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# SYSTEM IMPLEMENTATION ISSUES OF DYNAMIC DISCRETE DISASTER DECISION SIMULATION SYSTEM ($D^4S^2$) – PHASE I

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## ABSTRACT

Simulation has many advantages in modeling complex systems to facilitate decision making. In this research, an integrated computer system will be developed which incorporates an agent-based discrete event simulator, a geographic information system, a rule base, and interactive databases in addition to interfaces and other supporting components. The modules will seamlessly communicate with each other by exchanging a progression of data, and making a series of deductive decisions through embedded algorithms. This integrated system will be applied to disaster management planning and training and is designated Dynamic Discrete Disaster Decision Simulation System ($D^4S^2$). Here we address Phase I system implementation issues of $D^4S^2$ which is under development.

## 1 INTRODUCTION

The threat of terrorism activities combined with the recent large scale natural disasters are creating a demand for comprehensive decision making tools that will enable responsible personnel to be better prepared to respond to these potential events. This implies being able to respond to a large scale disaster while simultaneous dealing with the area's ongoing emergency incidents.

From a modeling perspective, this is clearly a very complex system. Simulation techniques have been extensively used in modeling and analyzing complex systems in the past decades with the advances of computer technology. Simulation can outperform mathematically modeling in such instances because of its capability to get around stringent assumptions that must be made for analytical models to be tractable. Further, stand-alone, hard-coded systems might work well in restricted scenarios but they can hardly capture the dynamic nature of the real systems. We aim to build a flexible, realistic simulation-based system - Dynamic Discrete Disaster Decision Simulation System ($D^4S^2$) - and apply it to disaster management planning and training. It uses discrete event simulation (DES) as the primary system modeler and evaluator, feeding progressive data into it to make the simulation model and decision making process dynamic. Besides the simulator, the components of $D^4S^2$ include a geographic information system (GIS), a rule base, several relational databases and a client interface. The system is also scalable enabling other supporting components to be introduced in a realistic fashion.

In addition to building $D^4S^2$, the two main research objectives of this project are: (1) Seamlessly integrate the different module components into one platform to realistically simulate the actual disaster management process. (2) Develop and then combine rule generation algorithms and simulation optimization methodologies into the system to better understand emergency response operations and improve disaster management. The full project will be accomplished in several phases. This paper addresses the Phase I tasks including certain system implementation issues. It is organized as follows: Section 2 discusses disaster management practices and past research on simulation-based emergency system modeling and analysis; Section 3 addressed the goals of implementation Phase 1; Section 4 discusses specific implementation issues including system work flow, agent-based modeling and rules, and client interfaces; Section 5 presents preliminary verification results of simulation experiments; the last section, will present conclusions and future work.

## 2 LITERATURE REVIEW

### 2.1 Disaster Management Practices

Small- and mid-scale civilian incidents (e.g., ordinary fires or traffic accidents that involve only a few casualties) require limited resources and are easy to control. Those incidents are manageable by the standard handbooks, codes and protocols for emergency management such as NFPA

1561: Standard on Emergency Services Incident Management System (Erikson 1999).

Responding to large-scale emergency incidents require much more careful planning and professional execution because the available responding resources are easily overwhelmed. Operations research (OR) methodologies can be helpful in evaluating the emergency plans and guiding the operations with regard to large-scale incidents including natural disasters and human-caused events (Larson 2004). Expert systems have been widely applied in reasoning and problem solving for large-scale complex systems. They are suitable to the organizations that have a high-level of know-how and experience that cannot be easily transferred to other members (Russell and Norvig 2003). Emergency response teams prominently have this characteristic. These teams are made up of experts from different fields and/or social sectors and may not sufficiently know each others' response knowledge and operations. For such cases, the expert systems are developed to combine the intelligence and information of the experts and provide this knowledge to other members for collaboratively solving hard problems.

### 2.2 Simulation Models

Simulation models can compensate for the disadvantages of analytical models and work around many of the unrealistic assumptions required for analytical models. Simulation is particularly useful in modeling complex systems with many interactions because it carries the stochastic, dynamic nature of real systems. In the past three plus decades, many researchers have studied emergency responses by simulation. Shuman et al. (1985, 1992) presented a sophisticated computer simulation model RURALSIM built in SIMULA to help plan and evaluate rural (as well as urban, e.g., Pittsburgh, PA and Lincoln, NB) emergency medical services (EMS) systems. The model was used as a test bed for various policies: it could study the potential effects of changes in existing vehicle placement and relocation strategies, vehicle dispatching policies and alternative forms of prehospital care, including the ability of the system to respond to a disaster. RURALSIM was a tremendously comprehensive model which was capable of generating random emergency events according to certain empirical probability distributions, considering communications, demand, response, equipment, training, etc., evaluating the cost and performance of alternative configurations, and so forth. Goldberg et al. (1990) reported their previous work of modeling and evaluating an EMS system in Tucson, Arizona by simulation. The paper focused on several strategies to rationally prove the simulation model's validity relative to the actual system, which were neglected by other researchers.

