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Simulation modeling for pandemic decision making: A case study with bi-criteria analysis on school closures

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ABSTRACT

Pandemic influenza continues to be a national and international public health concern, and has received significant attention worldwide with the A/H1N1 influenza outbreak in 2009. Many countries, including the United States, have developed preparedness plans for an influenza pandemic. Preparedness plans are falling under renewed scrutiny as decision-makers apply new findings and seek key leverage points for more effective preparedness and response. School closure has been recommended by the World Health Organization as one of the best ways to protect children and other susceptible individuals at the early stages of the pandemic. However, school closure is a difficult mitigation policy to implement from both strategic and operational points of view. Challenges include impacts on alternative education delivery services, such as student meals and after-school oversight, as well as direct and indirect economic outfalls. To help public health decision makers address these issues, we developed an epidemiological simulation tool for pandemic influenza which enables users to make decisions during a simulated pandemic. We then designed a school closure tabletop exercise using our simulation model as a decision-support tool for evaluating the effectiveness of school closure as a community mitigation strategy for pandemic influenza. We conducted two exercises in February 2009 for the Arizona Department of Health and Human Services including high-ranking health and education administrators from across the state. The purpose of these exercises was to test the state's pandemic preparedness plans with respect to school closure timing and impact. The exercises required participants to make (hypothetical) strategic and operational decisions to mitigate the impacts of pandemic influenza at the state and local levels. Our simulation and decision analysis tool was used to assess the impact of key decisions in the exercises. This paper presents the technical details involved in the design and evaluation of this pandemic decision-support tool. Based on the decisions made in the exercises, we present a bi-criteria decision analysis framework to evaluate analytical results obtained from the simulation model. Our analyses show that sequential school closure and re-opening strategy with a specific decision rule gives the best compromised solution in terms of minimizing the total number of infections and providing minimal educational discontinuity.

1. Introduction

In 2009, the influenza A/H1N1 virus quickly escalated to a global pandemic with sustained human-to-human transmission worldwide [13,41]. This recent influenza outbreak highlighted the importance of preparedness activities for all countries in today's global world. Current preparedness efforts for pandemic influenza focus on establishing efficient mitigation strategies for communities and planning for delivery of necessary medical services during an outbreak. School closure is a non-pharmaceutical influenza mitigation strategy and has been included in the federal guidelines for the Community Strategy for Pandemic Influenza Mitigation [8]. During the 2009 A/H1N1 influenza outbreak, local authorities across the United States closed schools in an effort to decrease influenza transmission rates. However, there is limited quantitative and scientific evidence available to support the efficacy of this influenza mitigation measure, which has profound legal, economic, and social implications.

Tabletop exercises are used by many agencies and organizations in preparation for various disasters. A tabletop exercise is an informed discussion by responsible authorities for testing the theoretical and hypothetical capabilities in response to a disaster, such as pandemic

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influenza [3]. These exercises are bounded by a scenario or set of scenarios and include public health professionals and policy-makers responding to prompted discussion questions. Although tabletop exercises for pandemic influenza preparedness have not typically included computer-based simulation models, decision support systems or multi-media enabled narrative and real-time feedback systems [7,36], these tools are becoming increasingly important for public health managers for surveillance, prediction and decision analysis [44]. Previous work by Yoon et al. has shown that computer based virtual systems can significantly improve the ability of trainees to respond to dynamic and chaotic environments interactively and collaboratively [43].

In an attempt to test existing influenza preparedness plans in Arizona, the Arizona Department of Health and Human Services (ADHS) hosted two tabletop exercises at the Arizona State University Decision Theater on February 12 and February 19, 2009. The Decision Theater is a visualization center where a collaborative decision-making environment is supported with various technological tools such as stereo sources, geospatial visualizations and dynamic simulation models. The participants of these exercises included key individuals who are involved in school closure decisions in Arizona (the director of the largest county health department in Arizona, several school superintendents, and Arizona Department of Education representatives). Participants also included school nurses, first responders and state, county, and local health officials as well as members of Parent Teacher Associations, large community businesses, and policy makers and planners at the K–12 and university levels.

The 2009 influenza tabletop exercises at the Decision Theater focused primarily on school closure decisions for pandemic mitigation. These exercises integrated traditional elements of a tabletop design with a computer-based epidemiological simulation model, science-based narratives using mock news videos, a web-based participant collaboration and discussion-feedback tool, and facilitated group discussion. Participants of the exercises were prompted to make critical decisions (i.e. when to close schools, how long to close and when to re-open them), which impacted the results of the model.

