Health Facility Siting Plans Approached as Maximum Covering Location Problems

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Abstract
Access to health care is pivotal to the well-being of citizens of any nation and in Ghana the need is particularly critical, especially for rural communities. Therefore the concept of Community Based Health and Planning Services (CHPS) was conceived as a national initiative to provide basic health services especially in the northern sector of the country. A major concern has been their accessibility to large numbers of communities. Consequently, this study viewed the problem as one of maximum set covering and formulated an integer programming model for it to determine optimal locations for the health facilities so that they are accessible to the largest number of communities. Secondary data on the populations of selected communities for the year 2010 was sourced from the Statistical Service of Ghana and projections made for 2016 figures. The longitudes and latitudes of the communities were obtained and converted into coordinates, while straight-line distances between the communities were permuted into a symmetric matrix. The results obtained via an Excel Solver indicated the best locations to site given numbers of the facilities to cover the largest numbers of communities within a prescribed service distance of five kilometers.

Keywords: *Maximum Covering; CHPS facilities; Population; Location Problems*

1. Introduction

Ghana National Health Policy (MOH, 2007) aims at reducing excessive risk and burden of morbidity, mortality and disability, particularly among the poor and the marginalized groups through accessibility to health care facilities. Meanwhile, access to health care is still a serious concern particularly in the rural communities. As part of Governments' efforts to improve access to health care delivery, the Community-Based Health Planning and Services (CHPS) model was conceived. The CHPS model aims at reducing geographical barriers to health care by providing community-based health care services to clients. The CHPS model combines public health and basic clinical care activities. With this model, CHPS facilities are sited within the communities and managed by Community Health Officers with the support of community volunteers. It is well known that siting CHPS facilities to cover an entire population requires optimal use of scarce resources and therefore requires careful planning.

1.1. Statement of the problem

In Ghana, hospitals and clinics are mostly located at the regional, metropolitan, municipal and district capitals. As such, a greater proportion of the population; particularly those in the rural communities have difficulty accessing them, due to transportation difficulties, poor roads and long distances resulting in lack of access to health services (MOH, 2007; Ghana Statistical Service, 2013 & Sulemana and Dinye, 2014). Thus, patients have to travel long distances on deplorable roads to seek health care. This sometimes leads to untimely deaths resulting from preventable diseases. Information from Ghana Statistical Service (2013) indicates that one in every eleven Ghanaian children dies before they reach the age of five years as a result of preventable childhood diseases. The government's efforts to eradicate sicknesses and diseases as enshrined in the 1992 constitution will be a mirage if pragmatic measures are not pursued. Consequently, the CHPS policy which aims at bringing health care to the doorstep of every Ghanaian is a laudable idea.

It is an undeniable fact that the establishment of health facilities is capital intensive and in competition with other social services; hence, careful planning is necessary to ensure optimum use of scarce resources. The study, therefore takes a scientific approach to the problem using mathematical programming as a planning tool to aid decision making to ensure that access to CHPS facilities can be available to the largest possible number of citizens in the communities.

1.3 Objectives

This study is focused on formulating a linear integer optimization model that will ensure that a limited number of CHPS facilities can be sited within selected communities to maximize population coverage. Specifically, the study seeks to do the following:

- To formulate a maximum covering location model for siting CHPS facilities in some selected districts in the Upper East Region of Ghana.
- To apply the model to optimally site CHPS facilities by using real data.
- On the bases of the findings, to make recommendations on the CHPS siting problem.