Agent-based simulations are models where multiple entities sense and stochastically respond to conditions in their local environments, mimicking complex large-scale system behaviors (Said, Bouron, and Drogoul 2002). Relative to this project, Carley et al. (2006) led her team to creatively program a scalable citywide multiagent model to systematically reason about the nature of disease outbreaks structured by social and institutional networks. The system incorporates various submodels including disease model, geography model, weather model, attack model, etc. with the agent model. Agents behave autonomously and interact with each other in the network to realistically simulate the actual operations. Agents are aware of and interact with their local environment through simple internal rules for decision making, movement and action.

## 3 FUNCTIONAL GOALS OF PHASE I

The $D^4S^2$ system implementation involves an extensive research team at the University of Pittsburgh. This long-term commitment will be divided into several stages. Phase I focuses on the following functions:

1. Design a system work flow with databases. In Phase I, all modules are linked to a database and exchange data "on the fly" through the database programming interface.
2. Programmatically describe various disaster incidents by disaster type and event size. Disaster types are described by Department of Homeland Security and the event size includes affected population size and victim severity distributions.
3. Implement an agent-based simulation model and simple agent rules. Emergency responders are basically modeled as autonomously controlled individuals that can perform rational tasks according to predefined rules and team work to achieve common goals.
4. Implement an effective client interface to facilitate users to visualize the disaster situations effectively and enhance their situational awareness. The interface should display a progression of simulation results, e.g., victim evacuation time, and geographical data that are extracted from GIS, e.g., route utilization.

## 4 SYSTEM IMPLEMENTATION

### 4.1 System Framework and Work Flow

$D^4S^2$ has several module components integrated on one platform for dynamically and realistically mimicking various disaster incidents. Figure 1 shows the basic framework. Visual Basic (VB) is used as the control structure because a large portion of commercial available software and industrial applications provide VB programming interfaces. For instance, Rockwell Arena for simulation, ESRI ArcGIS for GIS and SQL Server for databases all have such interfaces. This is a tactical consideration for long-term implementations as the VB-structured system is more scalable to other software and applications.

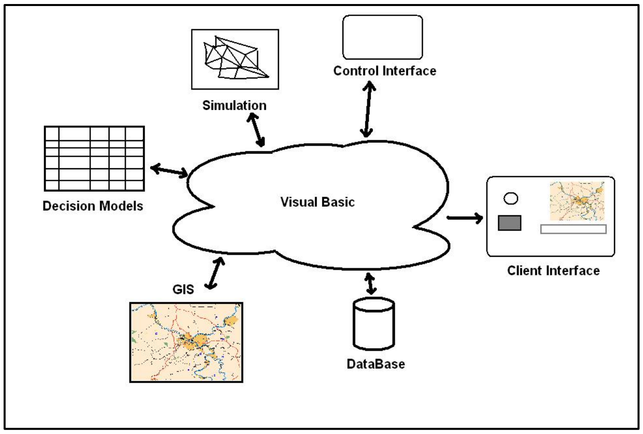


Figure 1: $D^4S^2$ system framework

In Phase I, a simulator, a GIS, a client interface and a relational database will be linked together to perform some basic functions of the system.

The system work flow is depicted in Figure 2. The flow mainly comprises of three parts: a VB application, an intermediate database and the Arena simulation package. The VB application initially prepares the data needed for running the simulation such as GIS data and event type and size. The data are stored in a well designed relational database. Arena then retrieves those data and runs several replications. Progressive results are collected iteratively and stacked in the database during the simulation run. Finally, useful results are extracted and complied by the VB application and displayed on the client interface for view and analyses. The simulated results can be affected by some dynamic factors such as weather and traffic congestion "on the fly." Although this can be done by updating the intermediate databases, it will not be implemented in Phase I. Some tables of the database that describe the simulation are summarized in Table 1.

