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Multi-objective optimization models for patient allocation during a pandemic influenza outbreak

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ABSTRACT

Pandemic influenza has been an important public health concern with several historical outbreaks in 1918, 1957, and 1968. During an influenza pandemic outbreak, hospitals are often overwhelmed by the surge demand of influenza patients. It is important to prepare response plans to react to a pandemic influenza outbreak. Because of the widespread effect of the disease and the increased demand on limited medical resources, collaboration among hospitals both in planning and in response is necessary. This paper focuses on patient and resource allocation among hospitals in a healthcare network. Mathematical models are built to optimize the patient allocation considering two objectives related to patients' cost of access to healthcare services: (1) minimization of the total travel distance by patients to hospitals; and (2) minimizing the maximum distance a patient travels to a hospital. Moreover, the models help to predict a resource shortage during an outbreak; this prediction will alert decision makers to consider increasing the medical capacity or requesting additional capacity from state or national agencies. In addition, the model aids in the determination of the optimal allocation of the additional resources, when available, among hospitals by considering the above two objectives related to patients' cost of access to services. A case study from Metro Louisville, Kentucky, is presented to demonstrate how the models would aid in patient allocation during a pandemic influenza outbreak.

1. Introduction

Pandemic influenza has been an important public health concern. During the 20th century, three major pandemics of influenza occurred in 1918, 1957, and 1968. The pandemic of 1918 caused 40–50 million deaths worldwide and more than 500,000 deaths in the United States. The 1957 pandemic, during a time with much less globalization than now, spread to the US within 4–5 months of its origination in China, causing more than 70,000 deaths in the US. Finally, the 1968 pandemic spread to the US from Hong Kong within 2–3 months, causing 34,000 deaths [8,31].

The outbreak of a pandemic influenza is considered to be a relatively high probability event, even considered inevitable by many experts [10]. Many researchers study the impact of the next pandemic. The Centers for Disease Control and Prevention (CDC) estimates that in the US there could be 839,000–9,625,000 hospitalizations, 18–42 million outpatient visits, and 20–47 million additional illnesses, depending on the attack rate of infection during the pandemic, based on extrapolation of the 1957 and 1968 pandemics [31]. The estimates based on the more severe 1918 pandemic suggest that substantially more hospitalizations and deaths could occur [31]. A software program called FluSurge [52] was developed by the CDC to calculate the potential impact of a pandemic on hospital resources, such as staffed beds and ventilators. The results from FluSurge indicate that hospitals would be severely stressed in a moderate 1968-like scenario, and completely overwhelmed in the case of a severe 1918-like pandemic [46]. Toner and Waldhorn [46] state that during a pandemic influenza outbreak, some key preparedness tasks could not be accomplished by hospitals individually, and that regional resource allocation, patient redistribution, and use of alternative care sites would all require collaboration among hospitals both in planning and in response. The research presented in this paper describes and illustrates optimization models that could be used by decision makers to determine how best to manage medical resources, as well as suggest patient allocation among hospitals and alternative healthcare facilities.

The remainder of this paper is organized as follows. In the next section, the problem statement is given. In Section 3, a comprehensive literature review is presented, including the literature related to pandemic influenza planning and response and literature related to healthcare resource allocation modeling for normal, non-pandemic instances. In Section 4, the formulation of the optimization models is presented. In Section 5, numerical results of a case study are presented to demonstrate how the model could help decision makers determine the patient allocation and potential resource shortages

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in the healthcare system. Finally, conclusions are given in the last section.

2. Problem statement

This research will focus on how to allocate the in-patients among multiple hospitals during a pandemic influenza outbreak. Previous work related to patient allocation mostly focuses on either long term planning (e.g. hospital network planning over a span of years) [6,16,17,19,35,40–42,44,45] or short term planning (e.g. emergency disaster response such as earthquake and hurricane in a matter of hours or days) [13,34,50]. Since a pandemic outbreak usually lasts several months, it is considered to be a medium term planning problem, which is different from either long-term or short-term planning as in most current research, in the following ways:

(1) This study will consider the length of stay of the patients in a hospital, which is included explicitly in the capacity constraints, while most current research models simplify the stay of length by estimating a general capacity rate, such as number of patients per time unit.
(2) The planning horizon can be divided into several shorter planning horizons to reduce the solution run time and to allow the interjection of real changes in the system during the disease spread such as surge capacity increase and healthcare personnel infection during the pandemic development. Most current research models utilize a single planning horizon;
(3) This study is problem-focused. Much work has been done related to pandemic influenza response, as discussed in the following literature review, Section 3. But to the best of our knowledge, the patient allocation along with resource allocation during an influenza outbreak has not been studied.

