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Evaluating scenarios of locations and capacities for vaccine storage in Nigeria

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ABSTRACT

Many developing countries still face the prevalence of preventable childhood diseases because their vaccine supply chain systems are inadequate by design or structure to meet the needs of their populations. Currently, Nigeria is evaluating options in the redesign of the country's vaccine supply chain. Using Nigeria as a case study, the objective is to evaluate different regional supply chain scenarios to identify the cost minimizing optimal hub locations and storage capacities for doses of different vaccines to achieve a 100% fill rate. First, we employ a shortest-path optimization routine to determine hub locations. Second, we develop a total cost minimizing routine based on stochastic optimization to determine the optimal capacities at the hubs. This model uses vaccine supply data between 2011 and 2014 provided by Nigeria's National Primary Health Care Development Agency (NPHCDA) on Tuberculosis, Polio, Yellow Fever, Tetanus Toxoid, and Hepatitis B. We find that a two-regional system with no central hub (NC2) cut costs by 23% to achieve a 100% fill rate when compared to optimizing the existing chain of six regions with a central hub (EC6). While the government's leading redesign alternative – no central three-hub system (Gov NC3) – reduces costs by 21% compared with the current EC6, it is more expensive than our NC2 system by 3%. In terms of capacity increases, optimizing the current system requires 42% more capacity than our NC2 system. Although the proposed Gov NC3 system requires the least increase in storage capacity, it requires the most distance to achieve a 100% coverage and about 15% more than our NC2. Overall, we find that improving the current system with a central hub and all its variants, even with optimal regional hub locations, require more storage capacities and are costlier than systems without a central hub. While this analysis prescribes the no central hub with two regions (NC2) as the least cost scenario, it is imperative to note that other configurations have benefits and comparative tradeoffs. Our approach and results offer some guidance for future vaccine supply chain redesigns in countries with similar layouts to Nigeria's.

1. Introduction

As one of the top 10 countries facing vaccination challenges, Nigeria is a suitable subject of study to improve its vaccination supply chain. At over 180 million people, Nigeria is the most populous country in Africa and the 7th most populous in the world [1]. With an average vaccine coverage of 80%, the country's problems with the outbreaks of vaccine preventable diseases has been persistent. In 2014 alone, the mortality for just tuberculosis was an estimated 170,000 individuals, not including individuals with HIV [2]. Recently, an outbreak of cerebrospinal meningitis was reported [3], and the polio eradication achievement suffered a setback with some newly reported cases [4]. Among other reasons, supply limitations due to inadequate storage capacities and the increasing costs of storing and moving the vaccines through the supply chain are responsible for these problems. The objective of this paper is to offer some guidance on scenarios of vaccine storage and location with a model that evaluates such scenarios taking into account distances and transportation costs with a high probability of meeting 100% fill rate using a method consistent with established modeling frameworks such as the HERMES model [5].

Evaluating supply chain infrastructure before a vaccine reaches the market is essential to the success of vaccine programs because of the effect of such systems on the decision making of the vaccine community [6]. For example, adequate storage facilities and transportation networks are not readily available in Nigeria. Thus, improving the vaccine supply chain will reduce costs by improving inventory needs, increase the safety of vaccines by keeping effective more vaccines that reach the target population [7]. There are

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problems with the implementation and execution of adequate vaccine supply chains around the world. In 2014, approximately 18.7 million infants worldwide did not receive routine immunization services [8]. Just 10 countries encompass more than 60% of these children: the DR Congo, Ethiopia, India, Indonesia, Iraq, Nigeria, Pakistan, the Philippines, Uganda, and South Africa [8]. In order to improve access to vaccines in these places, improvements to their vaccine supply chains must be considered. As of 2011, less than 10% of countries met WHO recommendations for Effective Vaccine Management (EVM) practices [9]. Factors that determine the effectiveness of supply chains include speed, dependability/reliability, cost and consumer satisfaction [10]. The cost of vaccines has gone up in recent years [11,12]. Indirect costs involved in getting vaccines to the end user include transportation, storage, personnel costs, and wastage [13,14]. Some previously attempted methods to keep these indirect costs down include ordering vaccines more often, but in smaller quantities, to avoid waste, using electronic records instead of paper, and adding safeguards against power outages in storage facilities or during transportation [13].

