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A Simulation Environment for the Dynamic Evaluation of Disaster Preparedness Policies and Interventions

Bryan Lewis, PhD MPH, Samarth Swarup, PhD, Keith Bisset, PhD, Stephen Eubank, PhD, Madhav Marathe, PhD, and Chris Barrett, PhD

Network Dynamics and Simulation Science Laboratory, Virginia Bioinformatics Institute, Virginia Tech, Blacksburg, VA, USA

Abstract

Disasters affect a society at many levels. Simulation based studies often evaluate the effectiveness of one or two response policies in isolation and are unable to represent impact of the policies to coevolve with others. Similarly, most in-depth analyses are based on a static assessment of the “aftermath” rather than capturing dynamics. We have developed a data-centric simulation environment for applying a systems approach to a dynamic analysis of complex combinations of disaster responses.

We analyze an improvised nuclear detonation in Washington DC with this environment. The simulated blast affects the transportation system, communications infrastructure, electrical power system, behaviors and motivations of population, and health status of survivors. The effectiveness of partially restoring wireless communications capacity is analyzed in concert with a range of other disaster response policies. Despite providing a limited increase in cell phone communication, overall health was improved.

Keywords

simulation; agent-based; disaster; preparedness; communication

Introduction

Disasters whether natural or human initiated remain a critical challenge for our societies. However, the increasing inter-connectedness of our society both through near ubiquitous cellular communication and rise in social media use abetted by increased smartphone prevalence presents a great opportunity to improve our response capabilities¹. Similarly, improvements in computer simulation technologies provide opportunities to enhance our ability to prepare. We present a novel simulation approach that facilitates the dynamic evaluation of policies and interventions in the days following disasters.

Much is understood about the keys to enhancing community resilience in the face of disasters.²⁻⁵ Much of this is based on previous experience and careful consideration of

Supplemental Digital content

Movie: Displays a mid-range view of ground zero. From the fallout cloud gradient of dose-rate,

Document: A list of data sources used by each module in the simulation environment

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hypothetical situations,⁶⁻⁹ yet gaps remain in our understanding as disasters present challenges for scientific study.¹⁰⁻¹² Data collection and experimentation are hardly concerns during the immediate response stage, and their unpredictable nature eludes controlled experimentation. However, we still need to collect data to inform our decisions and to evaluate how to turn our scientific knowledge into action.¹³ Simulation frameworks provide a natural environment for this endeavor.

A primary challenge faced by simulations attempting to represent an event as complex as a major disaster is accommodating the actions of the people affected by the disaster and the cascading of effects of these actions. These cascades, a common characteristic of complex systems, result from the interdependencies between the entities in the system. We address these challenges by using an agent-based approach where each individual in the population is guided by central motivation and chooses actions based on that motivation, their local environment, and their assessment of their situation. Additionally, we use a relational database to coordinate multiple distributed computational modules, which accommodates the inclusion of large numbers of interdependencies, thus allowing the effects of different actions to cascade through the simulated system.

To demonstrate the capabilities of this simulation environment we prepared a study to evaluate the potential benefits of partially restoring cellular communications following a large-scale disaster, specifically an improvised nuclear detonation of a 10 kiloton device in downtown DC on a weekday morning (for our purposes 16th and K Street at 11:15am on May 15, 2006). The prospect of an unanticipated nuclear detonation in a large metropolitan area has been considered and analyzed extensively.¹⁴⁻¹⁷ This event is overwhelmingly physical and destroys a large section of DC, causes widespread damage to buildings and roads, produces a plume of radioactive fallout that eventually stretches across rural Maryland, disrupts power to a broad area, injures 97,000 individuals, and kills 279,000. Due to space limitations, we provide an overview of the main features and capabilities of this approach, and briefly describe the outcomes to the study.

Methods

The simulation environment uses a data-centric agent-based approach and is centered on a relational database to coordinate multiple distributed computational modules. The database captures the state of the world at different time points and each of the modules updates this state for specific domains: Health, Behavior, Communication, Physical Effects, and Power. This database was initially populated by a series of data fusion and refinement steps specific to the population and the infrastructures represented.

For this study, we selected a population that would experience some effect from the blast. Specifically, we chose a contour line around at least 2.1 cal/cm² of thermal radiation and at least 0.01 rad/hour of radiation from fallout (at 1 hour following the blast). This includes 730,833 people in the District of Columbia and Prince George's County Maryland (Figure 1, inset).

Population

At the heart of the simulation each individual is represented and possess key attributes that determine their motivations and responses to the changing environment in which they are immersed. Using demographic distributions and sample household information from the American Community Survey 2009 (ACS) we generate synthetic individuals and place them in households while maintaining the demographic distributions. An iterative proportional fitting algorithm¹⁸ is used to ensure that joint distributions are preserved down to the block-group level. Thus the synthetic population has a detailed representation of household

structure, age, gender, and income level that will produce the same block group distributions as the real population, while maintaining the anonymity of the population.

