Exploring Efficiency and Accessibility in Healthcare Network Design

Edgar Duarte-Forero[1,2](✉) and Gustavo Alfredo Bula[1]

[1] Universidad Nacional de Colombia, Bogotá, Colombia
{eduartef,gabula}@unal.edu.co
[2] Universidad Libre, Bogotá, Colombia
edgarl.duartef@unilibre.edu.co

Abstract. Healthcare network design has a critical role in achieving sustainability goals because of their possibilities as drivers for wellness and patient-driven care. Healthcare systems with limited resources require not only to improve access for patients but also to define facilities location and limit operation expenditures. In this work, a study was conducted to understand the relation between accessibility and cost-efficiency in healthcare networks. A mathematical model is proposed to evaluate optimization consequences on accessibility for patients and location-related costs for networks. The proposed model defines the location of facilities and servers, the allocation of patients, and the configuration of network links. A computational study used a randomly generated instance with multiple service levels and covering distances. Each scenario is evaluated regarding accessibility and cost-efficiency concluding that those are conflicting objectives in an optimization approach.

Keywords: Healthcare network design · Accessibility · 2SFCA · MILP

1 Introduction

Healthcare Networks (HNs) provide services to promote community wellness through interconnected resources (public or private) such as facilities, specialized equipment, healthcare professionals, or administrative staff. From a logistic perspective, incoming patients use the resources allocated on the network nodes in order to be serviced. Nevertheless, the flow of patients across HNs experience frequent interruptions that cause long waiting lists for consultations, poor service quality, or repeated medical visits. This is known as fragmentation and is mainly due to complex administrative processes and wrong logistic decisions.

Aiming fragmentation reduction, HNs must satisfy multiple criteria such as accessibility, opportunity, continuity, and equity, among others [10]. Accessibility considerably influences system fragmentation because it defines how easy it is for a patient to receive services from a specific predefined place during the first and subsequent contacts with servers.

J. C. Figueroa-García et al. (Eds.): WEA 2021, CCIS 1431, pp. 374–385, 2021.
https://doi.org/10.1007/978-3-030-86702-7_32

Healthcare Network Design deals with the configuration of network components to provide suitable service levels for the population. Previous works show that operations research techniques provide adequate solutions for the design of healthcare networks [2]. Most of those works consider optimizing objective functions of cost-efficiency[1] and coverage. One of the limitations with this approach is that it does not explore the influence of network design optimization in system accessibility for patients [1,16].

This paper aims to examine accessibility and cost efficiency in Healthcare Network Design. The main contributions of the paper are as follows: a mathematical optimization model that provides an in-depth look at these measurements in multiple scenarios; inclusion of a gravity-based method to estimate patient access; and cost-efficiency metrics including allocation of servers and transfer and transportation of patients. The proposed mathematical model is formulated based on previous works for HNs design, but in this case it also includes the optimization of accessibility as an objective function.

The remainder of the paper is organized as follows. Section 2 provides an overview of relevant literature and positions this paper. In Sect. 3, it is proposed a formulation for Healthcare Network Design that includes cost efficiency and accessibility. Section 4 highlights the solution method and computational results. Finally, Sect. 5 states concluding remarks.

2 Overview of the Literature

This section states the concept of accessibility and its measurement in healthcare location, and the main trends for Healthcare Network Design using mathematical modeling techniques. Subsequently, we delimit the scope of the paper and locate it in the research field.

2.1 Accessibility Measurement

In the healthcare field, accessibility is defined as the level of spatial availability of services [12] and a system is considered as accessible if required services are available whenever and wherever the patient may need them.

Literature review presents multiple accessibility measurements [4,16]. This paper focuses on accessibility as a function of the movement of patients to receive attention in the HN. Gravity models are used to measure accessibility in health care systems incorporating variables of supply capacity, population size, and impedance functions that depend on the travel cost. This approach considers that accessibility of a demand point is the weighted sum of supply-to-demand ratios of all nearby suppliers. The Two-Step Floating Catchment Area (2SFCA) method allows for a more general solution for this problem where supply-to-demand ratios and their sums for each population location represent its accessibility [9]. 2SFCA method has been employed to analyze spatial access to healthcare services in a number of studies during recent years [8,17].

[1] In this study, the concept of cost-efficiency refers to the sum of location related costs for patients and service managers.

2.2 Healthcare Network Design

Designing a healthcare network involves making decisions about the supply and demand. For the first one, decision-makers must define facilities location, its capacities and, connections between them, among others. Demand related decisions include the allocation of patients to specific facilities and servers for their treatments. Those decisions shall consider multiple criteria including travel distance for patients, specialties of servers, demand patterns, resource availability, and capacity of facilities.

A great deal of previous research into Healthcare Network Design has focused on specific applications areas such as calculation of available professionals [5], enabled beds and other service capacity measurements for healthcare networks. Regarding optimization objectives, reviewed literature emphasize on minimizing costs for server allocations, travel times, and installed capacity costs [3,11]. Service level specifications are also included by some authors in order to minimize waiting times [15] and lost demand [13].