Nigeria comprises six geopolitical regions including North Central (NC), North East (NE), North West (NW), South East (SE), South West (SW) and South South (SS) [15], and the vaccines are distributed to these regions from the central National Strategic Cold Store (NSCS) located in Abuja. The Nigerian vaccine supply chain works on a push system through 5 tiers from the central hub through 6 regional hubs, to 36 state hubs, then local governments, and finally the health facilities where they are distributed to the end user [16,17]. Fig. A.6 in the appendix shows the current system in Nigeria. The prominent vaccine supply chain problems across the states in Nigeria include transportation hurdles and insufficient cold chains [18,19]. Solving the last mile problem would include more effective vaccine team transportation as well as vaccine cooling and tracking success [20,21].

Using Nigeria as a case study, we evaluate different regional supply chain scenarios to identify the cost minimizing optimal hub locations and storage capacities for doses of different vaccines to achieve a 100% fill rate. We find that improving the current system with a central hub requires more storage capacities and it is less cost efficient than systems without a central hub. While the proposed redesign under consideration in Nigeria offers promises to improve performance over the current layout, it is neither the most cost efficient solution nor does it provide the minimum coverage distance. This work contributes to offering realistic guidance in the redesign of a country's vaccine supply chain that countries with similar layouts may consider. The stochastic considerations on vaccine costs and demand volatility underscore the robustness of the outcomes and highlight the significant contributions of this paper to the literature.

2. Methods

The Nigerian government is contemplating moving from a six-region distribution system with a central hub in the capital, to a three-region distribution system without a central hub [16]. Thus, there are two phases in this research. The first is to determine the optimal location of the hubs based on distance between the states and the regional states to be served by the hubs. Based on the results of the first phase, the second phase seeks to determine the optimal scenario that minimizes costs. The research evaluates two groups of scenarios for partitioning the country into regions including a central hub (C#) at the Federal Capital Territory (FCT) and no central hub (NC#). Within these two groups are the existing supply chain, the proposed layout, and optimal scenarios that have been generated for comparison. Table 1 defines the scenarios.

Table 1
Description of the scenarios.

Origin	Label	Scenario description
Government alternatives	EC6	Existing current six regions with central hub in the FCT
	GOV NC3	Government alternative three regions with no central hub
Optimal scenarios	C4	Central hub at the FCT with four optimal regions
	C5	Central hub at the FCT with five optimal regions
	C6	Central hub at the FCT with six optimal regions (not EC6)
	NC2	No central hub with two optimal regions
	NC3	No central hub with three optimal regions
	NC4	No central hub with four optimal regions

2.1. Phase 1: Optimal regions and regional hub locations

We implement the shortest path optimization and cost minimization routines. Algebraic Mathematical Programing Language (AMPL) software was chosen to run the shortest path model [22,23]. There are 36 states in Nigeria with the FCT resulting into 37 network nodes. Distances between any two states (via their capitals) are collected to generate a marix. The AMPL optimization model was constructed using two decision variables: one to represent the hubs (i.e., which states will serve as regional hubs), and one representing the paths (i.e., which states are in the region served by the hubs). The objective function Z is to minimize the distance traveled between the states and the regional hubs for the no central hub scenario (and between the central hub and the regional hubs for the central hub scenarios) by choosing the states to use as regional hubs. Table A.2 describes the subscripts, variables and parameters used in the following equations.

$$\min_{P_{i,j},X_i} \quad Z = \sum_i \sum_j D_{i,j} P_{i,j} \tag{1}$$

$$\text{Subject to}: \quad \sum_i P_{i,j} = 1 \quad \forall j \tag{2}$$

$$\sum_i X_i = NumHubs \tag{3}$$

$$\sum_j P_{i,j} \leqslant X_i \quad \forall i \tag{4}$$

$$X_{i=FCT} = 1 \tag{5}$$

where Eq. (1) is the objective to minimize the total distance given that $D_{i,j}$ is the distance between a state i and state j multiplied by the path decision variable, $P_{i,j}$ where if $P_{i,j} = 1$, the path between i and j is used to deliver from regional hub in state i to state j and only one regional hub i can deliver to state j as given by Eq. (2); and if $P_{i,j} = 0$, then state (or regional hub) i cannot deliver to state j. In Eq. (3), if $X_i = 1$, then state i would be used as a regional hub. The number of hubs variable, *NumHubs* in Eq. (3) constrains or limits the model to an exogenous number of regional hubs. To keep the number of hubs bounded, Eq. (4) ensures that the number of hubs indeed serves all the states. Eq. (5) in this model is for the central hub scenarios, forcing the regional hubs to be served by the NSCS located in the FCT. Thus, the only difference in model set up of NC# and C# is the activation/deactivation of Eq. (5). In some cases the FCT, because of its location, tends to be optimal choice as the hub for its region.

2.2. Phase 2: Total cost minimization

The results of the AMPL optimization – both the hubs and the states they serve – become inputs for Phase 2 which focuses on