2. Literature Review

2.1 Linear Programming

Linear programming (LP) is one of the most widely used mathematical programming techniques for solving optimal decision problems (Dantzig, 2002; Darst, 1991). It has a lot of practical applications in real life, among which are financial portfolios management (Twum, 2012, 2013; Harrison & Mieghem, 1999; Speranza, 1993), transportation systems (Taha, 2011; Dantzig & Thapa 2003), manufacturing (Taha, 2011), Health (Briend *et al.* 2003; Blake & Donald, 2002), resources allocation to activities among other (Hillier & Lieberman, 2010; Bazaraa *et al.*, 2005; Shapiro, 1984). A LP model in standard form (William, 1999; Darst, 1991) is:

$$\begin{aligned} &\text{Maximize } \sum_{j=1}^{n} c_j x_j \\ &\text{Subject to: } \sum a_{ij} x_j = b_i, \ \ i = 1, 2, \ldots., m \\ &\qquad\qquad x_j \geq 0, \ \ j = 1,2,\ldots,n \end{aligned} \tag{2.1}$$

This formulation (2.1) is Mixed Integer Programming (MIP) when some of the decision variables are restricted to be integer values. It is Integer Programming (IP) when all decision variables are required to be integers; it is Binary Integer Programming (BIP) when the decision variables can take on only 0 or 1 values (Chen *et al.*, 2010; Hillier & Lieberman, 2010). In this case (2.1) becomes:

$$\begin{aligned} &\text{Maximize } Z = \sum_{j=1}^{n} c_j x_j \\ &\text{Subject to: } \sum a_{ij} x_j = b_i, \ \ i = 1, 2, \ldots., m \\ &\qquad\qquad \forall\, x_j \in (0,1). \end{aligned} \tag{2.2}$$

BIP is applied in solving discrete optimization problems such as: facility location, selection or rejection of an option, the turning on or off of a switch, an answer of yes or no, the assignment of persons to jobs etc. (Taha, 2011).

The most popular method of solution of LP problems is the Simplex Method (Dantzig, 1998) which algorithm seeks for the optimal solution moving from one extreme point to another (i.e. boundary points) of the feasible set in search of the optimal solution (Dantzig & Thapa, 2003) The Revised Simplex method was subsequently developed to make the algorithm more efficient (Dantzig, 2002). In recent times the Interior point methods have emerged and proven to be faster at locating optimal solutions, where one exists, especially in large size problems (Todd, 2001). Unlike the Simplex algorithm, they search for the optimal solution from the interior of the feasible set using various projection techniques.

The Simplex method or its variant is unsuitable for solving MIP, IP, or BIP problems due to their combinatorial nature. For such problems the Branch-and Bound, and Branch–and-Cut methods have been developed, among others, to address their peculiar characteristics (William, 1999; Chen *et al*., 2010).

2.2 Related Works

Facility location decision making is necessary for both the public and private sectors of the economy for optimum utilization of resources. While the private sector may locate facilities to maximize profit or minimize cost, the public sector aims at providing services to cover as many in the population as possible. ReVelle and Eiselt (2005) opined that there are four elements that characterize facility location problems: (1) customers that facilities will be assigned to, (2) number of facilities to be sited, (3) space in which customers and facilities should be located, and (4) a metric that indicates distances or times between customers and facilities.

Many studies on facility location problems focus on the above characteristics. For instance, Demir*döğ*en *et al.*, (2015) used multi-criteria maximal covering to find the optimal solutions for the re-deployment of Intervention Units to Social Events (IUSE). Their model achieved 22% improvement on the covering rate of the event. The model further indicated that establishing four new units more could provide 100% coverage. Curtin, *et al.*, (2007), determined optimal Police Patrol Areas using Maximal Covering and Backup Covering Location Models. The optimal solutions proposed five best locations that would cover the weighted incidents. The results showed remarkable improvement (18.9%) in the ability of the police to respond to calls for service; total distances traveled by police officers to incidents drastically improved the response times and reduced costs. The Backup Covering Location Models ensure that more than one patrol car covers an incident within the service distance. The optimal solutions clustered around the most serious incidents to the neglect of less serious ones.

