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A FRAMEWORK FOR MODELING AND SIMULATION FOR EMERGENCY RESPONSE

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ABSTRACT

A number of modeling and simulation tools have been developed and more are being developed for emergency response applications. The available simulation tools are meant mostly for standalone use. Addressing an emergency incident requires addressing multiple interdependent aspects of the situation. The simulation tools addressing different aspects of an emergency situation need to be integrated to provide the whole picture to planners, trainers, and responders. A framework is required to ensure that modeling and simulation tools can be systematically integrated together to address the overall response. This paper proposes a framework for integration of modeling, simulation, and visualization tools for emergency response. The development and implementation of the proposed framework will significantly improve the nation's capability in the emergency response area.

1 INTRODUCTION

The events of September 11, 2001 brought the focus to homeland security in the United States. A wide variety of efforts have been initiated to improve homeland security in addition to the ongoing efforts in this area. The efforts together cover multiple aspects of homeland security, e.g., physical security devices such as improved bullet proof glass, cyber-security software and devices, response equipment such as mobile decontamination units, improved training programs, and improved procedures and policies. Some efforts focus on prevention through better planning while others focus on improved response. An important set of technologies - modeling, simulation and visualization - offers the opportunity of effectively improving emergency response through applications that can be used at the planning stage and in real time after an incident.

A number of modeling and simulation tools have been developed and more are being developed for emergency response applications. These include applications for plume simulation for radiological device, chemical agent and bio-chemical agent dispersions, building fire simulations, and storm simulation. A state of the art survey of these tools indicates that a large number of efforts with highly qualified resources have been focused on this area (Jain, Mclean and Leong 2003). Each of these tools has focused on a specific aspect of the selected problem, for example, the modeling of dispersion of an agent in the environment using plume simulation. The emergency response agencies have to use their planning skills to take the output of such tools and develop their action plans. The simulations are also used in training to describe the event and its short-term impact and prepare the trainees to develop actions plans.

The available simulation tools are mostly meant for standalone use and do not attempt to address the overall emergency incident response. In the case of the plume simulation example, once the emergency response personnel have understood how the plume will spread, they need to plan the movement of first responder units, prepare evacuation plans, prepare plans for handling casualties, etc. A set of tools that can help develop and evaluate coordination among these multiple plans can significantly improve the response capabilities. These tools need to be integrated together to reduce the time and effort for their use. A framework is proposed in this paper to ensure that modeling and simulation tools can be systematically integrated together to address the overall response.

The remainder of the paper is organized as follows. Section 2 provides background on use of modeling and simulation in the area of emergency response. Examples of available simulation tools for the purpose are provided. Section 3 provides an operational concept for emergency response supported by modeling and simulation. The discussion brings out the benefits of integrated simulation models for an emergency scenario. Section 4 discusses the challenges to overcome to implement the concept. Section 5 presents the proposed framework and discusses its components. Section 6 concludes the paper.

2 BACKGROUND

The role of modeling and simulation for emergency response has been recognized for decades (see for example, Sullivan 1985). While the earlier literature focused on modeling of the major disaster event itself, current technological developments allow us to envision a systems approach that includes modeling of all major aspects of the disaster event, its impact on population and resources and the response by involved agencies. In the current socio-political environment, with the heightened security consciousness since the destruction of the World Trade Towers, modeling and simulation is being frequently suggested as the key ingredient for emergency response preparedness.

In a recent report, the Committee on Science and Technology for Countering Terrorism of the National Research Council identified "systems analysis, modeling and simulation" as the first of the seven crosscutting challenges to be addressed to counter the terrorism threat. The report states:

> Systems analysis and modeling tools are required for threat assessment; identification of infrastructure vulnerabilities and interdependencies; and planning and decision making (particularly for threat detection, identification and response coordination). Modeling and simulation also have great value for training first responders and supporting research on preparing for, and responding to, biological, chemical and other terrorist attacks.
> - National Research Council (2002)

The Department of Defense (DoD) has been using modeling and simulation effectively for war-gaming for years. It has led the development of the high level architecture (HLA) for integration of distributed simulation models, each modeling a part of the war-gaming scenario (Kuhl et al 1999). Similarly distributed simulation has been used to model supply chains, with each model representing the operation of one link in the supply chain. There is deep knowledge of using simulation spread around organizations such as DoD, Department of Energy (DoE) laboratories, National Institute for Standards and Technology (NIST), universities, and commercial companies for studying individual phenomena. A significant expertise for integrating distributed simulation models resides at DoD, NIST, and DoE laboratories. All this knowledge and intellectual capital needs to be brought together for the development of integrated distributed simulation models for emergency response. The integrated effort will allow study of the whole picture rather than being limited to studying one aspect at a time.