State health officials benefited from the simulation model by defining and testing key epidemiological metrics for school closure identified in preparedness plans. The simulation model allowed decision makers to evaluate alternative strategies for making school closure decisions (including duration of closure, timing of closure and number of schools closed) which helped prepare them for making critical school closure decisions during the A/H1N1 outbreak just a few months later. In this paper, we outline the organizational design of the school closure exercises, and explain the technical specifications of the supporting simulation–visualization tool. We then present the results generated by the simulation model and analyze them in a bi-criteria evaluation framework. In addition, this paper outlines a case in which a simulation–visualization based decision support tool can be effectively used for practicing policy decision making processes.

2. Literature review

Previous research in the field of pandemic influenza modeling is quite extensive and can be broadly categorized as: 1) modeling the spread of pandemic in a community [4,6], and building geospatial and temporal simulation models to estimate the global path of the pandemic spread [11,17,26,30], 2) evaluating possible non-pharmaceutical and pharmaceutical interventions at the global and local levels [10,14,42] and recently, 3) logistical issues related to the community response and preparedness activities [9].

Agent based models are widely used to analyze the behavioral patterns and its effects on the spread of diseases. Many have used agent-based simulations to model the spread of influenza with social contact networks in an individual based modeling framework [9,10,14,20,42]. On the other hand, mathematical insights can be easily obtained with compartmental models, e.g. [16,17,30,31]. In [4] an age-structured, differential equation based disease model is used and in [6] a differential equation based mathematical disease spread model of the 1918 pandemic is presented. In this paper, we also present an age structured, differential equation based disease spread model for pandemic influenza. We chose to use a deterministic compartmental model because of the computational difficulties that may arise in a real-time scenario-based exercise. The differences between stochastic agent based simulation modeling of disease spread with deterministic compartmental models and the convenience of these different modeling types in real time preparedness and planning exercises have been reviewed previously [2].

In addition to the papers listed above on modeling techniques, there is a substantial body of literature on the quantitative analysis of the effectiveness and cost effectiveness of school closure strategies under possible pandemic scenarios. Several studies have investigated the impact of school closures on cumulative influenza attack rates; however, they do not present any of the social and economic costs of school closures [22,25,34,35]. Other studies have demonstrated that school closures can have a significant impact on the basic reproduction number and spread of disease [15,18–20]. Economic costs of school closures are also investigated but these studies do not simultaneously evaluate the epidemiological impact of school closures [23,32]. In a study by Sander et al. [33] the authors analyzed the cost effectiveness of 26 weeks of school closure in conjunction with other policies. However, this duration of school closure is likely to be viewed as impractical when there are uncertainties about the virulence of the epidemic. In another recent study evaluating various influenza mitigation policies and including a single school closure policy option, the authors conclude that for a moderately severe pandemic, school closures can be a cost effective intervention [28]. Finally, multidisciplinary and system approaches have been suggested to evaluate school closure policies for pandemic influenza because of its complex epidemiological effects as well as the impact on multiple dimensions of social and business life [5]. In a previous analysis of Arizona influenza cases, we evaluated the effect of scheduled winter break school closures on the occurrence of influenza among children and demonstrated that school closures may prevent or delay as much as 42% of potential influenza cases among school-age children [40]. Here, we use our epidemiological model to simulate the spread of pandemic influenza in multiple communities to answer several questions about the timing and methods of school closures by integrating decision analytics and disease spread modeling.

3. System design and integration for dynamic decision making

For pandemic preparedness exercises, we have taken a systems approach and first developed a geospatial and age structured simulation model of influenza spread in Powersim, a system dynamics modeling and simulation software [29]. This model is fed with several parameters which are statically stored in an excel spreadsheet. The simulation model is also connected to a central database where several inputs and resulting outputs from the model are kept in different forms (spreadsheets, raster etc.). Through the simulation model–database integration, as presented in Fig. 1, we transfer the outputs generated by the model to this database for generating visualizations. These visualizations are generated for the decision makers in different platforms such as Google Earth and Quantum GIS, an open source geographic information system, where participants can visualize the geographic and temporal spread of influenza. Examples of some visualizations generated in one of the exercises are presented in Appendix D.

In a dynamic decision making environment, visual tools (i.e. graphs, maps etc.) can help decision makers, who are responsible for implementing appropriate policies for multiple communities in a wide geography, to better understand the risks about an ongoing public health crisis. After visualizing the situation through geo-special maps