Amponsah *et al.*, (2011) used maximum expected covering location model to determine the locations of seven ambulance emergency medical services in the Kumasi Metropolis. They used Floyd-Warshall algorithm to obtain the distance matrix from all pairs of shortest path of the edge distances between all nodes on the graph network and applied genetic algorithm to solve the problem. Rajagopalan *et al.*, (2007) proposed a multi-period set covering location model in the field of emergency medical services. The model minimized the number of ambulances that were needed to provide a given level of coverage, determining their location on different time periods and considering fluctuations in the demand patterns by means of a probabilistic approach. The model was solved by a tabu search algorithm using data from an emergency service agency.

5. Methodology

5.1 The Model

The Maximum Covering Location (MCL) model was first formulated by Church and ReVelle (1974). The model is reformulated to site a number of CHPS facilities (p) on a set of communities so as to maximize population coverage within a stated service distance (d). The input parameters are thus defined as:

I = *Set of communities indexed by* i
J = *Set of candidate CHPS facility locations indexed by* j.
d_{ij} = *The shortest distance between community* i *and CHPS facility location* j
D_c = *Distance beyond which community* i *is not covered.*
$N_i = \{j | d_{ij} \leq D_c\}$, *is the set of all CHPS facility locations that can cover community* i
h_i = *Population to be covered at community* i
p = *Fixed number of CHPS to locate*

The decision variables are defined as:

$$x_j = \begin{cases} 1, & \text{if a CHPS facility is located at site } j, \forall j \in J \\ 0, & \text{otherwise} \end{cases}$$

$$z_i = \begin{cases} 1, & \text{if population at community } i \text{ is covered} \\ 0, & \text{otherwise} \end{cases}$$

The resultant MCL model is:

$$\text{Maximize} \quad \sum_{i \in I} h_i z_i, \quad \forall i \in I \qquad (3.1)$$

$$\text{Subject to:} \quad \sum_{j \in J} x_j - z_i \geq 0 \quad \forall i \in I \qquad (3.2)$$

$$\sum_{j \in J} x_j = p \quad \forall j \in J \qquad (3.3)$$

$$x_j \in \{0,1\}, \quad \forall j \in J \qquad (3.4)$$

$$z_i \in \{0,1\}, \quad \forall i \in I \qquad (3.5)$$

The objective function (3.1) maximizes the population covered within the desired service distance. Constraint (3.2) ensures that demand at community i cannot be considered covered unless at least one CHPS facility that is able to cover the community is located. Constraint (3.3) ensures that exactly p CHPS facilities are located, (3.4) and (3.5) reflect the binary nature of the facility siting decisions and demand node coverage, respectively. It is important to note that this model maximizes the population coverage and not simply the number of communities covered.

5.2 Data

Two basic types of data were gathered: the population of each community and the distances connecting them. The 2010 Population data for the Bongo, Talensi and Builsa North Districts of the Upper East Region were obtained from the Ghana Statistical Service (GSS) and a linear growth model (at the rate of 1.2% as estimated by the GSS (2013)) used to estimate the 2016 population figures for the three districts. Excel spreadsheet was used for computation of the projected population figures. The Geographic coordinates (latitudes and longitudes) of each community were obtained from Google maps and the Geographic/UTM Converter software used to convert the latitudes and longitudes into Universal Transverse Mercator (UTM) Coordinates form. In Universal Transverse Mercator Coordinates form, the longitude represents the eastern coordinate (i.e. the x-axis) and the latitude the northern coordinate (i.e. the y-axis). The coordinates of the communities were fed into Microsoft Excel and the shortest distances linking the communities were computed. These distances were then permuted to form a symmetry matrix of demand and facility nodes for communities of each of the three districts.

5.3 Analysis

The numerical data were stored in Excel files and the MCL model programmed in Excel Solver V2016-R2 Software. The analysis was run with selected input parameter values to find optimal solutions to the resultant model. The use of Excel Solver V2016-R2 Software to solve the CHPS facility model was informed by Lee and Yang (2009) who formulated and solved both p-median and maximum covering problems using it. Their models were tested using hypothetical data and the solutions were reliable. Excel Solver uses branch-and-bound strategy in solving the integer problems.

