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Coverage models to determine outreach vaccination center locations in low and middle income countries

Jung Lim, Erin Claypool, Bryan A. Norman, Jayant Rajgopal *

Department of Industrial Engineering, University of Pittsburgh, 1025 Benedum Hall, Pittsburgh, PA 15261, United States

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ABSTRACT

The Expanded Programme on Immunization (EPI) was established in 1974 to ensure that children all around the world benefit from life-saving vaccines. However, in many low and middle income countries, it is extremely difficult to vaccinate the entire population with the standard regimen of vaccines. One important reason for this is geographically dispersed or nomadic populations. To improve vaccination rates, these countries typically use outreach, where health workers take vaccines to remote locations. Outreach is the last, critical link in the vaccine supply chain, and the locations selected to offer outreach directly impact the number of additional children that can be vaccinated. This research presents four quantitative models that can be used to optimize the selection of outreach locations, in order to maximize the number of residents that can be reached; each model addresses a different type of coverage possibility. The models are analyzed and contrasted using an example with inputs generated from a subset of data from the state of Bihar in India that was made available to the authors.

1. Introduction

The Expanded Programme on Immunization (EPI) was established in 1974 by the World Health Organization (WHO) to ensure that children all around the world benefit from life-saving vaccines [1]. However, vaccine delivery in many low and middle income countries is an extremely complex problem. The supply chains in such countries are limited in their cold-storage capacity and in their ability to transport vaccines quickly to various points throughout the country. In addition to these supply chain limitations, many of these countries have geographically dispersed or nomadic populations. Portions of their populations have limited or no access to vaccination locations due to poor infrastructure (poor road conditions or limited transportation) or other geographic barriers. As examples, in the country of Niger, 90% of the roads are unpaved [2]. In Nigeria, people from some rural areas may have to walk at least 26 miles to access health care [3]. In Kenya, 40% of the population must travel in excess of an hour to the nearest primary healthcare facility [4]. Thus, people from remote locations within resource-deprived countries have difficulty reaching immunization locations for their standard regimen of vaccines. This puts these individuals at a very high risk of mortality from infectious diseases such as measles, yellow fever, polio and tuberculosis.

One method to overcome this challenge is to use *outreach*. Sustained outreach is a strategy for reaching remote sections of the population with limited access to immunization locations. With this service, health care workers take vaccines from a fixed immunization location and travel to the remote locations, to immunize individuals there. This service is different from a *campaign* which is a one-time attempt to raise immunization rates. Outreach is extremely important to the overall immunization programs in resource-deprived countries. Without outreach, many countries would suffer from extremely low coverage rates. For example, a study was carried out in three zones of different population densities within Kenya to test the effectiveness of outreach programs as compared to only utilizing fixed immunization locations. The study showed that, with outreach, the coverage rate increased from 25% to 57% in the zone with lowest population density. Coverage increased from 54% to 82% in the zone with greatest population density [5].

Outreach is typically provided on a systematic basis, at regular time intervals and regular outreach locations. However, the outreach activities conducted from each immunization location can vary greatly depending on financial resources, time constraints, vaccine availability, population characteristics, usage rate of the fixed immunization location, health worker training, portable cold chain equipment available, and transportation available. The

* Corresponding author. Tel.: +1 412 624 9840; fax: +1 412 624 9831.
E-mail address: rajgopal@pitt.edu (J. Rajgopal).

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decisions about when and where to conduct outreach and which vaccines to administer may be made locally, depending on each location's available resources [6].

Outreach from health centers constitutes the critical final link in the vaccine supply chain, which can be quite complex and is typically comprised of four levels in addition to outreach: a central location where vaccines are received into the country from manufacturers, regional locations (typically five to 10) that serve as distribution hubs, districts (typically 25–100) which serve as the next layer of distribution and where some vaccinations may occur, and immunization health centers (typically 100–2000) which provide vaccinations to patients [7]. Outreach planning has a significant effect on the behavior of the entire vaccine distribution chain. As previously noted, in many countries successful outreach greatly increases the number of people vaccinated and therefore increases the number of vaccines that must flow through the entire vaccine supply chain. Thus, it is vital that countries consider the design and intended operation of their outreach programs as they are designing and equipping their entire vaccine supply chain.

In summary, vaccine delivery is a complicated problem and the effectiveness of delivery is critical to reducing mortality rates in many resource-deprived countries. To increase effectiveness, outreach is widely utilized. However, there are no quantitative outreach planning models available to help countries and individual facilities plan the optimal outreach strategy. The purpose of this research is to address this need.

