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A location-allocation model for casualty response planning during catastrophic radiological incidents

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ABSTRACT

A radiological incident is an event whereby the release of radioactive material leads to significant consequences to people, the environment, and facilities. It has the potential of being catastrophic. We seek to analyze casualty response to such an event by addressing issues such as the creation of surge capacity, casualty prioritization, and the incorporation of self-evacuees in planning. We develop a location-allocation model that locates alternative care facilities and considers triage and the movement of self-evacuees in devising a casualty allocation plan for catastrophic radiological events. The model minimizes the total weighted transportation time of casualties and uses triage results to tactically prioritize casualties, while considering resource limitations. We apply the model to the case study of a radiological dispersal device situation in Los Angeles. With analysis of the resulting optimal plan and sensitivity analyses on the budget of alternative care facilities and on medical center triage capacities, we come up with several rules of thumb for casualty response planning. Our model aims to help central planners respond effectively to radiological incidents and better understand the response supply chain. It can thus help avert deaths and reduce suffering, especially in the current climate, where the increasing threat of terrorism is raising concerns over the next radiological attack being more in the offing than ever.

1. Introduction

A radiological incident is an event whereby the release of radioactive material leads to significant consequences to people, the environment, and facilities. Its main sources include attacks on nuclear power plants, nuclear reactor meltdowns caused by human error or by the impact of natural disasters, and radiological dispersal devices (RDDs), or “dirty bombs” as they are known. Historical examples of radiological incidents are: the Three Mile Island accident in 1979, the Chernobyl disaster in 1986, and the Fukushima-Daiichi nuclear disaster in 2011. For the sake of distinction from nuclear incidents, we note that radiological incidents involve only small, if any, explosions and no nuclear fission.

Radiological incidents have the potential to be catastrophic. Casualty estimates due to an explosive RDD, which depend on many factors, such as the type and size of the device and weather conditions, can reach from the hundreds to thousands [22]. A Cesium-137 RDD, for example, can have catastrophic effects because of the penetrating nature, high dispersibility, high solubility, and long half-life (30 years) of Cesium-137 radionuclides. Increasing threats of terrorism and the higher likelihood of natural disasters – such as the Tohoku earthquake and tsunami responsible for the Fukushima-Daiichi disaster – due to climate change have recently raised concerns over radiological incidents. In 2007, two separate U.S. Homeland Security Presidential Directives were released, providing suggestions on measures to respond to catastrophic health events resulting from chemical, biological, radiological, and nuclear agents (see Refs. [49,50]). Various reports have ensued, with focus on radiological incidents (see Refs. [32,45]). Some in the research community have evoked the imperative of studying casualty response to nuclear/radiological incidents, ever since the September 11 attack on the World Trade Center (see Refs. [12,34,58]). Until now, research has come out with frameworks, such as the “RTR” framework [24], the radiological dispersal device playbook [37], and the bioterrorism preparedness and response framework [7], to triage, transport, and treat casualties during radiological catastrophes. Albeit providing guidelines on casualty response, these frameworks leave many issues, such as how many casualties to transport from one facility to another, open to ad hoc decision making. This can lead to ineffective implementation.

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Quantitative research is necessary. This paper focuses on using optimization modeling, in the form of a location-allocation model, to systematically plan tactical casualty response during catastrophic radiological incidents. The model provides a location plan for alternative care facilities (ACFs) and an allocation plan for casualties, while taking into account casualty triage and the movement of self-evacuees.

ACFs are facilities, such as schools, parks, and stadiums, where emergency responders can stage casualty triage and treatment. These facilities, usually manned by ancillary personnel, such as military and paramilitary teams, create additional surge capacity during incidents where the number of casualties is too large for existing medical centers to handle. In a catastrophic radiological incident, ACFs can act as shelters for evacuees and also as assembly points where triage, decontamination, and even treatment for those who do not require hospitalization can take place [11,52].

To have effective ACFs, incorporation of triage in planning is required. Triage is the process of running initial diagnostics on casualties so as to determine the types of treatment they need and the urgency with which they need these treatments. It is essential during most disasters where resources are insufficient to treat all casualties immediately [26]. Without it, a response system in a radiological incident may, for example, end up with casualties with low radiation doses occupying limited hospital capacities ahead of those with severe contamination. Researchers have extensively highlighted the importance of triage in radiological incidents (see Refs. [6,8,35,55]). There is limited guidance on triage for catastrophic situations [23]. Our model focuses on tactical triage, which involves sorting casualties depending on what kind of facilities can treat them.