6. Results and Discussions

The results are based on a predetermined service distance of 5 kilometers as suggested in Kemboi & Waithaka, (2015), Nteta et al (2010), South Africa Department of Health (2001), and Muhammed (2013); they are premised also on the number of CHPS facilities to site in order to achieve 100% coverage of the entire communities in a given district. The optimal outputs are the communities in which to site the facility and the size of the population that can be covered.

6.1 Bongo District

The Bongo district had 35 communities and therefore 35 potential CHPS facility sites. The distances between pairs of communities when permuted yield a 35×35 symmetric distance matrix. The estimated population of the district was 74,239.

The optimal solution as presented in Table 1 shows the best sites for the CHPS facilities, the communities they would serve within the 5 kilometer service distance, as well as the size of the population covered. The results indicate 100% coverage can be attained for communities in the Bongo district, if five (5) CHPS facilities are sited in Borogogo, Namoo, Feo Acharaba, etc.

Table 1: Best CHPS Facility Sites for Total Population Coverage

Best site	Communities served	Population covered
Bogorogo	Bongo, Adaboya, Beo Kumbusgu, Bogorogo, Akanaba, Akunduo, Asebuga, Beo, Sapuoro, Soe Kabre, Anafobisi, Beo dua	74239 (100%)
Namoo	Boko, Namoo, Feo Nabisi, Towongo	
Feo Acharaba	Soe Kanseringa, Soe Kuliyawgo, Feo Ashebre, Feo Akunka, Feo Acharaba, Feo Ayelbia	
Zoko Goo Awaa	Balungu Gantorisi, Nayorogo, Zoko Gambrongo Abagnabisi, Zoko Kadare, Zoko Gambrongo Azaabisi, Zoko Kanga, Zoko Goo Awaa, Zoko Goo, Samboligu	
Gowrie	Zoko Tarongo, Vea, Yorogo, Gowrie	

The results further indicate that the CHPS facilities so sited could serve the people in other surrounding communities which are within the stipulated service distance radius. For instance, a CHPS facility sited in Gowrie is expected to serve the people of Gowrie, Zoko Tarongo, Vea and Yorogo communities. It is also clear from Table 1 that each CHPS facility could serve at least four communities when sited in those strategic locations.

6.2 Builsa North District

The Bulsa North district had 30 communities and so 30 potential sites for CHPS facilities, leading to a 30×30 symmetric distance matrix. The estimated population of the District was 62,639. The optimal (best) communities for siting CHPS facilities in order to achieve 100% population coverage within 5 kilometer service distance were ten. The communities are Chuchulliga Namonsa Jaata, Sandema Balansa, Sandema Bilinsa Tankungsa, Nauwalise, Kadema Changsa, etc., as named in Table 2.

Table 2: Best CHPS Sites for Total Population Coverage

Best sites	**Communities served**	**Population covered**
Chuchulliga Namonsa Jaata	Chuchulliga Namonsa Jaata, Chuchulliga Azuguyeri Teedem	62639(100%)
Sandema Balansa	Sandema Central/Sandema Abiliyeri, Sandema Nyansa, Sandema Kandem, Sandema Balansa, Sandema Suwarensa, Farensa	
Sandema Bilinsa Tankungsa	Sandema Fiisa, Sadema Kobdem, Sandema Bilinsa Tankungsa, Sandema Korri, Sandema longsa	
Nauwalise	Chuchilliga Namonsa Adabissa, Chuchulliga Azuguyeri Yipala, Chuchulliga Azuguyeri Nawasa, Nauwalise	
Kadema Changsa	Kadema Changsa	
Wiaga Tandem Tankangsa/Tandem	Kadem Banyangsa/Kadem Central, Kadema Gobsa, Wiaga Tandem Tankangsa/Tandem	
Wiaga Senyansa	Kadema Gaddem, Wiaga Central/Wiaga Yisobsa, Wiaga Yemonsa, Wiaga Senyansa, Longsa	
Sunyensi Zungdem	Sinyensi Akpiokyeri/Sinyeri Central, Sunyensi Zungdem	
Sinyensi Yikpien	Sinyensi Yikpien	
Kologu Amodalg (Amodalga)	Kologu Amodalg (Amodalga)	