A number of ongoing efforts focus on using simulation for studying disaster events and their impact. These efforts can be grouped as discussed below.

Disaster impact modeling tools focus on studying and projecting the impact of a disaster event. The projections can then be used for planning the response to the disaster event. The National Atmospheric Release Advisory Center (NARAC) facility at Lawrence Livermore National Laboratory provides a capability to model the dispersion of hazardous atmospheric release (NARAC 2003). In fact, a number of such tools exist. Mazzola et al. (1995) surveyed 94 tools for modeling of atmospheric dispersion. NIST's Building and Fire Research Laboratory (BFRL) has developed a number of tools for modeling fire dynamics inside buildings (NIST-BFRL 2003).

Emergency response planning tools allow evaluation of alternative strategies to respond to a disaster event. They may allow input of impact of the disaster event estimated by experts or determined by using tools in the previous category, or they may themselves include the capability for disaster impact modeling. An example of tools in this category is the map analysis software provided by Innovative GIS/ Berry & Associates /Spatial Information Systems (BASIS) that can be used for planning responses to such events as a forest fire (Innovative GIS 2003).

Simulation tools for emergency response training mimic and present situations created by occurrence of a disaster event to human training subjects with the intent to improve their capabilities for emergency response. These tools extend from those targeted at decision makers to those targeted at first responders. Sandia National Labs has developed a program called the Weapons of Mass Destruction Decision Analysis Center as a way to simulate a war-room environment in the event of a terrorist attack (San Francisco Chronicle 2002). It is aimed at training public officials' response to a bio-terror attack. A development targeted at first responders is BioSimMER, a Virtual Reality (VR) application that immerses subjects in a computer-simulated setting (a small airport in which a biological warfare agent has been dispersed following a terrorist bombing) (SNL 2002).

Simulation tools for identification and detection of disaster events can be used for detailed analysis and developing techniques for identifying the possibility of occurrence prior to the event. The identification of factors that provide an early warning of impending disaster events can provide a valuable means to mitigate or even prevent the occurrence. The National Oceanic and Atmospheric Administration's National Weather Service and the National Severe Storms Laboratory (NSSL) are using modeling to explore ways to better detect the low-top, high-shear thunderstorms that are responsible for many of the short-lived events classified as weak tornadoes (NSSL 2003).

The modeling and simulation tools discussed so far typically address one kind of disaster event or one of its major aspects. A number of simulation tools have to be integrated to address multiple aspects of one disaster event as described in section 1. Work at Los Alamos National

Labs has moved in the direction of integrated simulation models. The urban security project is a multi-disciplinary research effort dealing with the relationship among urban infrastructures (e.g., power and transportation systems) and the natural environment (e.g., floods, earthquakes, meteorology). As part of the first-year pilot project, the dispersion of a toxic vapor spill was simulated in north Dallas (LANL 2003). The simulation involved modeling flow and plume dispersion around two buildings and then tracking the plume over several kilometers. The microscale modeling was performed using a computational fluid dynamics model called GASFLOW and the mesoscale modeling was done with the HOTMAC-RAPTAD system. The toxic plume concentration fields were then used by the Transportation Analysis and Simulation System team to compute exposures to the cars traveling through the plume.

3 INTEGRATED DISTRIBUTED SIMULATION FOR EMERGENCY RESPONSE

The value of the outputs of modeling and emergency response simulation tools can be enhanced many times if they can be brought together to address all aspects of one emergency incident. This section presents an operations' concept of the emergency response with a set of integrated simulation tools together addressing the whole picture.

An explosion at a commercial building results in a major fire and casualties. The information reaches the 911-call center within a couple minutes of the occurrence. First units of police and fire vehicles arrive at the scene in five minutes. The explosion happened at a peak business hour and appears to have resulted in a large number of casualties on a high floor of the building. All indications are that an explosive device was used and detonated remotely. The explosion was strong enough to be recorded on the seismograph at a nearby university research center.