### 4.2 Agent-based Modeling and Rules

An agent-based model comprises of "intelligent" entities that are autonomously controlled by perceiving the surrounding environment, compiling predefined rules to make operational decisions, and acting based on these decisions. It could simulate complex, dynamic actual systems realistically because their operations are highly analogous (Wu et al. 2007).

The disaster responders simulation primarily deals with a complex network flow problem which involves the responder agents' movement, designated actions decided by a set of rules, and environmental changes caused by victim behaviors, traffic, weather and other factors. A network comprises of arcs and nodes. Streets, roads and highways are modeled as arcs and their intersections are modeled as nodes. Agents are described by the status attributes attached to them such as trip start node, trip end node, past action and current action (Wu et al. 2007).

Table 1: Database tables for describing simulation

| **Table Name** | **Contents** |
|---|---|
| ResourceDescription | Descriptions of emergency resources, e.g., ambulances. |
| Destinations | The destination points of emergency resources, e.g., hospitals. |
| ResourceLocations | Emergency resource locations. |
| Rates | Emergency vehicle nominal traveling speed. |
| Network | Road network data. |
| Connections | Connectivity of the network. |
| DisasterScenario | Disaster type information. |
| Simulation | Simulation model parameters. |

While an agent performs many different actions, here we can classify them into three types: (1) traveling from one node to another, (2) staying at one node for some time to perform some tasks such as picking up victims, and (3) stopping at one node until starting up again. A whole event can be divided into and simulated by many discrete consecutive agent actions. After each small agent action, the simulation stops and fires the rule sets in the back to rationally determine what the next action will be based on the surrounding environment and other agents' status. In this way, the discrete event simulation and agent-based modeling are combined and controlled by rules. The rule sets can be implemented outside of the simulation model and are subject to changes under specific circumstances.

The rules are implemented in the format of Horn "what-if" clauses: *IF some condition(s) THEN some action(s)* (Wu et al. 2007). We focus on implementing the emergency medical services (EMS) ambulance rules in the current phase. Each piece of agent rules has antecedents and consequences as illustrated in Table 2. Take the rule (in bold) in Table 2 for an example. The rule says: "After an ambulance takes victims at the emergency drop-off site, it should go back to the pickup site." If the rule engine detects that the agent's type is ambulance, the agent's location equals emergency drop-off site, and the agent is not carrying any passengers, the algorithm will set the agent status as emergency and its destination as the pickup site then the ambulance can return to the pickup site.

