International Journal of Mathematical Archive-5(2), 2014, 83-89
Available online through www.ijma.info ISSN 2229 – 5046

AN OPTIMIZATION MODEL FOR LOCATION ROUTING PROBLEM IN HEALTHCARE MANAGEMENT

Dr. Sandeep Tiwari[1] & Sopnamayee Acharya[2]*

[1]Asst. Professor, S. S. in Mathematics, Vikram University, Ujjain, (M.P.), India.
[2]Research Scholar, S. S. in Mathematics, Vikram University, Ujjain, (M.P.), India.

(Received on: 03-02-14; Revised & Accepted on: 28-02-14)

ABSTRACT

The provision of cost-effective healthcare facilities becomes particularly important for a developing country. For a mobile healthcare facility, a closed tour with stops selected from a given set of population nodes has to be found. This is a location routing problem in healthcare management sector considered as a multi-objective combinatorial optimization formulation. Tours are evaluated according to three criteria: (i) An economic efficiency criterion related to the tour length, (ii) the criterion of average distances to the nearest tour stops and (iii) a coverage criterion measuring the percentage of the population unable to reach a tour stop within a predefined maximum distance.

Keywords: *Facility location; Metaheuristics; Mobile healthcare; Multi-criteria decision making; Routing.*

INTRODUCTION

Developing countries frequently face the dilemma of very restrictive budget limitations for healthcare expenditures and a growing population. In such a situation, the provision of cost-effective healthcare facilities becomes particularly important. Distance proved to be one of the most influencing factors for the utilization of healthcare facilities (see 36, 45, 7, 47). In developed countries and mainly in urban areas, distance rather influences the decision on which kind of medical services (e.g., a medical doctor or a hospital) the patients use [34], whereas in rural areas of developing countries, distance is the decisive factor whether or not to use medical services *et. al* [38]. Therefore, in these regions, the provision of medical facilities close to the residences of the people becomes crucial for appropriate medical supply.

As a possible way to provide cost-effective primary healthcare under the very restrictive budget limitations of a developing country (cf. [18]), some governments and institutions have supplemented hospitals and stationary dispensaries with mobile healthcare facilities (see [23,20,21,33,43,17,28]). One of the most salient purposes of such mobile facilities lies in the extension of access of people to health services. Achieving the same accessibility effect by building a larger number of spatially fixed healthcare units would increase the costs for equipment and staff considerably, which often cannot be afforded. Small mobile units, on the other hand, are able to travel to distinct places at distinct times and to offer service for the people in a certain radius. Obviously, mobile units cannot make all the services available a hospital can offer. Thus, they can be seen as supplemental to other medical services, satisfying either the most urgent needs, or providing services of certain specialized medical divisions like dental treatment [3], the expertise of eye specialists, or CT scanners. Of course, in the situation of a developing country, the medical equipment will usually not meet very advanced standards [48], but basic medical services can be offered at a high quality level.

Already for fixed facilities, the question where they should be built and how they should be staffed is a difficult planning problem. Several types of location-allocation models aim at a decision support for this question based on quantitative data (see, e.g., ([1], [27], [39], [14], [35], [5], [41], [24] or [22]).

In the case of one or more mobile healthcare facilities, the planning problem gets even more complex since both tours and stops on tours have to be selected in a way that satisfies different criteria, cost-effectiveness (influenced by travel distances) being one of them, accessibility and coverage being others. Hodgson *et al.* [28] and Hachicha *et. al* [26], have addressed the tour planning problem for one or more mobile facilities in the Suhum district in Ghana. In their optimization model, tours and stops on tours are computed from geographical and demographic data both for the road conditions in the dry and in the rainy season. As a coverage constraint, the authors demand that each population center (settlement) that can, in principle, be reached within a given maximum walking distance (the cases of 3 and of 8 km are considered) is actually provided by a tour stop within this distance. In the literature, the considered distance limits for

Corresponding author: Sopnamayee Acharya[2], E-mail: sopna75@gmail.com*

such coverage constraints vary significantly depending on the concrete situation. Berghmans *et al*., for instance, suggested a maximum walking distance of 750 m to the nearest health center, whereas Patel suggested in his model for the rural region Dharampour in India a maximum walking time of 1.5 hours. In any case, where a maximum walking or driving time of 15 minutes for more than 70% of the population is strived for, the limits for rural areas of developing countries must necessarily be set to a far less ambitious level.