The city's first responders have been trained using simulation tools for explosions in buildings. Arriving first responder units note some debris half a mile away from the scene as they are driving in and enter it into their incident response system. This data and other tactical information entered by the first responders goes real-time into the Consequence Management Interoperability Services (CMIS) system. The Incident Command System (ICS) at the Emergency Operations Center (EOC) receives messages reporting the massive scale of explosion together with the input from the university seismograph and sends activation messages to pre-selected personnel from pre-selected agencies. The Incident Commander requests activation of the emergency response modeling and simulation system (ERMSS) with the known parameters of the incident.

The ERMSS starts accessing the required data on the incident including:

- Detailed street map, including location of emergency response locations
- Detailed building configuration and structure drawings
- Building use information to estimate the number of people in the building
- Community layout of nearby buildings and expected occupancy for the hour and risk for structural damage from the explosion
- Traffic density in the local area based on the time of the day
- Hospital locations and capacities
- Availability of emergency response personnel at the time of the day
- Information network for city, state, and federal agencies.

The ERMSS calls on the required simulation capabilities for the specific incident. The data is used to initiate a set of integrated simulations within 10 minutes of the explosion. The simulation capabilities are organized at designated centers of expertise. For this incident, simulation of the following events and activities is required:

- Explosion and its impact on the structure of the building
- The fire as a result of explosion, its growth through the building and its impact on the structure of the building and the occupants
- Flow of information on explosion and fire to emergency response agencies. This will include 911 calls and subsequent dispatching of police, fire and ambulance vehicles. This will also include the flow of information to the city, state and federal agencies.
- Response by emergency vehicles including their travel from their base locations and their actions at the emergency scene
- Traffic around the emergency site that may interfere with the movement of emergency response personnel
- Movement of injured by ambulance to hospital
- Hospital operations and capacity for caring for the injured.

The ERMSS invokes the following simulation models at different centers of expertise across the nation and providing the above required capabilities:

- A building and fire simulation model
- A traffic simulation model
- An information flow simulation
- A hospital simulation.

The models are able to read all the data as it is provided in a standard format. All of the data and the models comply with the respective standards facilitating the rapid generation and execution of the models specific to this incident. Figure 1 shows the example scenario together with the simulation capabilities and data needs.

While the simulations are executing, the first responders are moving into the building. The building and fire simulation model provides its results within 10 minutes of being invoked by the ERMSS, that is, 20 minutes since the original explosion. The ERMSS starts flashing a warning of a floor caving in. At 25 minutes past the explosion, the JOC sends the call to first responders to evacuate the particular floor. The building simulation results show that the rest of the building is not in danger, and the first responders continue their operations on other floors. No first responders are injured.

The JOC calls additional help based on the extent of casualties predicted by the simulation model. Additional first responder units are called. Information is sent out to additional hospitals to bring in additional emergency staff. The police close one major artery to all traffic and keep it open for use by emergency vehicles.

Emergency vehicles arrive at times close to simulated schedules and receive their orders from the incident commander. The victims are rapidly moved out from the site to designated hospitals, severe injuries to the nearest ones and non-life threatening ones to hospitals further away. There is no moving around of ambulances from one hospital to another as each hospital receives only the number of casualties that can be accommodated.

Data from the site is continuously fed through CMIS. Large variance between simulated and actual events trigger new simulation runs thus closing the loop.

The benefits of the modeling and simulation in this scenario can be summarized below:

- The first responders are better equipped with an understanding of what to expect based on training simulations.
- The structural damage and imminent danger is known and results in safety of first responders.
- The knowledge of the damage being limited to certain floors allows continuation of operations on other floors enabling faster rescue of casualties.
- The traffic is managed better based on simulation results.
- The casualties are taken directly to appropriate hospitals without any backtracking and confusion.

The above scenario admittedly requires a number of technical and functional implementations. Most of the required technology is available now, what is needed is to bring all the pieces together enabled by a set of standards. The example demonstrates that synergistic use of the available capabilities can make significant improvements in emergency response capabilities of the Nation.