Individuals in this synthetic population are assigned activity templates which were derived from the National Household Travel Survey (NHTS) and the National Center for Education Statistics (NCES) based on demographics. These activity templates contained both the type (eg. home, work, school, shopping, other) and timing of the activities. This approach generates a dynamic “*in silico*” society where each individual moves between its activity locations throughout the simulated day in a very realistic approximation of the represented population¹⁹. Additionally, populations that aren’t represented in the ACS, like tourists and students living in dorms were added.

Infrastructures

The behaviors and movements of the individuals are constrained by the physical world around them. A highly detailed representation of the physical world was constructed based on locations. Locations are any geo-locatable site that has an attribute that could be influenced by the event or would influence the movement or behavior of an individual. A listing of the data sources used and links when open-source can be found in the supplemental digital content.

For the **Power** module to determine which locations maintain power after the event, the electric grid was added to the database, and the impact from the blast estimated. Additionally, the power load shift immediately following the blast was simulated separately and found a high probability that the power outage would cascade further reducing the area with power.

For the **Communication** module to route cellphone calls, the location of all the cell towers were loaded into the database. The module handles each call in the order initiated by the agents and determines when the tower will be over capacity and starts to reject calls. Several towers are destroyed by the blast itself, and many more are without power. The power level of the backup batteries at each tower is also taken into account as is the “Emergency Broadcast” system (Commercial Mobile Alert System) messages. This module also determines the placement of the mobile “cells on wheels” that begin to arrive to restore communications in areas without power (in the branch of the study with partial communication restoration).

For the **Physical Effects** module to update the built infrastructure based on the effects of the event, data from a NucFast simulation of the nuclear blast was imported into the database. This included a temporally dynamic location of thermal radiation, blast overpressures, and their subsequent damage to the buildings, taking into account the type of building. Additionally the radiation both prompt and from fallout were also calculated over a 72-hour period, and the module updates these dynamic effects.

Agent Dynamics

In a disaster several factors play into the actions and movements of an individual. Primarily their actions are determined by the time from the event, their physical well being, their knowledge of their current risk, and their ability to ascertain the safety of their loved ones. The simulation updates the state of the individual and is influenced by the physical environment, which is driven by the infrastructure modules (Figure 2).

The Behavior module coordinates the motivations and actions of an individual. The complex decision-making process of human behavior was simplified into a decision tree (Figure 3), which uses the individual agent’s state (both physical and mental) to probabilistically

determine a primary motivation. These motivations were then used in turn to direct the immediate actions of the individual. **Household Reconstitution** seeks to ensure the well being of their household. To achieve this goal, they will make phone calls and travel towards the location of their household members. They will continue to do so until all members are together, or they know that all members are safely out of danger, at that point they (and whatever members they've gathered) will evacuate the area. Those following an **Evacuation** motivation seek to ensure safety by leaving the area as quickly and efficiently as possible. To achieve this goal if an individual is mobile they will travel towards the closest major "evacuation route" until they are outside of the event area. When **Shelter-seeking** individuals seek to limit exposure to harm from the event outside by finding shelter and remaining there. In this particular study, individuals would try to avoid the effects of the radioactive fallout by finding buildings with minimal damage and remain there for as long as they were healthy or in some cases until their patience ends. The **Healthcare-seeking** motivation seeks to obtain medical attention for an injury. An individual will call 911 if they are unable to move or if mobile they will travel to the nearest hospital. If the individual begins to **Panic** they become irrational and essentially begin following one of the other motivations without regard to other factors. The likelihood of panic reduces over time from the initial blast, such that very few people are panicking after 5 hours. The **Aid and Assist** motivation seeks to rescue and aid small children and the injured. An individual will seek to find others to help at the nearest locations that can provide shelter, and upon finding them will take them to the nearest healthcare location, after which they will then evacuate.

The **Transportation** module calculates routes from the current location to the chosen destination (e.g. healthcare center, home) and updates the location of the individual as they progress to their goal based on time traveled. Routes are based on the road network (also including prominent footpaths), new routes are dynamically generated when the route is blocked by rubble, and progress is slowed when travel is over damaged terrain. To initially place individuals a normal day was simulated and each individual's location at 11:15 was determined, including locations of those in transit either by public transportation or by personal vehicle.

