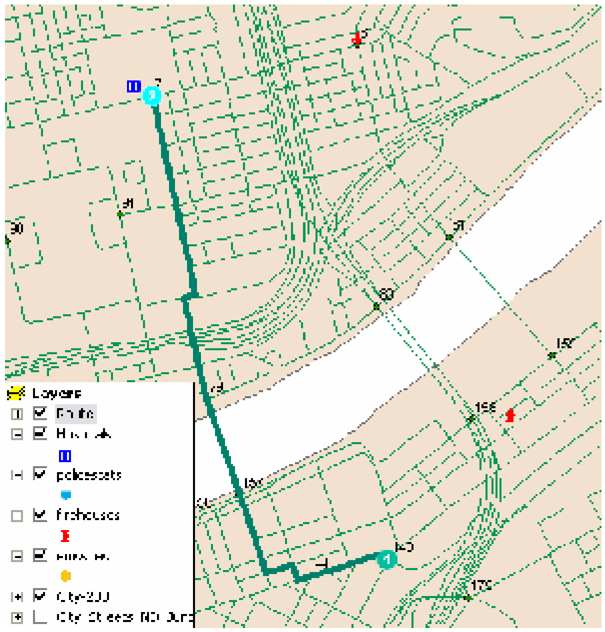

Figure 2: GIS interface

Besides discrete event simulation, agent-based simulation (ABS) techniques are also utilized in the system to incorporate more realistic and flexible entity operations and interactions. The concept of agent-based model was originated from the field of artificial intelligence in computer science. A computer agent is defined as an autonomously controlled entity that can perceive its own operations as well as the surrounding environment, compile the predefined rules to make operational decisions, and act based on these decisions [2]. This definition complies with the nature of rational objects such as the emergency responders so they are regarded as intelligent agents. The individual agents operate on their own but are affected by other agents and the environment. The rules of operations and interactions need to be specifically defined which will be described in the next subsection.

This project is responsive to the need to develop hybrids of discrete event simulation and agent-based simulation to efficiently model complex phenomena for personal computational devices. DES is much more computationally efficient than ABS. To simulate such a large-scale system as a disaster response system, a pure agent-based model requires large computational resources to generate solutions within the constraints of real-time events. On the other hand, ABS is preferred in the system to model the detailed, rule-driven responder operations. Furthermore, the disaster responders have to change their operations accordingly based on the interactive GIS data. The ABS implementation can help the responder entities (agents) better and more easily adapt to the changes inside and outside of the simulator.

2.3 Rule-based System

In the simulation, the responder agents' operations are regulated by a set of rules. These rules are maintained in a separate rules database that is accessed by an inference engine. The rule-based system architecture is depicted in Figure 3.

The workspace comprises of a set of databases which can facilitate the data exchange among various components. The simulation engine and the GIS data base provide data to the workspace as the environmental variables. The change in the environment triggers the inference engine to compile the rules for the agents. New rules generated will be reflected to the simulation and GIS through the workspace. This forms a significantly interactive modeling process. All the rules in the rule base are formulated to the "if-then" format to explicitly state the conditions and consequences. They are derived from standards and protocols (see e.g., [3]).