In this research optimization models will be formulated and solved to help decision makers address the patient and resource allocation issues faced by a multi-facility healthcare network in a medium term influenza outbreak. The models optimize the patient allocation in terms of the following:

(1) Minimizing the patients' "cost" of access to service: as measured by the total patient travel distance.
(2) Minimizing the maximum patient travel distance.
(3) Satisfying resource capacities: constraints to incorporate limited availability of resources at each hospital. Resources include both the equipment resources, such as ICU (intensive care unit) beds, non-ICU beds, and ventilators, and healthcare personnel, such as doctors, nurses, and lab technicians.

Moreover, the models can be used to predict when (i.e. which day), where (i.e. which hospital) and what (i.e. which resource) is exceeded by the surge demand during the outbreak. The decision makers can then determine if hospitals need to increase medical capacity or request additional capacity from the state or national emergency agencies. In addition, if additional resources become available, the models help to determine the allocation of additional new resources.

Overall, the models help to determine which healthcare site the patients should attend, no matter how they are transported; either patients transport themselves to the healthcare site or are delivered by EMS (emergency medical services). The results can be used to encourage patients to go to specific healthcare sites as implemented through physician recommendations, Internet site/telephone information, EMS delivery policies, and other public policy approaches. Additionally, these models will help to predict the resource utilization over time, which would aid in facility preparation as well as predict the resource shortage, therefore identifying surge capacity required and finally allocate resources among hospitals when additional resources become available.

3. Literature review

This literature review divides the relevant literature into two categories: literature related to pandemic influenza planning and response, and literature related to healthcare allocation modeling for normal, non-pandemic instances.

Pandemic influenza planning/response involves various aspects. Disease spread modeling is used to estimate the infectious disease progression which aids the preparation for a pandemic influenza outbreak. Various researchers have developed disease spread models using optimization or simulation models [4,23,36,38].

Based on the disease spread model, a growing amount of literature studies the impact of a variety of mitigation strategies including the use of vaccination, prophylaxis, social distancing, quarantine, and travel restrictions. Difference scale models (such as local, regional, national, and global) are studied in the literature to investigate the spread of a pandemic influenza outbreak under various mitigation strategies [5,7,8,11,12,14,15,18,20–29,49]. Mass vaccination is one of the important mitigation strategies. Various papers focus on the logistics aspect of mass vaccination, such as the location problem of the point-of-dispensing (POD) facilities, and the resource allocation in the POD, which can be considered as a short term planning problem since the mass vaccination takes place in a short period (days or hours) [24–27,1,2].

Hospital planning during a pandemic influenza outbreak is another important research area. The Centers for Disease Control and Prevention (CDC) of the US Department of Health and Human Services provides pandemic influenza response tools FluAid 2.0 and FluSurge 2.0 to assist state and local level planners; these tools provide a range of estimates of potential impact in terms of deaths, hospitalizations and outpatient visits due to pandemic influenza [32,51].

A number of researchers applied FluAid and FluSurge to study the pandemic response in areas. For example, Zhang et al. [52] discuss Metropolitan Atlanta as an example to demonstrate the results, using population-based rates of illness and death in an influenza pandemic adapted from Meltzer et al. [31]. Sobieraj et al. [43] use FluSurge 2.0 to determine the hospital capabilities at William Beaumont Army Medical Center (WBAMC) in response to patient arrival surges resulting from mild 1968-type and severe 1981-type influenza pandemics. Lum et al. [30] apply FluSurge 2.0 and FluAid 2.0 to estimate the demand for critical care hospital admission in Victoria, Canada, resulting from a rapid rise in the number of pandemic (H1N1) 2009 influenza cases, and compare the estimate with the data obtained from daily hospital reports of pandemic (H1N1) 2009 influenza-related admissions and transfers to intensive care units (ICUs). Rico et al. [39] present a simulation model to optimize the nurse allocation in a Veteran's Hospital during a pandemic influenza outbreak by using FluSurge 2.0 to determine the arrival rates of patients to the hospital. Wilson et al. [48] apply FluAid to estimate the impact of the next influenza pandemic on population health and health sector capacity in New Zealand. Finally, Menon et al. [33] use FluSurge to model the impact of an influenza pandemic on critical care services in England.

It should be noted that all the reviewed literature regarding hospital planning for pandemic influenza focuses on one hospital, not a hospital network, or simply compares the existing hospital resources with the estimated demand, not related to the collaboration among hospitals in a network. It appears that the patient allocation