The above example highlights the need for integration of multiple component models required for complete modeling of a single emergency incident. Similarly, the capability of modeling other emergency incidents ranging from man-made events such as release of a hazardous bio-agents to natural events such as hurricanes will require integration of a myriad of modeling and simulation tools and databases. Simulation can be an effective tool for planning responses to terrorist attacks, training response personnel, and providing decision support capabilities if an event occurs.

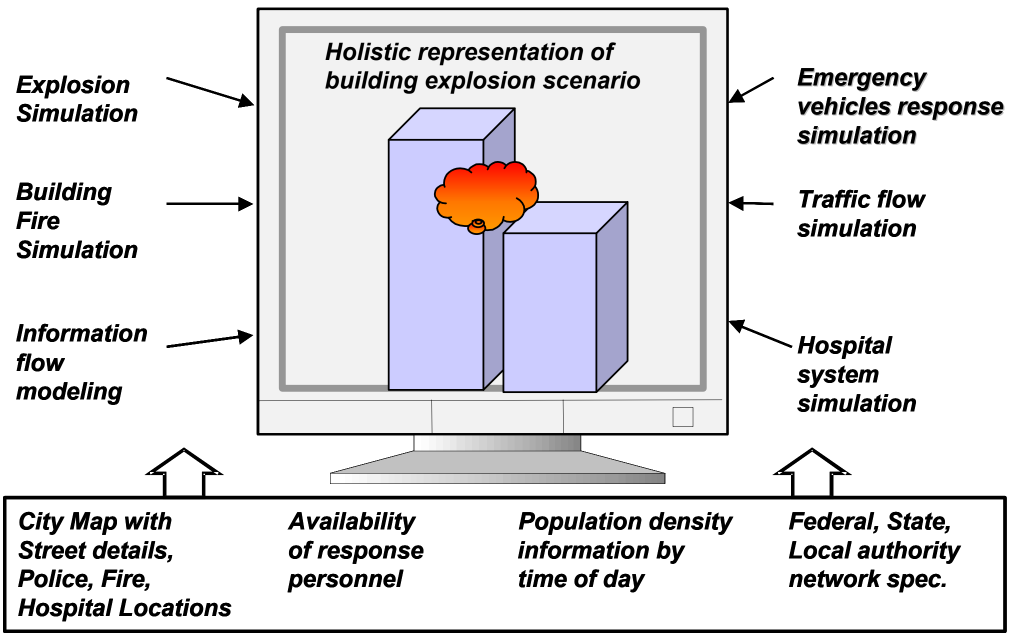

Figure 1: Component Models and Data Required for Modeling of a Commercial Building and Fire Scenario

4 CHALLENGES

A number of challenges need to be addressed to reach the stage of rapid integration and use of simulation models as envisioned in section 3. These challenges are parallel to those faced in the field of manufacturing simulation as described by Mclean and Leong (2001). Among the challenges, the "interoperability challenge" is particularly significant. Interoperability includes a number of system integration, data translation, and model development issues. What is the nature of this problem?

1. Interoperability between emergency response modeling and simulation applications is currently extremely limited.
2. The cost of transferring data between emergency response simulation software applications is often very high.
3. The simulation model development process is labor-intensive.

In addition to the "interoperability" issue, several other factors are worth noting:

- Building simulation models from "scratch" is a high expertise requirement and time-consuming process. Typical emergency response organizations usually do not have the technical expertise or the time for building simulation models.
- When a simulation involves a new system, process, or technology, good reference models or historical data may not be available to support the development effort (Law and Kelton 2000).
- Simulation model developers typically require considerable training and a diverse set of skills to be effective in their job (Rohrer and Banks 1998).
- Simulation models must be verified and validated. Does the model accurately represent the system or the process being modeled (Knepell and Arangno 1993, Balci 1998)?
- Interpretation of the simulation output data might not be a straightforward process. Even after considerable resources are invested in the development of simulation models, it may not be clear what action should be taken based on the results.

