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Agent-based modeling and evolutionary computation for disseminating public advisories about hazardous material emergencies

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ABSTRACT

In the event of a large-scale disaster, an important aspect of humanitarian logistics is the distribution of information or warnings to the affected population. This research develops the problem formulation and solution approach for a specific routing for relief problem, in which warnings should be disseminated to an affected community, using public announcement systems mounted on emergency vehicles. The problem statement is formulated to maximize the number of individuals of a community who are protected. An evolutionary algorithm framework is developed by coupling an agent-based model with a variable-length genetic algorithm to route emergency vehicles. The dynamics of interactions among consumers, emergency vehicles, and the spatiotemporal trajectory of the hazard are simulated using an agent-based modeling approach, and a variable-length genetic algorithm approach selects routes to warn a maximum number of consumers before they are affected by the emergency. The example that is explored in this research is contamination of a water distribution network. A fleet of emergency vehicles is equipped with public address systems and is deployed to warn consumers to stop using contaminated water. The framework is demonstrated for an illustrative virtual city, Mesopolis. The results of the evolutionary algorithm framework are compared with two conventional routing optimization approaches, including a covering tour problem approach and a manual routing approach, for four contamination scenarios. The evolutionary algorithm can be applied to route emergency service vehicles to broadcast information for other emergencies, such as flash flooding, hazardous materials incidents, and severe weather.

1. Introduction

In the aftermath of large disasters, vehicles can be routed to carry critical resources, services, or information to the affected population. Logistical and transportation planning in relief efforts differ from routine decision-making, however, and new problem formulations and solution methods are needed. In planning relief efforts, lead times are low; stakes are high; supply and transportation data are typically unreliable, incomplete, or non-existent; and there are few performance measures that have been established to evaluate success (Beamon, 2004). Classic routing problems that are formulated to minimize cost, total travel time, or tour length do not properly reflect the relevant priorities in disaster relief. Deliveries should be fast and also fair to the affected population. For example, Campbell, Vandenbussche, and Hermann (2008) explored vehicle routing for relief efforts and formulated problem objectives to minimize suffering and the loss of life for a set of static demands. The traditional traveling salesman problem has been reformulated for application to relief effort planning by minimizing the cumulative waiting time of customers, rather than minimizing the tour length of a vehicle (Ngueveu, Prins, & Calvo, 2010; Ribeiro & Laporte, 2012). Relief operations may also be represented as maximal covering tour problems, in which stations and routes are selected to maximize the demand that is covered (Doerner, Focke, & Gutjahr, 2006; Naji-Azimi, Renaud, Ruiz, & Salari, 2012; Noltz, Doerner, Gutjahr, & Hartl, 2009; Tricoire, Graf, & Gutjahr, 2012).

The research presented here is motivated by the need for vehicle routing for a specific case of humanitarian efforts, in which information or warnings about a hazard should be disseminated to an affected community as a crisis progresses. To broadcast emergency information in disasters such as flash flooding, hazardous materials incidents, and severe weather, emergency service vehicles can be equipped with sirens and a built-in public announcement system (Golnaraghi, 2012). Alerts are disseminated by vehicles, which follow predetermined routes to warn citizens in designated neighborhoods. To distribute information most effectively, vehicle routing should be coordinated with the movement of the population and the concurrent spatiotemporal movement of the hazard. Individuals in the population may be mobile, adjust resource use, and exchange information about the emergency, which increases the dynamic and complex nature of the problem. For the problem of distributing information, the routing problem is formulated here to protect lives, rather than meet demands or minimize travel time.

An optimization approach is developed here to route vehicles for the dynamic problem described above. More broadly, this study explores

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the improvement in routes, based on the number of lives saved, that are identified using dynamic optimization with respect to static optimization. In the system defined in this research, the routing ecosystem is changing due to the interactions and movement of consumers and the hazardous material and is represented using an agent-based modeling approach. Routes are developed to distribute information or resources by anticipating the movement of hazardous material and the interactions of consumers. An agent-based modeling (ABM) approach is developed to simulate the dynamics of the transport of a hazardous material, the movement of emergency vehicles, and the exposure of individual members of a community based on their movement in a city and their communication about the event. While ABM has been used in many studies for vehicle routing (e.g. Baykasolu & Kaplanolu, 2015, Dia, 2002, Martinez, Correia, & Viegas, 2015), few studies have applied ABM for vehicle routing in emergency conditions. These studies simulate driver decisions in evacuation of urban areas (Chen, Meaker, & Zhan, 2006; Chen & Zhan, 2008; Naghawi & Wolshon, 2012). An optimization problem is formulated to maximize the number of consumers that are protected, or warned before they are affected by a hazard. An optimization approach is developed using a variable-length genetic algorithm (VGA), which uses a variable-length chromosome to represent routes of any length (e.g., number of nodes) for a fleet of vehicles. The VGA is coupled with the ABM to design tours for a fleet of vehicles to protect consumers. The simulation-optimization approach is demonstrated for a hazardous material emergency in which a water supply system is contaminated with arsenic. The framework is developed and demonstrated for routing emergency vehicles to warn consumers to change their use of contaminated water.