Without a proper location-allocation plan, the benefits of ACFs and triage will, in all probability, fail to materialize. An important factor in such a plan is the movement of self-evacuees. Self-evacuees can overwhelm resources and block the way for more severe casualties [41]. In most disasters, they form the most significant part of the response system. The September 11, 2001 terrorist attack on the World Trade Center counted 85% of its victims as self-evacuees [14]. In the 2004 Madrid bombing, the Gregorio Maranon University General Hospital, the closest hospital from the attack site, reported that around 78% of the casualties it received were self-evacuees [15]. The 2005 London bombing produced the largest number of casualties in the UK since World War II, 86% of which were self-evacuees [4]. The problem of incorporating the movement of self-evacuees in response planning is one of the least analyzed in the literature. In radiological incidents as well, self-evacuees play a significant role. The official report of the Fukushima Nuclear Accident Independent Investigation Commission [48] lists the lack of planning for self-evacuees as one of the failures of the emergency response system, along with others such as shelters being placed in regions of high radiation dosage or put in place with great delay because of a lack of planning.

This paper is organized as follows. Section 2 reviews the literature on optimization models for disaster casualty response. Section 3 provides a detailed description of our problem and illustrates the framework of the location-allocation model. Section 4 gives the full model formulation, accompanied by a detailed explanation of the objective and constraints. Section 5 applies the model to an RDD case study in Los Angeles. Results are discussed and insights are made via sensitivity analyses. Section 6 summarizes the findings of this paper and provides future work directions.

2. Literature review

Our model combines several aspects, namely ACFs, triage, and the movement of self-evacuees, in a single location-allocation framework. In this section, we compile a review of the literature on optimization models for disaster casualty response, placing special emphasis on these aspects. The literature on disaster response planning is extensive. Caunhye et al. [9] provide an in-depth review of the optimization models for disaster response. Only four of their reviewed models have specific links to casualty response. The rest involve the distribution of commodities, such as tents, food, and clothing, to people affected by disasters.

Our literature search on disaster casualty response has found articles that fall into three relevant categories: 1) models that consider the location of ACFs, 2) models that take into account triage results of casualties to plan for treatment, and 3) models that carry out casualty response planning without ACFs or triage. In the third category, there is a sizable body of literature related to pandemic and bioterrorism response, which is the closest we come to radiological response.

2.1. ACF location

The literature uses several terms interchangeably for ACFs or facilities that are conceptually close to ACFs. Most location-only models are problems where these facilities are located to cover casualty demand. Drezner [17] and Drezner et al. [18] use the term "casualty collection points" for ACFs. Drezner [17] formulates models to locate casualty collection points via five means: p-median, p-center, p-maxcover, min-variance, and Lorenz curve. Drezner et al. [18] follow up the study by elaborating on a multi-objective problem with five objectives: p-median, p-center, two max-cover, and min-variance. Both studies assume that casualties will move to the nearest casualty collection points and that all other facilities have become nonoperational and only casualty collection points are left to provide treatment for casualties.

Another term that is close in meaning to ACF is emergency medical service facility, or EMS facility. Jia et al. [27] establish a general location framework for EMS facility location during large-scale emergencies. Their model locates facilities to cover demand points so as to achieve maximum efficiency in covering demand. Huang et al. [25] also build an EMS facility location model, in the form of a p-center problem, with the additional assumption of possibility of facility failure to respond to demand.

The only ACF location model accompanied with allocation planning that we have found is in Yi and Özdamar [59]. This model is a capacitated dynamic model that routes different modes of transport through a network to deliver various types of commodities to people and move casualties of different priorities to temporary or permanent emergency sites, which we can equate to ACFs. The model minimizes the delay in the arrival of commodities at aid centers and in the provision of healthcare for the injured.

2.2. Treatment planning with triage

Models for treatment planning mainly deal with dynamic treatment planning, with the possibility of casualty priorities changing over time. Gong and Batta [20], Argon et al. [3], and Kilic et al. [29] use queuing theory to prioritize casualties for treatment. Gong and Batta [20] develop a preemptive two-priority single-server queuing system with equal service rates for low- and high-priority casualties to study the treatment of casualties in disaster response. Argon et al. [3] order casualties in a queue to minimize abandonments caused by impatient casualties who leave the system if not taken care of within a time limit. Kilic et al. [29] use a two-priority nonpreemptive S-server configuration to determine the treatment rate for each priority category following a mass casualty event. The model seeks to minimize both the expected value of the square of the difference between the number of servers and