Two aspects emerge from the studies discussed so far. Firstly, the need to examine the healthcare network design problem from a combined perspective of facility location and network design. Secondly, the possibility of exploring the relationships between cost-efficiency and accessibility in HNs. The following section integrates these aspects with the formulation of a mathematical model for the design of healthcare networks.

3 Healthcare Facility Location Network Design Problem

In general, the Healthcare Facility Location Network Design Problem (HFLNDP) deals with the location of a set of healthcare servers at some available facilities to satisfy the needs of patients subject to constraints of quality of service, capacity management, and patients flow, among others. It also aims to define the necessary connections among users and servers to allow patients flow [14]. Figure 1 shows a hypothetical network where three groups of patients with different required treatments have to choose one from the available facilities (medical centers). Each considered facility has a group of servers of different specialties. The links represent the connections and possible allocations between places of residence and facilities and between the servers for patient referrals.

Consider a patient from group A that visits facility *f1*. A general practitioner attends the case and, with a certain probability, passes a referral to a specialist in *f2*. After that, the patient will have to visit the specialist in *f2* who may then send a new referral to *f3* for a medical test. Results of this test will be sent from *f3* to the specialist in *f2*. Finally, in a new appointment, the specialist will formulate recommendations to the patient according to the diagnosis. Similar flows may take place with patients for treatments B or C. This study considers just one hypothetical flow of patients for a specific group.

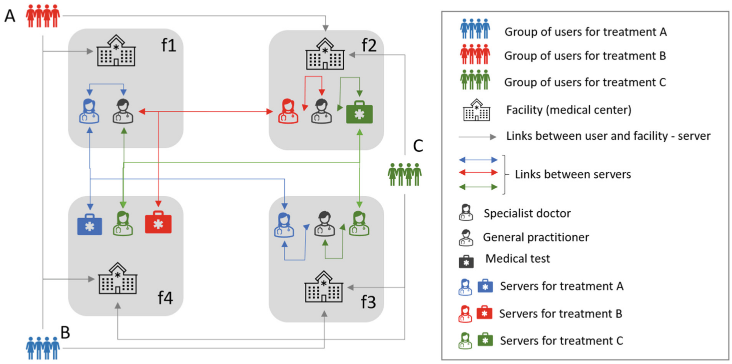

Fig. 1. Model of a hypothetical network

The proposed model for the HFLNDP determines (i) the selected facilities, (ii) the allocation of servers to facilities, (iii) the allocation of patients to servers, and (iv) the required links for referrals. The constraints include demand covering, capacity management at servers and facilities, flow of patients and referrals across links, and service level for patients[2].

The model considers a HN as a graph with a set of nodes and links. Let I denote the set of population zones indexed by i, $i \in I$. J denote potential facility locations indexed by j , $j \in J$. Finally, K represents the set of medical specializations for patient treatments indexed by k, $k \in K$. It is assumed that population at demand nodes I generate a stream of deterministic and inelastic demand denoted by h_i. Every server allocated to a facility j provides a specialized service k with a patient capacity c_{jk}. A facility at j has a maximum number of servers for specialty k denoted by s_{jk}. Coverage parameters a_{ij} and $b_{jj'}$ represent the possibility of visiting j from i, and j' from j, respectively. In addition, the distance commonly traveled by patients between demand regions i and facilities j is denoted by d_{ij}. There is also a cost for every referral between servers represented by $e_{jj'}$.

In this model, it is assumed that specialty $k = 1$ corresponds to the first level of attention commonly provided by a general practitioner. Additionally, specialists ($k \geq 2$) cannot refer patients to general practitioners. The patient entering the network has to select a facility for a first appointment ($k = 1$). Then, the practitioner may assume the treatment or refer the case to a specialist ($k \geq 2$). The selection of subsequent specialists depends on the parameter $t_{kk'}$ representing the percentage of patients referred from specialty k to k'. The number of available facilities for the first appointment is defined as Service Level and is modeled with the parameter q_i.

[2] Service level refers to the number of available facilities for first appointments.

The network design also defines the links for patient movement and referrals of cases between specialists. Corresponding decision variables are as follows. Links representing the possibility of patients visiting facilities are denoted by z_{ij}. The possibility of sending referrals from a specialist of type k located at j to another specialist of type k' located at j' is represented by $v_{kk'jj'}$. Finally, the flow of patients from i to a facility j is denoted by y_{ij}, while $w_{jj'kk'}$ represents the flow of referrals from servers type k located at j to servers of type k' located at j'. In order to present and discuss a mathematical model for the optimization of the HFLNDP, the notation of Table 1 will be used throughout this section.

Based on these assumptions, the problem is to find the network design that fulfills objectives of cost and accessibility, given sets of nodes (users and facilities), available servers, and covering constraints. The total cost of the system is modeled by the sum of transportation costs for patients (TCP), allocation costs at facilities (ACP), and referring costs of patients among servers (RCS). Those components are formulated as follows:

$$TCP = r * \sum_{ij} d_{ij} y_{ij} \tag{1}$$

$$ACS = \sum_{jk} f_{jk} x_{jk} \tag{2}$$

$$RCS = u * \sum_{jj'kk'} w_{jj'kk'} e_{jj'} \tag{3}$$

Accessibility measurement is formulated using the Two-Step Floating Catchment Area (2SFCA) method [9]. The reason that 2SFCA is selected is because of its predominance as a proper measurement of accessibility for healthcare locations [8,17]. It measures the accessibility of a demand location i considering the supply and a threshold of availability for those services and demand. The procedure for computing the measure value is shown next.