The remainder of the paper is organized as follows. Section 2 describes the characteristics of a water contamination event and the actors who are involved. Section 3 formulates the vehicle routing problem as a conventional Covering Tour Problem (CTP) and describes the application of an established approach, a coupled genetic algorithm (GA) and ant colony optimization (ACO), to solve it. Section 4 formulates the new routing problem to maximize the number of consumers who are protected, which introduces additional complexity to the problem definition. An evolutionary algorithm framework is developed in Section 5 for solving the vehicle routing problem by coupling a VGA and ABM. The evolutionary algorithm framework is applied for a mid-sized virtual city that is based on realistic pipe network characteristics and demographic data for a population of 150,000, as described in Section 6. A set of contamination scenarios are described in Section 7, and results are reported in Section 8. Results that are identified using the evolutionary algorithm framework are compared with a manual approach and the covering tour problem approach, which neglect the complexity of *sociotechnical* interactions among society, emergency services, and infrastructure, as the event progresses. Results demonstrate that the sociotechnical dynamics of a water event alter the effectiveness of routes for emergency vehicles, and the evolutionary algorithm framework identifies routes for a fleet of emergency vehicles that protect a larger number of consumers, compared to other routing approaches.

2. Water supply contamination event

Public health is threatened when chemical toxins or bacterial pathogens enter water distribution networks through deliberate actions or accidental incidents and are delivered to a large population dispersed over a wide geographical area (Hrudey & Hrudey, 2004). A water contamination event is a dynamic and complex event in which the interactions among the social and infrastructure systems create a sociotechnical system (Vicente & Christoffersen, 2006). The movement of the contaminant in the pipe network and public health consequences emerge from a set of complex adaptive interactions between consumer demands, utility operations, and the water distribution infrastructure (Rasekh, Shafiee, Zechman, & Brumbelow, 2014; Shafiee & Zechman, 2013; Zechman, 2011, 2013). A contaminant that enters a water network may be detected by water quality sensors, which alert managers about the threat of a contaminant. Once a contaminant is verified, a utility manger can select actions to protect consumers, including warning consumers to encourage a reduction in water contact uses. Consumers may become aware of a contaminant through symptoms of exposure, public advisories, and communication with peers and family members. As consumers reduce their use of water, they change their water demand patterns and the movement of contaminant plume from its expected coverage of the network.

Using public announcement systems mounted on emergency vehicles can be an effective approach to warn and protect consumers during an emergency (Perry & Lindell, 2003; Sorensen, Shumpert, & Vogt, 2004). Sorensen and Rogers (1988) report that 16% of communities with hazardous materials industries rely on route alert or door-to-door as a warning system, and 45% of these communities rely on a combination of media reports, emergency alert (siren) systems, and door-to-door or route alerts. Though recent technologies, such as microblogging and text messaging, may seem to make the use of route alerts obsolete, utility managers may continue to use route alerts for specific cases. In addition, recent surveys that were conducted to estimate the perception of consumers with warnings during a water contamination event show that only a portion of consumers complied with warnings after a water main break in Boston (Lindell, Mumpower, Wu, & Hwang, 2010). Similarly, surveys conducted in West Virginia after the Elk River Spill that occurred in January 2014 report that 37.0% of households surveyed under the Do Not Use order used West Virginia American Water (WVAW) water despite knowing about the restriction, 78.8% of these households reported showering in contaminated water, 46.8% reported using water to wash hands, and 27.7% reported drinking water or using it to prepare food (Disease Control et al., 2014). A mere 2.3% of households interviewed first learned about the Do Not Use Order from social media. It is evident that rigorous strategies are needed to warn an entire population and communicate real threats of danger, and while social media provides a promising strategy, it may not be the most effective approach in all communities at the current time. Cities such as San Francisco, CA, have developed plans to alert citizens about evacuation orders through several media outlets, including plans for officials to drive with bullhorns through an evacuation zone to make roving announcements. For emergencies in which citizens lose power, public-address vehicles may be the most effective broadcasting system. Route alerts may also be more effective in localized events in densely populated areas, such as college campuses and urban centers. Managers may select to use route alerts to communicate the severity of an event directly and reach segments of the population who may not use television, radio, or text messaging.

The effectiveness of routes chosen for emergency vehicles may be significantly impacted by sociotechnical interactions during an event. Public health consequences of emergencies emerge from complex dynamics, including interactions and feedbacks among consumers and the water distribution system. Consumers travel throughout a city during a day, and these patterns can impact their proximity to a vehicle route and their communication with other consumers about the presence of a contaminant threat. As consumers receive information about a water event, they may dynamically update their water demands by adopting personal protective actions to reduce their use of water and exposure to the contaminant. The exposure of any consumer depends on the route of the emergency vehicles, travel among nodes, consumption of contaminated water at diverse locations in a network, and changes in personal water use activities based on exposure symptoms and alerts about the event. As consumers change their water use, new demand patterns can change the flow directions and volumes in the pipe network and expose a different segment of the population than would be originally expected or predicted.

An agent-based modeling-water distribution (ABM-WD) approach is developed to address the complexity of a water contamination