In the present article, we extend the model in [28,26] to a multi-objective problem formulation: Whereas in the indicated articles, an optimization problem with tour length as the objective function is solved, we do not judge the quality of a tour plan only based on a single criterion, but rather take account of the multi-criteria nature of the task and intend to provide the political decision maker with a computer-based Decision Support System (DSS) which outputs several candidate solutions for final choice. They are visualized and can be evaluated and discussed on a political level. So, the final decision remains up to the human decision maker, but the system assists him/her in coping with the complexity of the problem. Literature examples show that decision makers in the governmental departments seldom transformed the results of healthcare location/ allocation models unchanged into concrete policies (cf., e.g., [2, 10, 25, 35]). Already for this reason, it seems advisable to integrate the decision makers as early as possible into the solution procedure. In the case of our problem, at least the following three criteria should be taken into consideration:

(1) Effectiveness of workforce employment, measured by the ratio between medical working time and total working time including travel time and facility setup time.
(2) Average accessibility, measured by a low average time required by the inhabitants of the considered region to reach the nearest tour stop or the nearest stationary facility.
(3) Coverage, expressed by the percentage of inhabitants living within a given maximum walking distance to a tour stop or stationary facility.

In some sense, this definition of coverage aims at the aspect of equity (or fairness) of accessibility: As far as possible, no citizen should be excluded at all from medical services by an extraordinary distance to the nearest facility. Let us mention that our criterion (1), effectiveness, will turn out as closely related to the tour length criterion which is the objective in the well-known classical routing problems TSP and VRP.

The two other criteria (2) and (3), on the other hand, refer to the location aspect of the problem: Optimizing only the average accessibility (2) would amount to solving a p-Median Problem (see, e.g., [42]), while optimizing only the coverage (3) would mean that a Maximal Covering Location Problem (MCLP), as formulated by Church and ReVelle [6], is solved. There are tradeoffs between the three criteria above: Evidently, effectiveness can be increased by reducing the number of stops, leading to a reduced average accessibility or coverage. Vice versa, average accessibility and coverage can be increased by increasing the number of stops, which reduces effectiveness. Also average accessibility and coverage contradict to some extent: A low overall average walking distance can be achieved by leading the tour mainly through areas with dense population and planning a large number of stops there, which, however, affects an inequitable solution with comparably low coverage. Vice versa, to achieve high coverage, tour stops must be spread broadly over the whole region, which increases distances in those parts that ‘‘count most’’ from the viewpoint of average distances, namely the densely populated areas.

THE MODEL

This is, of course, a simplification that usually does not represent the real situation, not even in a region with low healthcare standards. Nevertheless, for the sake of a better isolation of the methodological questions raised by the considered location-routing problem, it is convenient to start with the mentioned. Let us restrict ourselves to the case of one single mobile facility (MF). Moreover, we assume here that medical supply for the considered region is to be delivered exclusively by the MF, without support by fixed hospitals or dispensaries assumption.

We use the following formal model description to represent the problem:

As in [28], a problem instance is based on a graph $G = (W, E)$, where the nodes $v_i \in W$ are settlements (population centers of any kind, from cities to very small villages), and the edges $e_l \in E$are traffic links (roads or paths) between these settlements. An edge e_l can be represented as the pair (v_i, v_j) of the two incident nodes. In each settlement$v_i \in W$, there lives a population of p_i inhabitants. The sum of the values p_i is the total number of inhabitants, N. A subset V $\subseteq$ W contains the potential stops of the MF. Without loss of generality, the nodes $v_i \in W$ can be labeled in such a way that the nodes in V get the lowest indices: $V = \{v_1, v_2, \dots v_{|v|}\}$ and $W = \{v_1, v_2, \dots v_{|w|}\}$ with $|V|$and $|W| \geq |V|$denoting the number of elements in V and W, respectively.