The challenge is to create modeling and simulation tools that have the capability to rapidly and automatically create a model configured to a specific disaster event occurring at a specific locale. The tools should be validated and proven using a wide range of scenarios prior to being made available for use. The simulation tools need to be completely data driven and the data needs to be available in standard formats. The tools needs be interoperable to allow bringing them together for an integrated distributed simulation of the whole scenario. For example, in one case the users may need to integrate a plume simulation, a traffic simulation, and a gas distribution network simulation, while in another case, one may need to integrate a building and fire simulation, a traffic simulation and a hospital simulation. The goal is to provide a number of interoperable modeling and simulation tools, an ability to select and integrate the appropriate tools based on the emergency situation at hand, and to create a simulated representation of the situation using data available in standard formats and structures.

5 PROPOSED INTEGRATED EMERGENCY RESPONSE FRAMEWORK

A number of efforts based on using modeling and simulation for emergency response were briefly described in section 2. While all these are laudable efforts, it is clear that their impact on the emergency preparedness can be significantly higher if they were to be integrated together for coherent analysis and planning of emergency events.

5.1 Integrated Emergency Response Framework (iERF) Concept

An integrated Emergency Response Framework is defined in this section to enable an organized approach to use modeling and simulation for emergency response. The emergency response domain can be classified using various criteria, but the three major dimensions are described below.

5.1.1 Disaster Event

The emergency response agencies have to respond to a number of man-made and natural disaster events. The report by the National Research Council (2002) identifies nine focus areas for countering the threat of terrorism (man-made disasters) using science and technology: nuclear and radiological threats, human and agricultural health systems, toxic chemicals and explosive materials, information technology, energy systems, transportation systems, cities and fixed infrastructure, the response of people to terrorism, and complex and interdependent systems.

The disaster event will have large influence on the kind of modeling and simulation capabilities that need to be brought together. For example, a building explosion and fire event requires capabilities for modeling the impact of explosion and fire on the building structure and its occupants, while a hazardous release in the atmosphere requires capabilities to model the dispersion of the release in the atmosphere. Admittedly there are some capabilities that are required for a number of scenarios, such as traffic simulation and information flow simulation. Also, a few of the man-made and natural disasters may have similar impact. For example, forest fires can be initiated by intentional or unintentional actions of people or by natural causes.

5.1.2 Entities of Interest

The interest of all the agencies is to minimize the impact of disaster events on entities of interest. These include first and foremost, the human population. The impact of the disaster also needs to be understood and contained on the resources, in particular, on the infrastructure resources.

The response agents are the second major class of entities of interest. The actions of response agents need to be modeled to understand how they can contain and mitigate the impact of the disaster event. It is quite possible that the response agents will become the affected entities of interest themselves, for example, fire personnel suffer injuries while fire fighting. The models should allow understanding of the risk exposure for the response agents. The planners can test out different strategies that minimize the risk exposure for the response agents while allowing them to contain and mitigate the impact of the event

5.1.3 Applications

The capability of the needed modeling and simulation tools will differ based on the application for which they are designed. An application for understanding the impact of the disaster event will have capabilities somewhat different from one for training emergency response personnel. The training applications will have more interactive features and the ability to unfold alternate simulated event sequences based on the response of the trainees. Similarly, applications for identification and detection of threat will have capabilities for pattern matching against a number of historical scenarios to determine the likelihood of threat development. Various applications for the emergency response domain are briefly described below.

5.1.3.1 Planning

The planning application will include tools for determination of impact of a disaster event and the tools for aiding development of the response action plans and strategies. The planning applications can range from those for long term issues such as location of emergency response facilities and manpower or for focused issues such as aiding development of specific response procedures. Examples of planning applications include:

- Location of police and fire stations and hospitals
- Development of evacuation procedures
- Setting up a communication infrastructure.

5.1.3.2 Vulnerability Analysis

The vulnerability analysis application is focused on evaluation and assessment of emergency response preparedness plans and strategies. Modeling and simulation tools can be used to create a number of disaster event scenarios and evaluate the performance of action plans and strategies. Examples of vulnerability analysis applications include:

- Evaluation of security plans and procedures at a nuclear plant
- Evaluation of city emergency response plans.

5.1.3.3 Identification & Detection

The identification and detection application will include use of tools that study given scenarios and determine the possibility of the occurrence of a disaster event. It is anticipated that such tools will use pattern matching logic and past history databases to identify and detect potential threats. Examples of identification and detection applications include:

- Selecting security sweep targets in areas with majority of inhabitants from a target background
- Identifying the potential of tornado occurrence given the weather conditions.