The CHPS facilities so sited could serve the people in the beneficial communities and those surrounding ones within 5 km radius. For instance, a CHPS facility sited in Chuchulliga Namonsa Jaata is expected to serve Chuchulliga Namonsa Jaata and Chuchulliga Azuguyeri Teedem communities as displayed in Table 2. Furthermore, some of the facilities can only serve communities in which they are sited, if the service distance is anything to go by (see, for instance the last row of the Table 2).

6.3 Talensi District

The Talensi district had 26 communities with an estimated population of 134,157. Inputting the resulting distance matrix and population figure among the others yield the results given in Table 3.

Table 3: Best CHPS sites for total population coverage

Best sites	Communities served	population covered
Balungu	Pwalugu, Balungu	134157(100%)
Tenzugu	Shiga Winduri, Tenzugu, Santienga, Gorogu	
Yazore	Yamnega Yamsoko, Yazore, Gbega, Dusi Gaare	
Winkogo	Pusu-Namogo, Winkogo	
Gbeogo	Gambibigo, Tongo Baare, Tongo, Gbeogo, Dusi Yale	
Pelungo	Dushe, Pelungo	
Kalboka	Datuku, Datuku Zanwure, Kalboka, Biungu	
Nungu	Nungu	
Kupielga	Shega, Kupielga	

Table 3 indicates that 100% coverage of the population could be attained if nine CHPS facilities are sited. Each CHPS facility could be within the service distance access to the people within the communities where they are sited and others in neighboring communities which are also within the service distance. For instance, a CHPS facility sited in Yazore would serve Yamnega Yamsoko, Yazore, Gbega and Dusi Gaare. However, there is an instance (see last-but-one row of Table 3) in one of the nine sites where the facility could only serve people in the beneficiary community alone, if the service distance criterion is anything to go by.

7. Conclusions and Recommendations

This study explored the prospects of making healthcare (CHPS facilities) accessible (within a prescribed service distance) to the largest possible populations of people in communities of three selected districts of the Upper East Region. The matter was given a scientific view and investigated using the analytical tool of linear optimization. Specifically the Maximum Covering Location modeling approach was used. The results show that total (100%) accessibility can be realized for the communities by strategically siting a few CHPS facilities (5, 10 and 9 for Bongo, Bulsa North and Talensi respectively) and still stay within the prescribed service distance of 5 kilometers.

The following recommendations are therefore made:

1. Siting a CHPS facility in Bogorogo, Namoo, Feo Acharaba, Zoko Goo Awaa and Gowrie would provide access to healthcare to all the people in Bongo District within 5 km of the nearest CHPS facility.
2. Siting a CHPS facility in Chuchulliga Namonsa Jaata, Sandema Balansa, Sandema Bilinsa Tankungsa, Nauwalise, Kadema Changsa, Wiaga Tandem Tankangsa/Tandem, Wiaga Senyansa, Sunyensi Zungdem, Sinyensi Yikpien and Kologu Amodalg would provide access to healthcare to all the people in the Builsa North District within 5 km of the nearest CHPS facility.
3. Siting a CHPS facility in Balungu, Tenzugu, Yazore, Winkogo, Gbeogo, Pelungo, Kalboka and Nungu would provide access to healthcare to all the people in Talensi District within 5 km of the nearest CHPS facility.

4. Sensitivity analysis should be carried out as a matter of course to investigate the range of possibilities for the solutions. This can reveal parameters of the model which are critical and shed further light on the ways to tackle the problem.

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