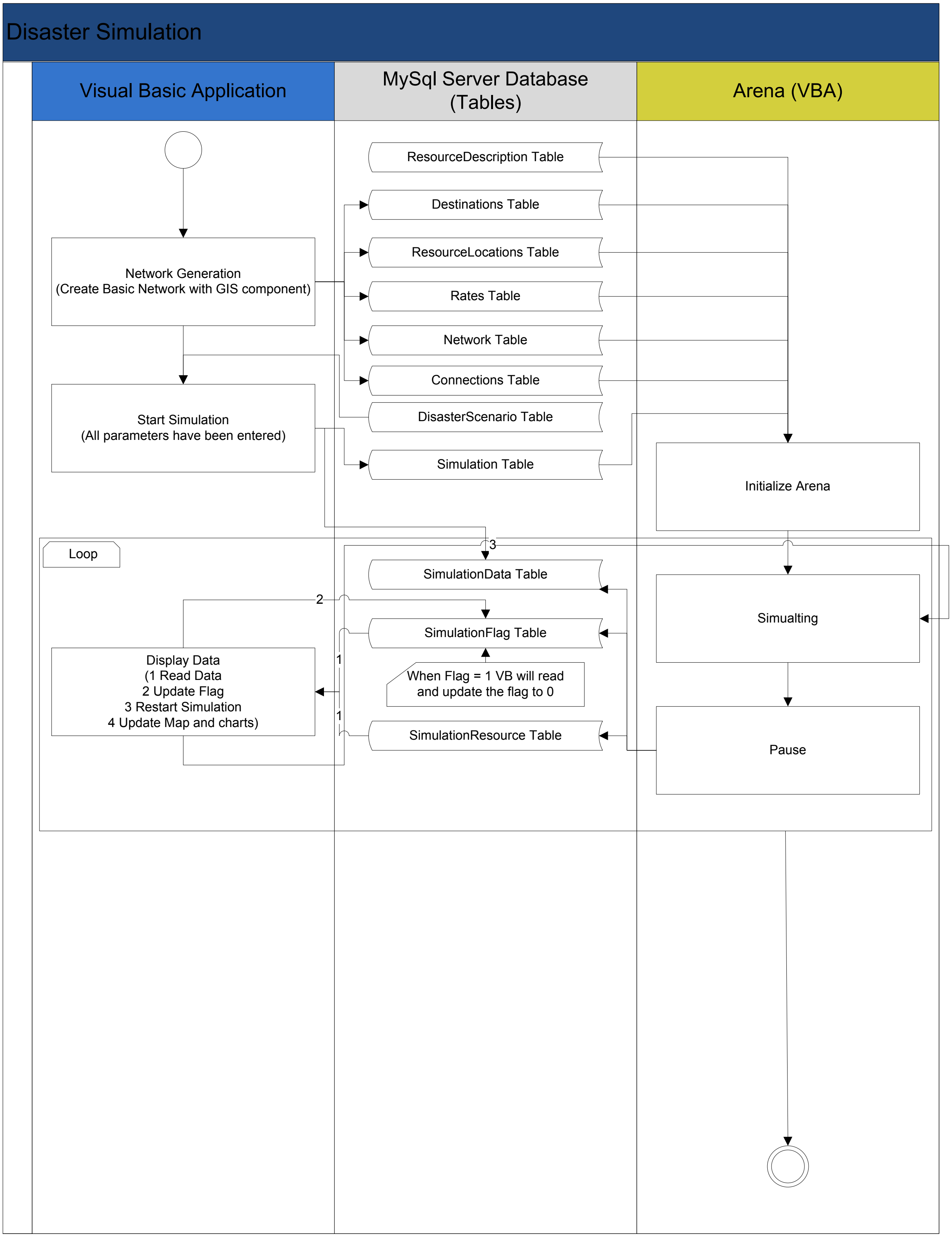


Figure 2: $D^4S^2$ (Phase I) work flow

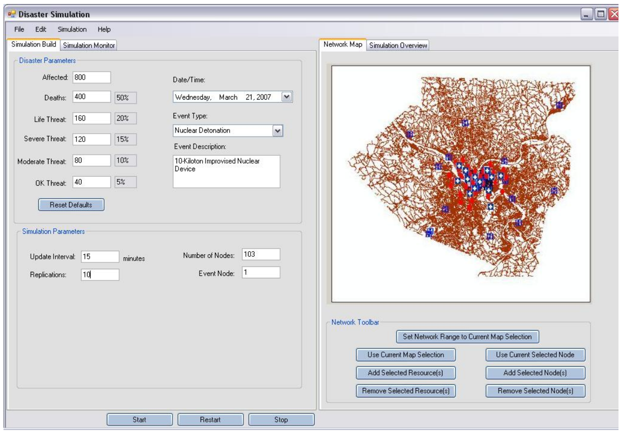
Table 2: Simple agent rules for EMS ambulance actions

| Antecedents | Consequences | Actions |
|---|---|---|
| <Vehicle-Type Ambulance><br><Vehicle-Status Idle> | <Vehicle-Status Emergency><br><Vehicle-Destination Emergency-Pickup-Site> | Send idle ambulance to emergency pickup site. |
| <Vehicle-Type Ambulance><br><Vehicle-Status Responding><br><GreaterThan(Respondance-Severity, Moderate)> | Nothing | Leave ambulance status and destination unchanged. |
| <Vehicle-Type Ambulance><br><Vehicle-Status Responding><br><LessThan(Respondance-Severity, Severe)> | <Vehicle-Status Emergency><br><Vehicle-Destination Emergency-Pickup-Site> | Send empty ambulance that was responding to a prior emergency to the emergency pickup site. |
| **<Vehicle-Type Ambulance>**<br>**<Equal(Vehicle-Location, Emergency-Dropoff-Site)>**<br>**<Equal(Vehicle-Passengers, 0)** | **<Vehicle-Status Emergency>**<br>**<Vehicle-Destination Emergency-Pickup-Site>** | **Send ambulance to emergency pickup site from emergency dropoff site.** |
| <Vehicle-Type Ambulance><br><Equal(Vehicle-Location, Emergency-Pickup-Site)><br><Vehicle-Status Emergency> | <Vehicle-Destination Emergency-Dropoff-Site><br><Vehicle-Passengers Min(Victims, Vehicle-Capacity)> | Send ambulance to emergency dropoff site from emergency pickup site. |

## 4.3 Client Interfaces and Instance Generation

Visualization is a critical part of this research because one of our purposes is to provide incident managers with insightful information about potential of ongoing disaster events and enhance their situational awareness through the D$^4$S$^2$ system. Most emergency incident managers are not simulation or computer expert so a user-friendly interface becomes essential if they are to use the system as a management tool. The client interfaces are comprised of two parts: disaster instance generation and result display and analyses. One advantage of the system is that it can generate the simulation model and disaster instances flexibly given the data specified in Table 1 so it is highly portable and easy for deployment. Figure 3 shows the interface for generating a disaster simulation. Users can choose the disaster type and specify the event size with severity distribution. The simulation network model is generated automatically with the geographical data extracted from GIS.