2. Problem development and literature review

The objective in each of the various models formulated in this paper is to maximize the number of people vaccinated through outreach, when resources are limited. We assume that outreach is necessary whenever one or more villages are more than a distance D_1 (typically, 5 km as per WHO guidelines [8]) from an existing Immunization Health Center (IHC). An outreach team from the IHC visits one or more such villages, and residents from that village and all villages that are within a distance D_1 of it are able to go there to be vaccinated. We refer to a village that serves as an outreach vaccination center as a "center" and the other nearby villages (within distance D_1) from which residents travel to the center as "satellite" villages. The maximum number of centers that can be selected for outreach during the planning horizon depends on the financial and other resources available at the IHC. The objective is to select centers so as to maximize the number of residents that can be served at each of the central villages and its respective satellite villages.

As an illustrative example, Fig. 1 shows seven villages (represented by the small circles) located near an IHC along with their corresponding patient populations (represented by the numbers above the circles). Three options are shown for the selection of an outreach center from that IHC. If village A is selected as the center [Case A], then the satellite villages that are within 5 km are villages B, C, and D, and thus people in villages A, B, C and D can be vaccinated. People in villages E, F and G will not be vaccinated. In this case, the number of residents that can be covered by outreach is 170. Similarly, 180 people can be covered in Case B and 160 in Case C. Therefore, if we are restricted to a single outreach location, then among these three villages, B would be the best option for a center.

While more than one outreach strategy might be possible, there will typically be constraints that limit the final choice of outreach options. For example, outreach to a particular location has a cost associated with it (that might depend upon distance or terrain or equipment used) and there might be some overall budget for outreach that constrains our choice of outreach trips. Alternatively, costs might be similar for outreach to different sites but we might have a direct limit on the number of outreach sessions (e.g., because of personnel, vehicle, or equipment limits). In other cases, there might be limits on the length of a trip or preferences for certain trips over others. Different strategies are possible depending on these constraints and the assumptions made on the type and amount of patient coverage that can be obtained at a center.

Prior research that most closely relates to that described in this work is reported in a paper by Verter and Lapierre [9], who address the location of preventive health care facilities to maximize participation, under the assumption of a linear decrease in participation probabilities as distance to the nearest facility increases. They present an integer programming formulation and illustrate results using data from two locations in the US and Canada. These authors as well as Daskin and Dean [10] discuss how the location set covering model, maximal covering model and P-median model have been used for location planning in health care and reviewed other models derived from these three basic facility models. The different model types are applied selectively according to a problem's characteristics and objective. The problem addressed here may be viewed as a covering problem, which is well-known among facility location models [11]. In particular, it is related to the Maximal Covering Location Problem (MCLP), which was developed by Church and ReVelle [12], with the objective of maximizing the amount of demand covered by a facility. In this model, it is assumed that all of the demand is covered if the demand location is within an acceptable service distance, otherwise it is not, i.e., coverage is binary. An extension to this is the concept of partial coverage, in which there are two distances: the maximum full coverage distance D_1 and the minimum non-coverage distance D_2. The demand within distance D_1 from a facility is fully covered while none of the demand beyond distance D_2 is covered. For demand at locations between distances D_1 and D_2 from the facility, the coverage level is assumed to be a decreasing function of the distance to the demand location. Thus, some customers are fully covered and the others are partially covered [13]. This variation has been called the gradual covering problem by Drezner, Wesolowsky, and Drezner [14], or MCLP with partial coverage by Karasakal and Karasakal [15]. Berman and Krass [13] collectively refer to this class of models as the Generalized Maximal Covering Location Problem (GMCLP). In order to apply linear programming, they assume that the decreasing function for partial coverage is stepwise, so that the model is similar to MCLP. In these models, all of the demand at a location is assigned to the nearest facility, even though there might be two or more facilities near the demand location that are capable of serving the demand. Berman, Drezner, and Krass [16] introduce the cooperative coverage model where the effect of facilities is combined if there are more than two facilities near the demand location. However, in this model the coverage is once again binary, with a demand location being fully covered if an aggregation of partial coverage possible from nearby facilities exceeds a certain threshold; otherwise there is no coverage. That is, there is no partial coverage of demand points.

3. Coverage models

In this paper, we consider four types of models to optimize coverage from outreach. In all of our models we consider multiple outreach locations that can be selected. We start with a basic model that is similar to the binary MCLP model. The second model extends this by drawing from the GMCLP approach, with coverage being a stepwise and decreasing function of distance. The third model is a new generalization of the cooperative cover model: rather than being binary, an accumulation of partial coverage becomes the partial coverage of the location. The final model is a larger one that could be viewed as a generalization of any of the first three models.