The shortest distance between two nodes $v_i \in W$ and $v_j \in W$ is d_{ij} kilometers, the shortest driving time of the MF between two nodes $v_i \in W$ and $v_j \in W$ is c_{ij} hours. (Hodgson *et al.* [28] comprise these two types of variables to a single variable. With respect to different quality types of roads, however, it makes sense to consider them separately from each other.)

The time interval during which the MF performs its (closed) tour is called a *period*. The number of days of a *period* is considered as a given constant fixed in advance. It forms an aspect of the quality of service and should not be fixed at a too high value; otherwise continuity of medical treatment would not be guaranteed. The decision variable is the chosen (closed) tour,

$$\pi = (\pi(1), \cdots \pi(k)),$$

where $\pi(j)$ *is* the index of the j[th] visited node ($v_{\pi(j)} \in V; j = 1, \ldots, k$) and after visiting node $\pi(k)$, the MF returns to the start node $\pi(1)$. This start node is a fixed given depot; it is always possible to choose the indices of the nodes in such a way that $\pi(1) = 1$. The reader should be aware that, contrary to the well-known travelling salesperson problem (TSP) or to most types of vehicle routing problems (VRP), not every node $v_i \in V$ needs to be part of the tour.

The number of stops on the tour is k = k(π). Thus, the total driving time during the tour is given by $\boldsymbol{t(\pi) = \sum_{j=1}^{k-1} c_{\pi(j),\pi(j+1)} + c_{\pi(k),1}}$.

The following constant parameters are used as input data:

T: total working time of a member of the MF personnel during the period (expressed in hours),
μ: time for the setup of the MF at a stop per member of the MF personnel (expressed in hours),
M: an acceptable walking distance to the nearest tour stop (in kilometers).

The three objective criteria are formulated in terms of *costs* are described below.

Objective -1: Effectiveness of workforce employment

The ineffectiveness of the MF personnel employment is measured by the ratio of medically non-productive time (the required time for the setup of the MF at a certain location, plus the driving time between locations) to the overall working time,

$$\mu k(\pi) + t(\pi)/\,T \qquad (8.2.1)$$

Therefore, our first objective is a weighted average on both the number of stops and the tour length: Being $\gamma_1 = \frac{\mu}{T}$ and $\gamma_2 = \frac{1}{T}$, then

$$Z_1 = \gamma_1 k(\pi) + \gamma_2 t(\pi) \qquad (8.2.2)$$

It is also possible to interpret Z_1 exclusively as a tour length: By setting $c_{ij}^{'} = (c_{ij} + \mu)/\,T$, one obtains Z_1 as the tour length with respect to distances $c_{ij}^{'}$. Both the numerator and the denominator of (8.2.1) are expressed in hours, such that Z_1 becomes a dimension less number (between 0 and 1).

Objective -2: Average accessibility

Average accessibility can be measured by computing the average distance a member of the population has to walk in order to reach the nearest stop of the MF. Thus, we set

$$Z_2 = \frac{1}{N} \sum_{v_i \in W} p_i d(i, \pi), \qquad (8.2.3)$$

Where, d(i ,π) = min{$d_{i,\pi(j)}$| j=1, …k} is the minimum distance of v_i to a node contained in the tour π. Objective function value Z_2 is expressed in kilometers as distance units.

Objective -3: Coverage

To measure the aspect of coverage, we introduce as a third objective function the share of the population living in a distance larger than the pre-defined value M to the nearest tour stop. Expressed in formulas:

$$Z_3 = \frac{1}{N} \sum_{v_i \in W(M,\pi)} p_i, \qquad (8.2.4)$$

where W (M, π) is the set of all nodes $v_i \in W \; wit \; d(i,\pi) > M$. Objective function value Z_3 is a ratio between numbers of inhabitants and hence a dimensionless number (between 0 and 1).