After the simulation run, various resulting charts are displayed on the interface shown in Figure 4. The charts depict the progressive situations of the event by breaking the results down into consecutive segments. The incident manager can manipulate the rules and parameters and rerun the system to search for management improvements. In later stages, optimization algorithms will be incorporated in the system to automatically search for better solutions.



Affected: 800
Deaths: 400 50%
Life Threat: 160 20%
Severe Threat: 120 15%
Moderate Threat: 80 10%
OK Threat: 40 5%
Date/Time: Wednesday, March 21, 2007
Event Type: Nuclear Detonation
Event Description: 10-Kiloton Improvised Nuclear Device
Update Interval: 15 minutes
Replications: 10
Number of Nodes: 103
Event Node: 1

Figure 3: Interface for generating a simulation instance

Event Start: Wednesday, 3/21/2007 15:3
Elapsed Time: 0
Time of Day: 17:5
Death Counts
Interval Count: 1
Total Count: 7

Figure 4: Interface for displaying simulation results

## 5 SIMULATION EXPERIMENTS

### 5.1 Spreading Event Locations and Scales

Currently, the system is developed for simulating the EMS system in the Pittsburgh downtown area. Sixteen experiments were conducted at four different locations spreading out the area with four scales of disaster incidents. The total evacuation time was evaluated for each experiment. See Table 3 for the results.

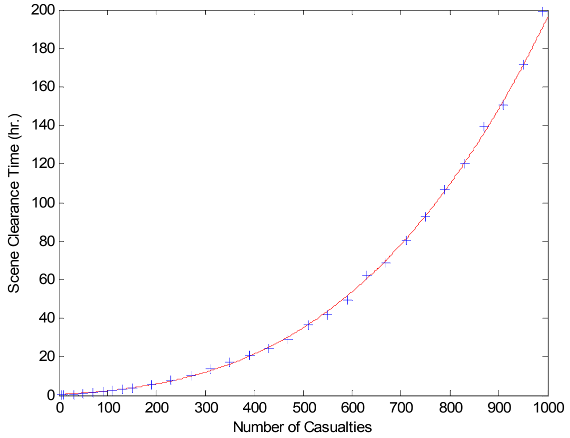
The total evacuation time increases more and more slowly with the identical increase (i.e., 21) in number of victims. This makes sense because the EMS system needs some time to prepare and start up when it is initially called to respond. After running for a while the system become stable and more efficient. When there are 21 victims, the minimal evacuation time appears at Location #18; when there are more than 21 victims (i.e., 42, 63, and 84), minimal evacuation time appears at Location #30 because Location #30 is closer to many city hospitals and it is more accessible to emergency resources.

Table 3: This table shows the total evacuation time results of 16 simulation experiments conducted at four different locations spreading out in the Pittsburgh downtown area with four scales of disaster incidents. All results are in the unit of minutes.

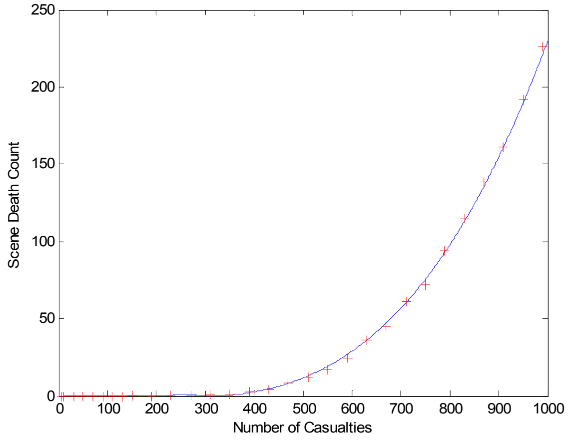
| ***Victim #*** ***Location #*** | ***21*** | ***42*** | ***63*** | ***84*** |
|---|---|---|---|---|
| **8** | 17.34 | 52.13 | 83.46 | 111.05 |
| **18** | 17.29 | 49.02 | 79.89 | 111.35 |
| **30** | 17.48 | 47.26 | 76.23 | 106.92 |
| **44** | 17.80 | 49.86 | 82.21 | 111.17 |
| **Average** | 17.48 | 49.57 | 80.45 | 110.12 |