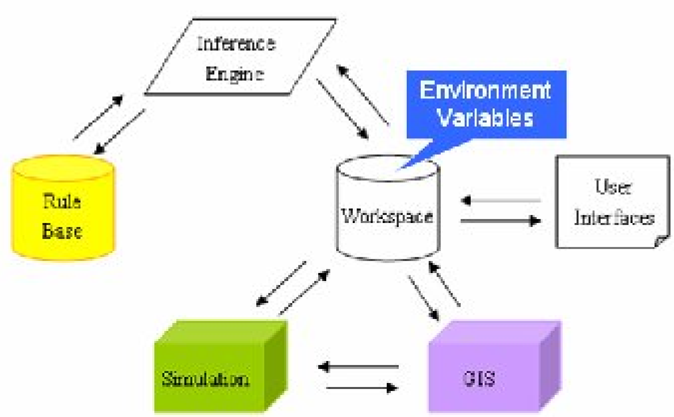

Figure 3: D^4S^2 rule-based system architecture

3. The Pittsburgh Framework

D^4S^2 was implemented based in the Pittsburgh downtown area as a test bed of the system, called the Pittsburgh Framework. The terrain of Pittsburgh presents significant challenges to disaster response planning. Transportation routes are constrained by features such as rivers, hills, bridges and tunnels in an urban environment, which serve as potential critical bottlenecks for responders during a major disaster event. Co-localization of infrastructure such as railroads, telecommunications assets, utilities and hospitals also create significant planning challenges. The prevailing atmospheric conditions in the river valleys surrounding the city (witness the well-known industrial smogs of the previous century) also need to be considered in the case of toxic plumes. It thus provides a microcosm of the spectrum of potential issues that need to be considered for disaster responses in any locale. The GIS map of the downtown area is shown in Figure 4.

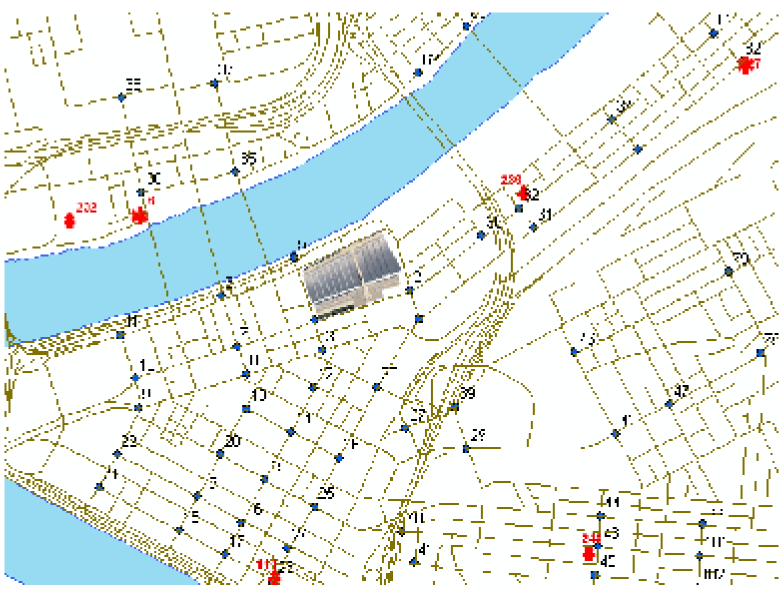

Figure 4: Pittsburgh downtown GIS map

The simulation model developed in Arena is shown in Figure 5. It can be observed that the shape of the simulation model matches the GIS map well because the Arena model was built using the exact GIS data.