5.1.3.4 Training

The training application will include tools that allow training response agent personnel for handling emergency events. These may include interactive simulations where the tools create an imaginary scenario and the trainees input their response actions. The tools will help evaluate the response actions and thus help the trainee learn what works best under a given situation. These tools may range from interactive simulations using a monitor to totally immersive environments. Examples of training applications include:

- Antidote deployment sequence
- Evacuation management.

5.1.3.5 Real-time Response Support

The response application will include tools that evaluate the impact of a disaster through real-time updates on the situation, and use the available information to project current and future impact of the disaster. It also includes tools for evaluating alternative response actions and strategies based on the current and projected impact. The evaluations are then used to direct the response actions on the ground. Examples of response applications include:

- Antidote deployment sequence
- Evacuation management.

Figure 2 shows the concept of an integrated Emergency Response Framework (iERF). The three major dimensions described above form the three axes of the cube that is used to represent the emergency response domain. Each cell in the top half of the cube along the entities of interest dimension will capture the impact of a particular disaster event on a particular entity of interest. Cells along the lower half of the cube along the same dimension capture the response by a particular response agent for the

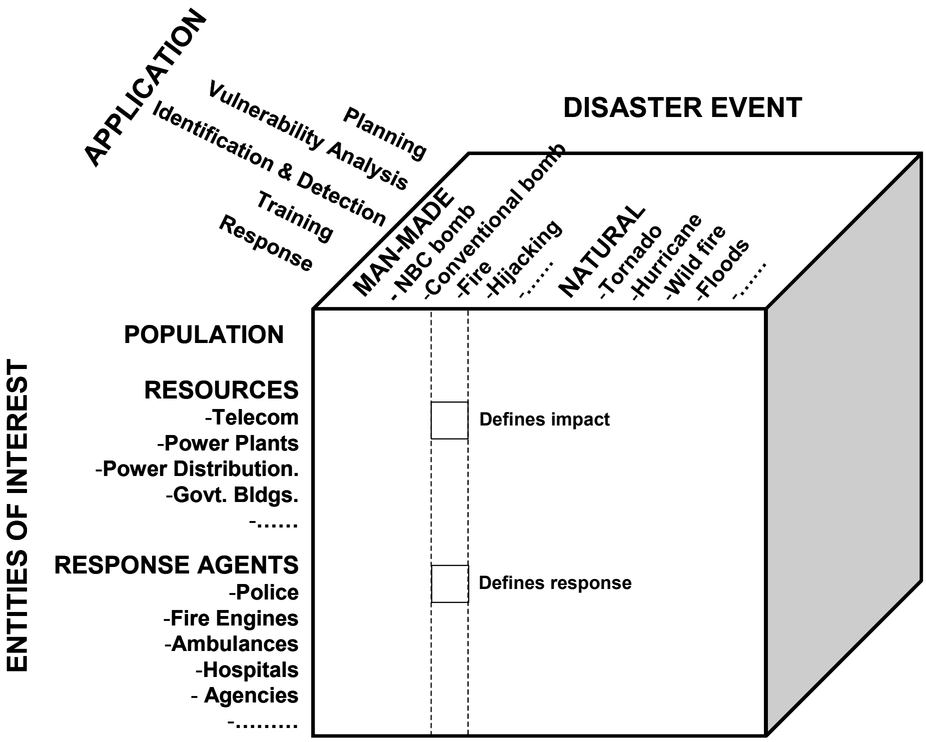

Figure 2: Integrated Emergency Response Framework (iERF)

specific disaster event. The location of the cell along the application dimension classifies the capability of the tool for modeling and simulation of the impact of the specific disaster event on specific entities of interest.

5.1.4 Example Scenarios in iERF

The following example scenarios in iERF demonstrate its use for planning emergency response events. Other applications can be similarly supported using the framework. The example in Figure 3 shows the iERF representation of a planning application of a man-made disaster event, release of anthrax at a public place. Modeling and simulation tools are used for creating this imaginary scenario and testing out the efficacy of the response agents. Modeling and simulation tools will be used to determine the dispersion of the virus based on the method of release, the wind patterns in the area, and the building structure. The building-use data will help model the number of people exposed to the virus. Human behavioral models will help estimate the panic reaction of the population and the resulting rush to evacuate the area. The resulting traffic jams will be modeled using traffic simulations. Action plans and strategies for the response agents can be evaluated by integrating the models with models previously discussed for charting out the impact of the anthrax release.