We can give a three-objective integer linear programming (ILP) formulation of our problem (8.2.2)–(8.2.4); Let us re-encode the combinatorial decision variable π by introducing the integer variables

$$x_{ij} = \begin{cases} 1, & if\ v_j\ is\ immediate\ successor\ of\ v_i\ on\ tour\ \pi \\ 0, & otherwise \end{cases}$$

For $v_i, v_j \in V$. Moreover, we introduce the additional integer variables

$$y_i = \begin{cases} 1, & if\ v_i\ is\ selected\ as\ a\ tour\ stop (i.e., element\ of\ of\ \pi), \\ 0, & otherwise \end{cases}$$

For $v_i \in V$, the integer variables

$$z_{ij} = \begin{cases} 1, & if\ population\ node\ v_i\ is\ supplied\ by\ astop\ in\ v_j, \\ 0, & otherwise \end{cases}$$

For $v_i \in W, v_j \in V$, and the integer variables

$$u_i = \begin{cases} 1, & if\ population\ node\ v_i\ is\ covered\ within\ distance\ M, \\ 0, & otherwise \end{cases}$$

For $v_i \in W. Finally,$ we define the coverage matrix A = $(a_{ij})\ by$

$$a_{ij} = \begin{cases} 1, & if\ d_{ij} \leq M, \\ 0, & otherwise \end{cases}$$

For $v_i \in W, v_j \in V$. Then, an equivalent representation of our problem is given by

$$\min \left(\sum_{v_i, v_j \in V, i \neq j} c'_{ij} x_{ij}, \sum_{v_i \in W} p_i \sum_{v_j \in V} d_{ij} z_{ij}, - \sum_{v_i \in W} p_i u_i \right) \quad (3.2.5)$$

s.t.

$$\sum_{v_j \in V} x_{ij} = y_i (v_i \in V), \quad (3.2.6)$$

$$\sum_{v_i \in V} x_{ij} = y_j (v_j \in V), \quad (3.2.7)$$

$$\sum_{v_i \in S, v_j \in V \setminus S} x_{ij} \geq y_t (S \subset V, v_1 \notin S, v_t \in S), \quad (3.2.8)$$

$$\sum_{v_j \in V} z_{ij} = 1 (v_i \in W), \quad (3.2.9)$$

$$y_j - z_{ij} \geq 0\ (v_i \in W, v_j \in V), \quad (3.2.10)$$

$$\sum_{v_j \in V} a_{ij} y_j \geq u_i (v_i \in W), \quad (3.2.11)$$

$$x_{ij} \in \{0,1\}\ (v_i \in V, v_j \in V), \quad (3.2.12)$$

$$z_{ij} \in \{0,1\}\ (v_i \in W, v_j \in V), \quad (3.2.13)$$

$$u_i \in \{0,1\}\ (v_i \in W), \quad (3.2.14)$$

The first component of (3.2.5) is objective function Z_1, represented by means of the modified costs c'_{ij} introduced after Eq. (3.2.2).

The second component is objective function Z_2, multiplied by N. The third component is obtained from objective function Z_3 by first multiplying Z_3 by N, and then subtracting the constant N from the result. Conditions (3.2.6) and (3.2.7) ensure that every node on the tour has exactly one successor and one predecessor, and that nodes outside the tour have neither successors nor predecessors. Conditions (3.2.8) are the usual sub-tour elimination constraints for the TSP, applied to tour stops. Conditions (3.2.9) and (3.2.10) together ensure that every population node is supplied by a tour stop. Condition (3.2.11) states that a population node can only be covered within distance M by a node if this node is within distance M and chosen as a tour stop. Conditions (3.2.12) – (3.2.14), finally, are the usual binary integrality constraints.