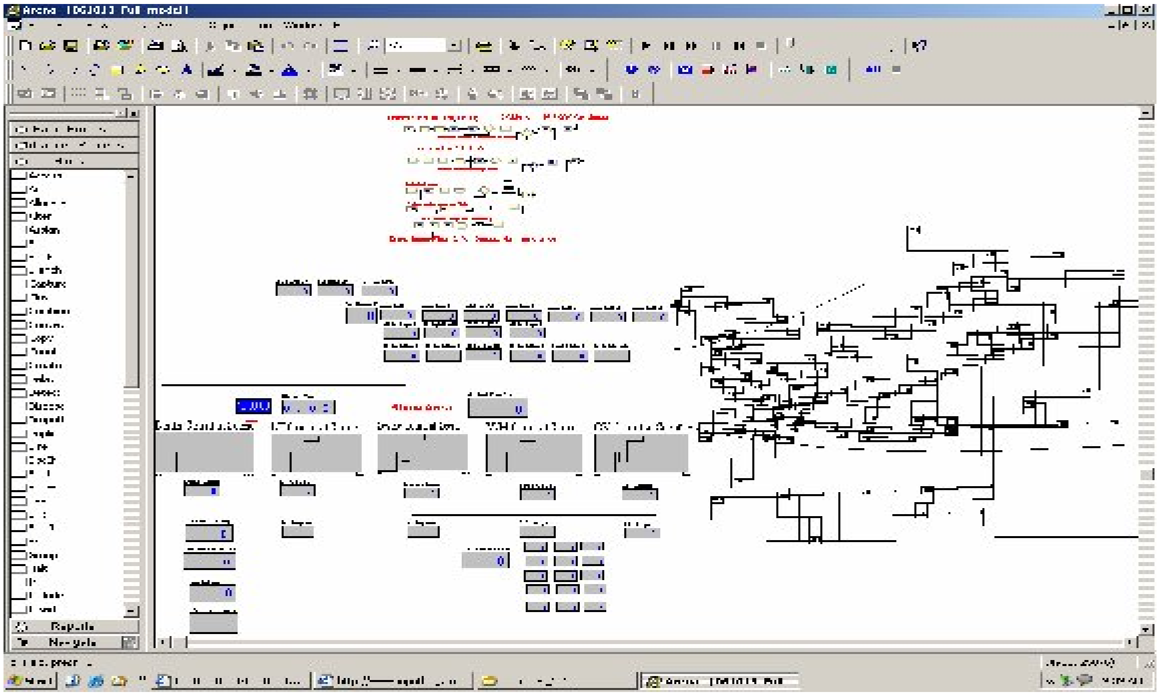

Figure 5: The Pittsburgh Framework Arena model

Figure 6 shows the user input interface of D^{4}S^2. The users can simulate the Department of Homeland Security national planning scenarios [4]. The interface allows selection of input parameters to control type of event, size of event and time of event. After the simulation run, the results are reported in the interface as in Figure 7.

