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Innovative Applications of O.R.

A new epidemics–logistics model: Insights into controlling the Ebola virus disease in West Africa

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ABSTRACT

Compartmental models have been a phenomenon of studying epidemics. However, existing compartmental models do not explicitly consider the spatial spread of an epidemic and logistics issues simultaneously. In this study, we address this limitation by introducing a new epidemics–logistics mixed-integer programming (MIP) model that determines the optimal amount, timing and location of resources that are allocated for controlling an infectious disease outbreak while accounting for its spatial spread dynamics. The objective of this proposed model is to minimize the total number of infections and fatalities under a limited budget over a multi-period planning horizon. The present study is the first spatially explicit optimization approach that considers geographically varying rates for disease transmission, migration of infected individuals over different regions, and varying treatment rates due to the limited capacity of treatment centers. We illustrate the performance of the MIP model using the case of the 2014–2015 Ebola outbreak in Guinea, Liberia, and Sierra Leone. Our results provide explicit information on intervention timing and intensity for each specific region of these most affected countries. Our model predictions closely fit the real outbreak data and suggest that large upfront investments in treatment and isolation result in the most efficient use of resources to minimize infections. The proposed modeling framework can be adopted to study other infectious diseases and provide tangible policy recommendations for controlling an infectious disease outbreak over large spatial and temporal scales.

1. Introduction

Infectious disease outbreaks have been an immense challenge for humanity. The recent example of an infectious disease outbreak is the 2014–2015 Ebola outbreak (World Health Organization, 2014c). Despite recent signs of slowing down, the deadly Ebola virus disease (EVD) has spread rapidly across West Africa including the three most-affected countries–Guinea, Liberia, and Sierra Leone–since early March 2014. As of June 12, 2016, the Centers for Disease Control and Prevention (CDC) reported that the total number of Ebola cases and deaths in West Africa has reached 28,652 and 11,325, respectively (Centers for Disease Control & Prevention (CDC), 2015).

The Ebola virus is considered one of the deadliest viruses ever known, with a case fatality proportion varying from 25 to 90% in past outbreaks (World Health Organization, 2014c). Ebola symptoms include sudden onset of fever, weakness, vomiting, diarrhea, headache, and sore throat. Severe and fatal stages of the disease are accompanied by internal and external bleeding and multiple organ failures (Chowell & Nishiura, 2014; World Health Organization, 2014c). EVD is transmitted among humans via direct contact with bodily fluids from an infected person or indirect contact with contaminated surfaces (World Health Organization, 2014c). EVD transmission is further aggravated by traditional West African funeral practices such as washing, touching, and kissing the body and unsafe burial of Ebola-infected bodies (WHO Ebola Response Team, 2014; World Health Organization, 2014c). Ebola has no cure, vaccine or specific treatment for infected individuals. Therefore, short-term intervention strategies to control transmission include medical treatment in the form of supportive therapy, such as maintenance of fluids (World Health Organization, 2014c), quarantine, isolation of cases, contact tracing, and safe burial practices. Safe burial consists of sanitizing and placing the dead body in a disinfected body bag, and burying it in a grave at least 2 meters deep (Nielsen et al., 2015). On the other hand, Ebola treatment centers (ETCs) play a significant role in isolating and treating infected individuals, thereby helping to curb the Ebola outbreak (World Health Organization, 2014b).

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Controlling epidemics such as Ebola over a spatial scale and in a prompt manner is a challenging optimization problem. First, infectious diseases spread through the air or other mechanisms that need to be accounted for when modeling an epidemic (Cohen, 2000). Second, capturing spatial considerations is essential because critical disease parameters such as transmission and fatality rates among the population may change in various geographical regions. In addition, infectious diseases such as Ebola can be easily transmitted from one region (e.g., city, country, continent) to another region (other cities, countries, and continents) due to the mobility and migration of the population (Wang & Zhao, 2004). Third, the epidemic intervention resources are limited and insufficient in most circumstances, forcing policymakers and healthcare providers to determine the most effective policies to allocate resources strategically and rapidly to the right locations for controlling an infectious disease outbreak.

Compartmental models in epidemiology decompose the members of a population into different subgroups (compartments) according to the stages of the infectious disease and characterize the rates of transiting from one subgroup into another, duration of the infection, and contact rates (see, e.g., Bailey, 1975; Frauenthal, 2012). For example, the susceptible-infected-recovered (SIR) model and its variations have been widely used to predict the growth of epidemics and to inform intervention strategies (Anderson & May, 1991; Kermack & McKendrick, 1932; Tebbens & Thompson, 2009). Epidemic models have been developed to analyze a number of infectious diseases, including Ebola (Althaus, Gsteiger, & Low, 2014; Chowell, Hengartner, Castillo-Chavez, Fenimore, & Hyman, 2004; Chowell & Nishiura, 2014; Legrand, Grais, Boelle, Valleron, & Flahault, 2007; Meltzer et al., 2014; Pandey et al., 2014; Zaman, Kang, & Jung, 2009), tuberculosis (Long, Vaidya, & Brandeau, 2008), measles (Babad et al., 1995), influenza (Rachaniotis, Dasaklis, & Pappis, 2012), plague (Allen, Brauer, Van den Driessche, & Wu, 2008), human immunodeficiency virus (HIV) (Lasry, Zaric, & Carter, 2007), smallpox (Ferguson et al., 2003), and anthrax (Craft, Wein, & Wilkins, 2005). Some studies focus on discrete-time epidemic models (Allen, 1994) in order to alleviate the difficulties pertaining to differential equations.