The **Health** module updates the health state of an individual, which in turn drives their behaviors, affects their mobility, and influences their response to treatment. For these purposes a simple model that represents health on a continuum for injury triage (based on the SALT triage²⁰) is used as the main health state. This continuum consists of states from 0 (death) to 7 (full health), with states 4 and lower corresponding to moderate injury or worse. Secondary effects of health (mobility, health care requirements, etc.) are based on this state as are the effects of additional injuries and treatments. Risk of injury is based on the location of the individual and thus captures damage to buildings, roadways, etc. and in the case of this study exposure to radiation.

Healthcare locations consist of the existing hospitals in the area, and mobile health centers that may be deployed following the disaster. The capacity of the health care center is based on the number of employees at the center and the damage it has incurred. Individuals seeking care are evaluated on a first-come first-served basis, after evaluation a triaged queue is created. Individuals who are moderately injured may give up if the wait is too long. If the individual survives until they are treated, their health is adjusted based on the severity and type of their injury (not all treatments are successful).

Response Policies and Interventions

Disasters of the nature of this scenario have been extensively studied by many different parties^{16,17,21} to inform preparedness activities. Many response policies and proposed interventions have been developed and were included in the simulation environment for this

study. Deployment of emergency health care centers ranging from a single well-equipped Humvee to an entire federal medical station were included in the environment, and placed nearly 200 mobile centers in appropriate locations over the 72 hours simulated. Emergency Broadcasts representing the use of the Commercial Mobile Alert System (CMAS) were included in the environment, and receipt of these broadcasts influenced individuals' behavior (Figure 2). Several independent groups provide safe-and-well registries to help disseminate news of an individual's well being. We expanded on these policies and represented a centralized registry that is accessed and updated by any individual who was initially triaged at a healthcare center. Evacuation routes and centers have been identified and were represented in the simulation, which guided the destination choices of individuals seeking to evacuate.

Results

The developed simulation environment represented the complexities of a disaster of this extent and the following 72 hours. The overall effects in terms of injuries (roughly 97,000) and deaths (roughly 279,000) were similar to those produced by other studies. In addition a high-resolution estimate of both place and time of the surviving population was generated. This includes where individuals are seeking healthcare and their level of injury (Figure 1 and Supplemental Digital Content movie), the call capacities on each cell tower, traffic flow throughout the area, and many other details.

The demonstration study focused on evaluating the effectiveness of partially restoring the communications infrastructure. As shown in Figure 4, in the partially restored case more individuals are seeking sheltering and fewer are panicking than in the case with no restoration. Additionally, in the first few hours more individuals are attempting to reconnect with household members due to enhanced situational awareness from emergency broadcasts (EB). Then as more of them are successful, they switch to healthcare seeking, evacuation, and aid and assist. These behavioral differences peak in the early stages following the blast (2.5 hours) yet remain significant for the first 6 hours. Connecting with household members form plans with their households so they are more likely to shelter in place or evacuate rather than remain ignorant of the fate of their household and risk potential injury trying to physically reach them by any means possible. Additional analyses (not shown) indicated that this can lead to several hundred additional survivors and decreases the time it takes survivors to leave the disaster area.

Conclusion

This simulation environment provides the capability to explore the complex interplay of policies and interventions over time following a disaster. The demonstration study illustrates the interdependence of human behavior on the communication infrastructure (which in turn impacts the use of the transportation network for evacuation, access to health care centers, and so on). The study also provides an example for how this tool could be used by emergency planners to inform and evaluate their policies and real-world intervention capabilities. With contributions from a wider range of stakeholders this framework can provide a path to an evidence-based approach to defining our disaster response policies.

The level of detailed data needed to represent a realistic scenario limits this study and simulation environment. While an extensive literature search was conducted and many outside experts were consulted, gathering this volume of data was time intensive and still remains incomplete. Furthermore, the simulation's ability to represent complex cascades of interdependent events presents some unique challenges for analysis and study design. As a

result, and many of the dynamics captured in these simulations have yet to be analyzed and due to space limitations many of the existing results are not reported.

The advantage of this environment, however, is it provides a framework for collecting these disparate data sets. By collecting and defining both the resolution and relation to other data layers, the framework provides a natural environment for collaboration. Analysts from different agencies and academics from different institutions can contribute data and/or computations specific to their area of expertise, which is integrated into the simulation dynamics. This approach supports multiple stakeholders and experts in a way that enables innumerable policy studies.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

A view of ground zero at 90m following the blast, yellow gradient indicates the radiation dosage from fallout. The bars indicate aggregate counts of individuals in different health states (red=severe or dead, yellow= moderate injury, blue uninjured) at the various locations. Inset: outline of disaster study area

Figure 2.

Model interdependencies. How each module is influenced by and influences the others

Figure 3.

Behavior Model. The decision tree used by the simulation to determine the motivations of each individual. Probability of shelter given receipt of emergency broadcast (p) is set to 0.1 in this demonstration study.

Figure 4.
Difference in motivations over time (partially restored – no restoration).