8.3 CONCLUSIONS

We have given a multi-objective combinatorial optimization (MOCO) formulation for a location-routing problem in healthcare management: For a mobile healthcare facility, a closed tour on a suitably selected subset of a given set of population nodes has to be found. Tours are evaluated according to the following three criteria: (i) an economic efficiency criterion that can be expressed as a weighted average of the number of tour stops and the tour length, (ii) the p-median criterion of average distances to the nearest tour stops, and (iii) a coverage criterion that measures the percentage of the population unable to reach a tour stop within a predefined maximum distance.

The focus of this study is on problem formulation and suitable optimization techniques. For test purposes, we can investigate the decision problem for the any rural region of a developing country on the simplifying assumption that all medical services are to be covered by the mobile facilities alone; existing fixed healthcare facilities have not been included into the consideration.

The results can indicate the assumptions, even in the absence of healthcare facilities in the considered region; four mobile units can provide access to medical service for about 85% of the population within 8 km distance, with an average distance of about 2 km. The overhead of personnel costs for non-medical activities would be about 100% in this case. Of course, these assumptions need to be discussed, but we feel that the results can indicate at least that supplementing locally fixed medical stations by mobile healthcare units should be taken into consideration as a possibly useful measure when an extension of access to medical service in a country with a low healthcare budget is intended. The advantages of mobile units will have to be traded off against evident disadvantages, for example, the lack of continuous care for patients by medical personnel. It should be kept in mind, however, that by a suitable mix between the ‘‘stationary’’ and the ‘‘mobile’’ policy, the system can be fine-tuned to the particular needs of a concrete region. It may be preferable to supplement the stationary hospitals or healthcare stations by some few mobile units providing care even at a rather low level instead of excluding large parts of the population totally from medical supply.

We can give few examples. First, of course, the above-mentioned assumption of coverage by mobile facilities alone could be dropped since medical supply in the considered area will not be provided exclusively by mobile healthcare units. Instead, existing (or planned) stationary facilities could be taken into account as well. In a first approximation, this extension will be very easy to perform: Just reduce, in the problem instance description, the numbers of inhabitants of each settlement by the (estimated) numbers of people who are already supplied by stationary healthcare facilities such as hospitals or primary healthcare dispensaries (located close enough to the settlement). However, what would not be obtained in this way are overall objective function values for average accessibility and coverage, including the services of the fixed facilities. Therefore, it would be desirable to include the supply delivered by the fixed facilities explicitly into the model, which requires an essential (although rather straight forward) generalization of the model formulation.

Second, results of studies on the effect of the distance from home to health facilities (cf. [04, 134]) could be used to refine the model.

Third, an availability criterion (influenced by opening times, relation between demand and supply, queues, types of diseases, medicaments and doctors) could enter into the model as a fourth objective. In our model in its present form, the overall duration of the tour is fixed in advance, and the distribution of the durations of stay of the mobile facility to the single tour stops is left open. Evidently, duration of stay has significant influence on the quality of service, but this question is confronted with a tradeoff: Prolonged stays facilitate the reduction of queues and improve service, but on the other hand, they also increase the overall time for one cycle of the tour, which means that the visits of the MF at a special tour stop occur less frequently. Thus, also durations could be considered as decision variables to be optimized, preferably based on statistical data about demands and with the aid of an appropriate stochastic model. Finally, the patient data could be classified according to the severity of their diseases. For example, a distinction between emergency and non-emergency cases could be carried out. In our basic framework, we assume that not only the chosen tour itself, but also the durations of stay are fixed in advance (otherwise, people could not rely on meeting the MF at a known date). Formally, tour planning with possible tour changes would require a stochastic-dynamic optimization model. Such optimization problems are notoriously hard to treat computationally; effort invested in a ‘‘on-line’’ decision support system enabling reactions on emergency cases may be well-spent nevertheless.

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Source of support: Nil, Conflict of interest: None Declared