The framework can also be used in a real-time response support application for the same event, anthrax release, by having the actual situation data fed in for the impact of the release as it becomes available. Modeling and simulation tools can be used to supplement the current impact estimates until real time information becomes available. The tools can project the impact in near future and the response plans evaluated with respect to current and projected events. Selected plans can then be implemented by the response agents.

5.2 iERF Modeling, Simulation and Visualization Tools

The iERF will utilize a wide range of modeling and simulation tools. The tools will vary based on their application, disaster event, and their consideration of entities of interest as discussed in the previous section. In addition they will vary based on the scope and abstraction level (or the level of detail) and the modeling technique used.

The scope of the tools can vary from national level modeling for large disaster events such as volcanic explosions to those modeling a city block for a scenario like a building explosion and fire. A tool may have the capability to model at more than one abstraction level.

The modeling techniques may include:

- State graphs
- Agents and objects
- Systems dynamics simulation

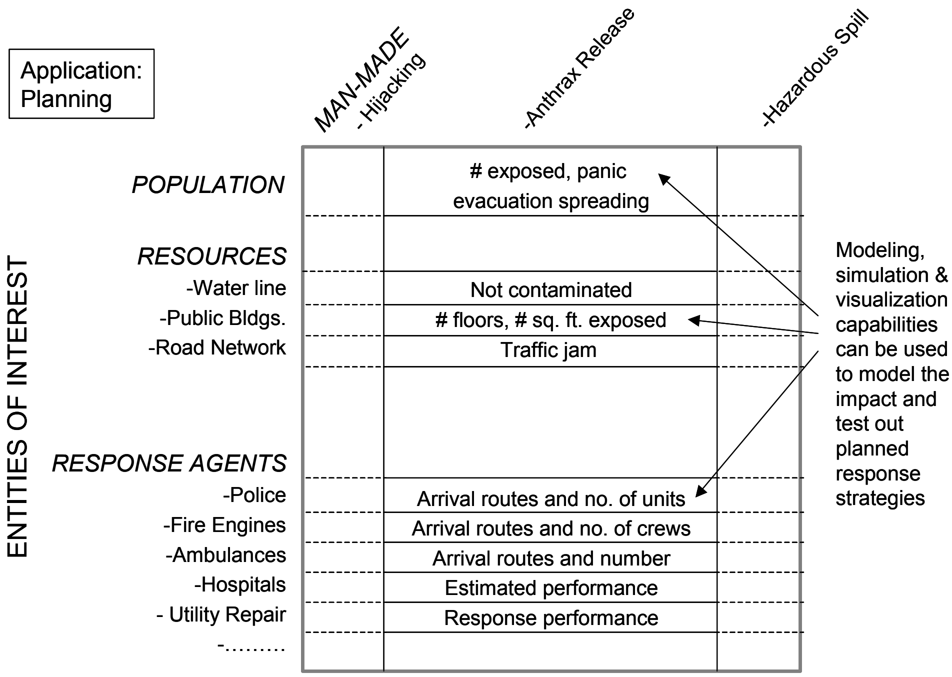

Figure 3: iERF Representation of a Planning Application for an Anthrax Release at a Public Place

- Discrete event simulation
- Physical process simulation employing models that use equations capturing the physical phenomenon
- Emulation or live exercise supported by simulation models.

6 CONCLUSIONS

The need for improved emergency response can be met by extensive use of modeling and simulation tools. A number of individual M&S efforts for emergency response are already in progress, however, each individually can address only a small part of the problem. Effective emergency response requires a coordinated response by all responsible agencies. Effective use of modeling and simulation requires study and analysis of all aspects of a disaster event occurrence and its follow through. Modeling and simulation of all aspects can be achieved by integrating the individual tools that model complementary aspects of the disaster event. This paper proposed an integrated emergency response framework for modeling and simulation of emergency response. The need for interoperability of modeling and simulation tools was highlighted. Requirements for data and architecture standards need to be established as a first step towards such interoperability.

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