### 5.2 Simulating One Location with Different Scales

David L. Lawrence Convention Center in the Pittsburgh downtown area is a busy location where a lot of traffic passes and structures exist. It is a good place to demonstrate the $D^4S^2$'s capability of simulating various disaster events. Suppose some events with different scales happen in this location and EMS is called to respond to the events. A series of simulations are run to evaluate the scene clearance time and death of victims versus number of victims. The results are fitted and showed in Figure 5. It is obvious that break point appears when number of casualties reaches around 330, from there the number of deaths increases exponentially. Thus additional responses are needed to deal with this level of events when resources saturate and traffic is highly congested.



(a): Scene clearance time vs. number of casualties



(b): Scene death count vs. number of casualties

Figure 5: The two charts (a) and (b) are fitted by the results of a simulation experiment conducted at one location (David L. Lawrence Convention Center) in the Pittsburgh downtown area.

## 6 CONCLUSIONS AND FUTURE WORK

The main goal of this research project is to build a comprehensive, interactive, multi-module computer simulation system – $D^4S^2$ – for testing how the type and scale of the event, situational variables and command decisions affect responders' efficiency and effectiveness in dealing with complex and evolving disasters. Such a system can be of great assistance to emergency officials in managing emerging events.

Discrete event simulation is a superior tool for modeling complex, large-scale systems. When combined with agent-based models, it becomes even more powerful because it bears more flexible scalable operational rules and it is easier to interface with other modules that can introduce more reality and dynamics into the system.

$D^4S^2$ is an extensively collaborative project conducted by a large research team. It will involve many phases. This paper outlined the goals and implementation issues of Phase I. The issues include basic system work flow, agent-based modeling and rules, client interfaces, and instance generation. The fundamental system has been tested through some experiments done for the City of Pittsburgh downtown area. The results showed several reasonable outcomes so that the system has been verified to some extent.

There will be several more phases in the system development process. The later phases will focus on the followings:

- Building more realistic factors into the system, e.g., traffic factor, weather factor and social behaviors.
- Adding more first and secondary responder agents into the model, e.g., fire trucks, police cars and mutual aids.
- Enlarging the rule base to include more valid rules and enhancing the interactions among them.
- Incorporating decision models in the system to help make decisions "on the fly."
- Implementing optimization algorithms in the system to improve the decisions.

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## REFERENCES

Carley, K. M., D. B. Fridsma, E. Casman, A. Yahja, N. Altman, L.-C. Chen, B. Kaminsky, and D. Nave. 2006. BioWar: Scalable agent-based model for bioattacks. *IEEE Transactions on Systems, Man, and Cybernetics – Part A: Systems and Humans*. 36(2):252-65.

Erikson, P.A. 1999. *Emergency Response Planning: For Corporate and Municipal Managers*. San Diego: Academic Press.

Goldberg, J., R. Dietrich, J. M. Chen, and M. Mitwasi. 1990. A simulation model for evaluating a set of emergency vehicle base locations: Development, validation, and usage. *Socio-Economic Planning Sciences* 24(2):125-41.

Larson, R. C. 2004. O.R. models for homeland security: Decisions involving deployment of people, equipment and supplies serve as ideal setting for operations research to create better emergency response plans. *OR/MS Today* 31(5):22-9.

Russell, S. and P. Norvig. 2003. *Artificial Intelligence – A Modern Approach*. 2nd ed. New Jersey: Prentice Hall.

Said, L. B., T. Bouron, and A. Drogoul. 2002. Agent-based interaction analysis of consumer behavior. In *Proceedings of the International Conference on Autonomous Agents* 2:184-90.

Shuman, L. J., J. Sepulveda, H. Wolfe, and G. Esposito. 1985. Computer modeling of rural emergency medical services delivery systems. *Journal of World Association for Disaster and Emergency Medicine* 1, supplement I:44-8.

Shuman, L. J. and H. Wolfe. 1992. RURALSIM: The design and implementation of a rural EMS simulator. *Journal of the Society for Health Systems* 3(3):54-71.

Wu, S., L. Shuman, B. Bidanda, M. Kelley, K. Sochats, and C. Balaban. 2007. Disaster policy optimization: A simulation based approach. In *Proceedings of the 2007 Industrial Engineering Research Conference*, ed. G. Bayraksan, W. Lin, Y. Son, and R. Wysk, in press.

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