While the spatial characteristic is a central feature of many epidemic control problems, where infections show migration or dispersal patterns, most previous work has oversimplified the problem by ignoring the spread of disease over space. To our knowledge, none of the previous studies on Ebola modeling has incorporated the logistics of treatment using a spatially explicit optimization model in order to allocate limited resources to control the spread of the disease. Most studies on Ebola have considered continuous-time differential equations and stochastic simulation models, which are difficult to include in an optimization model. Furthermore, the current epidemic modeling literature does not consider treatment capacity and thus assumes a constant treatment rate, which leads to suboptimal solutions for capacity allocation over time and space.

The objective of this paper is to develop a general spatio-temporal optimization modeling framework to help decision-makers minimize infections and death due to an epidemic. The model provides information on the spread dynamics of infections, and where and when to allocate limited resources. The strength of the model is demonstrated by a case of determining effective strategies to suppress the 2014–2015 Ebola outbreak. To the best of our knowledge, there have not been any known spatially explicit optimization studies that integrates both epidemic growth and optimal resource allocation modeling in one optimization model for controlling an infectious disease outbreak over a finite planning horizon.

This paper is organized as follows. Section 2 reviews the relevant literature on epidemic disease modeling and logistics for controlling disease outbreaks. In Section 3, we present the epidemics–logistics optimization model including the susceptible-infected-treated (and quarantined)-recovered-funeral-buried (SITR-FB) compartment model. Section 4 presents a real case regarding the 2014–2015 Ebola outbreak in Guinea, Liberia, and Sierra Leone and provides related economic, geographic, population, and disease transmission data. More detailed information on the data and data sources is provided in Appendix A. In Section 5, we present the validation of the proposed model, detailed computational experiments, and numerical results to explain the Ebola spatial spread and disease dynamics in each of the three most-affected nations. Here we also provide insights into optimal intensity, location, and timing of intervention for controlling the Ebola epidemic. Finally, in Section 6, we summarize our findings and present policy implications and recommendations. Section 7 presents conclusions and directions for future research.

2. Literature review and paper contributions

Operations Research (OR) approaches have been implemented to incorporate treatment capacity and evaluate the performance of different control measures for Ebola and other epidemic diseases. Previous OR or management science (MS) approaches on epidemics control involve compartmental model-based simulations (Legrand et al., 2007; Meltzer et al., 2014; Pandey et al., 2014), differential equations (Craft et al., 2005; Kaplan, Craft, & Wein, 2003), cost-effectiveness analysis of resource allocation (Tebbens & Thompson, 2009; Zaric, Brandeau, & Barnett, 2000), network models (Ancel, Newman, Martin, & Schrag, 2003; Eubank et al., 2004), simulation optimization (Lee, Pietz, Benecke, Mason, & Burel, 2013; Longini, Halloran, Nizam, & Yang, 2004; Patel, Longini, & Halloran, 2005), and mathematical programming (Ren, Ordóñez, & Wu, 2013; Tanner, Sattenspiel, & Ntaimo, 2008; Yarmand, Ivy, Denton, & Lloyd, 2014). Various type of facility location models, including maximal covering, location-allocation, and P-median models, have also been studied in response to large-scale emergencies and disaster management (Jia, Ordóñez, & Dessouky, 2007a,b). A number of surveys regarding OR/MS contribution to epidemics and disaster control can be found in (Altay & Green, 2006; Dasaklis, Pappis, & Rachaniotis, 2012; Dimitrov & Meyers, 2010).

The majority of mathematical models that study the logistics of controlling epidemics use simulation methods (e.g., Arinaminpathy & McLean, 2009; Berman & Gavious, 2007; Dasaklis, Rachaniotis, & Pappis, 2017; Liu & Zhao, 2012; Longini et al., 2007; Porco et al., 2004; Riley & Ferguson, 2006). Some of these studies model simulations using network relations among disease compartments to study the spatio-temporal aspects of the problem (e.g., Berman & Gavious, 2007; Longini et al., 2007; Porco et al., 2004; Riley & Ferguson, 2006). Those simulation models usually evaluate various policies (e.g., vaccination of contacts, limited response capacity, heterogeneity in symptoms and infectiousness, more rapid diagnosis due to public awareness, and isolation of cases) on intervention to control the disease spread (Porco et al., 2004).

A number of studies have used agent-based simulation models and social networks to explicitly capture interactions and contacts among sub-populations, such as susceptible, infectious, recovered, or immuned of the Ebola virus disease (Ajelli et al., 2016; Kurahashi & Terano, 2015; Siettos, Anastassopoulou, Russo, Grigoras, & Mylonakis, 2011; 2016; Wells et al., 2015). These simulations are used to assess the impact of various intervention strategies, such as ring vaccination (Kurahashi & Terano, 2015), case isolation (Wells et al., 2015), and burial practices (Siettos, Anastassopoulou, Russo, Grigoras, & Mylonakis, 2016). Some of the dynamic models are driven by the spatial correlation of individuals in the population (e.g., Wells et al., 2015). They study spatial heterogeneity in