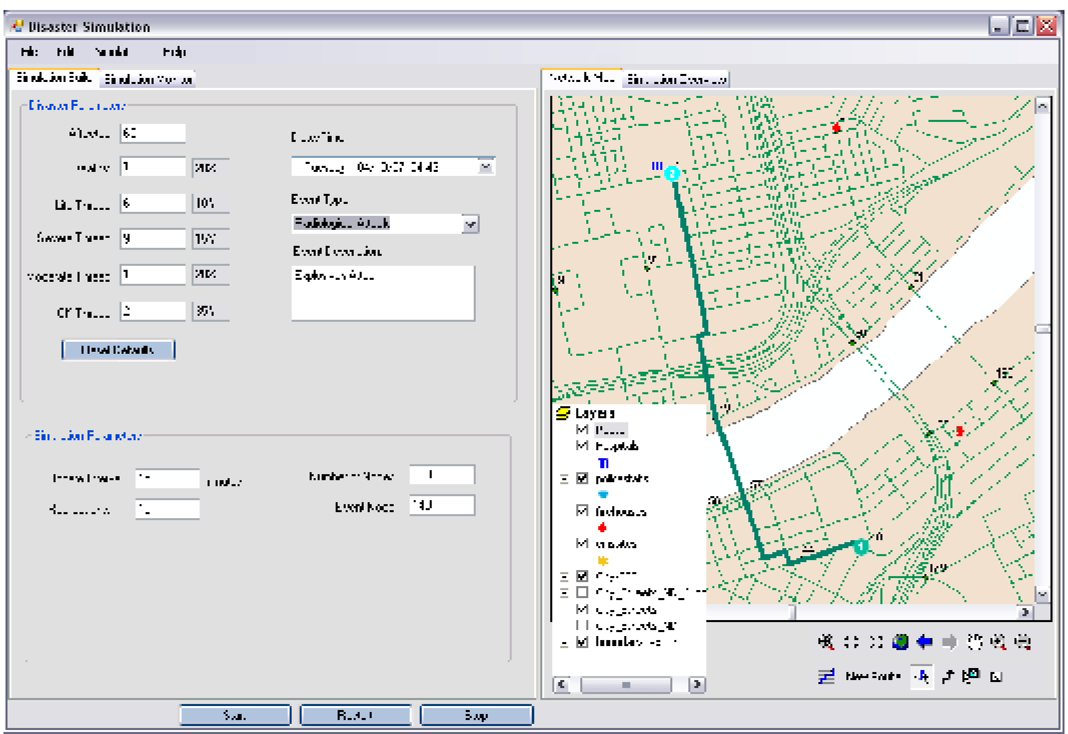

Figure 6: D^{4}S^2 user input interface

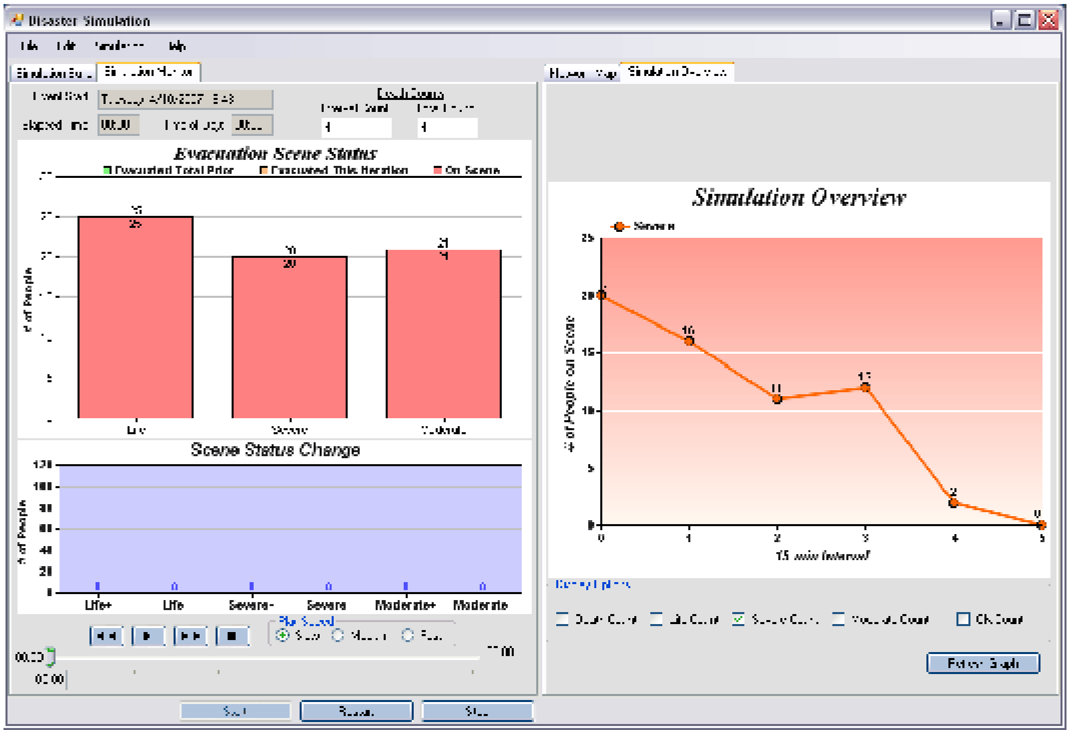

Figure 7: D^4S^2 result report interface

4. Conclusions

This paper summarizes key features of the design and implementation of a comprehensive disaster simulation system. The simulation system has several unique features compared with other existing systems. The architecture incorporates hybrid discrete event and agent based simulation capabilities and has embedded GIS capabilities. In addition, strategies for streamlining computations allow for the system to operate in real time on a standard desk top or portable personal computer. This single platform has the potential to provide realistic decision support for planning and mitigating catastrophic events.

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