Step 1. Given a solution for the HFLNDP, for each location j, and a service k, search all demand locations i that are within a threshold travel distance from location j. Threshold distances a_{ij} depend on decision-maker criteria. Calculate the server-to-population ratio, R_{jk} as follows:

$$R_{jk} = x_{jk} / \sum_{i} (a_{ij} h_i) \quad \forall jk \tag{4}$$

Step 2. For each demand location i, search all server locations j that are within a threshold travel distance (a_{ij}) from location i and sum up the ratios at these locations.

$$A_{ik} = \sum_{j} a_{ij} * R_{jk} \quad \forall ik \tag{5}$$

Table 1. Notations of sets, parameters and decision variables for the HFLNDP.

Symbol	Description
Sets	
I	Set of users demand nodes. $i \in \{1, 2, ... \lvert I \rvert\}$
J	Set of potential facilities. $j \in \{1, 2, ... \lvert J \rvert\}$
K	Set of services required by users. $k \in \{1, 2, ... \lvert K \rvert\}$
Parameters	
d_{ij}	Distance on link (i, j)
$e_{jj'}$	Referral cost on link (j, j')
f_{jk}	Fixed cost of resource k at j
h_i	Demand of users at node i looking for a first appointment
a_{ij}	Equal to 1 if and only if $i \in I$ can be covered by $j \in J$
$b_{jj'}$	Equal to 1 if and only if $j \in J$ can be covered by $j' \in J$
c_{jk}	Capacity of a specialist of type k located at facility j to attend users
s_{jk}	Maximum number of specialists of type k that can be hosted at facility j
q_i	Minimum number of facilities to choose from for a first appointment from i
$t_{kk'}$	Percentage of users referred from specialty k to specialty k'
r	Traveling cost for users visiting servers
u	Referring cost of users between servers
Decision variables	
x_{jk}	Number of servers of type k allocated at facility j
y_{ij}	Number of users allocated from region i to facility j
z_{ij}	Binary variable equal to 1 if and only if users travel from i to j
$w_{jj'kk'}$	Number of users referred from a specialist type k at facility j to a specialist k' at a facility j'
$v_{jj'kk'}$	Binary variable equal to 1 if and only if a specialist type k at facility j refers patient to a specialist k' at a facility j'

The larger the index value A_{ik}, the better accessibility at this location. Equation 4 calculates an initial ratio for every service location and Eq. 5 sums up different ratios within a threshold distance for every demand location. Finally the whole accessibility of a system is the sum of every A_{ik}.

$$TAS = \sum_{ik} A_{ik} \tag{6}$$

Special attention must be given to the modeling of links activation. Binary variables z_{ij} and $w_{jj'kk'}$ change if and only if there is flow of users between i and j, and between jk and $j'k'$ respectively. A ceiling function provides this formulation establishing limits for z_{ij} with the quotient of the flow y_{ij} and its maximum possible value $\sum_i h_i$. The following equation represents the implementation of this ceiling function for z_{ij}.

$$\frac{y_{ij}}{\sum_i h_i} \leq z_{ij} \leq \frac{y_{ij}}{\sum_i h_i} + 0.999 \quad ; \forall ij; z_{ij} \in \{0, 1\} \tag{7}$$

Regarding the case of referrals (flows from j to j'), the implementation of the ceiling equation stands as follows:

$$\frac{w_{jj'kk'}}{\sum_i h_i} \leq v_{jj'kk'} \leq \frac{w_{jj'kk'}}{\sum_i h_i} + 0.999 \quad ;\forall jj'kk', v_{jj'kk'} \in \{0,1\} \tag{8}$$

The resulting mathematical formulation for the HFLNDP is as follows:

$$\text{maximize} \quad Z_1 = TAS \tag{9}$$

$$\text{minimize} \quad Z_2 = TCP + ACS + RCS \tag{10}$$

$$\text{subject to} \quad \sum_j y_{ij} = h_i \;\; \forall i \in I, \tag{11}$$

$$z_{ij} \leq a_{ij} \;\; \forall i \in I, j \in J, \tag{12}$$

$$v_{jj'kk'} \leq b_{jj'} \;\; \forall (j,j') \in J, (k,k') \in K, \tag{13}$$

$$\sum_i y_{ij} \leq c_{jk} x_{jk} \;\; \forall j \in J, k = 1, \tag{14}$$

$$\sum_{jk} w_{jj'kk'} \leq c_{j'k'} x_{j'k'} \;\; \forall (j') \in J, k' \in K, k' \neq 1, \tag{15}$$

$$\sum_{j \in J} z_{ij} \geq q_i \;\; \forall i \in I, \tag{16}$$

$$x_{jk} \leq s_{jk} \;\; \forall j \in J, k \in K, \tag{17}$$

$$t_{1k'} * \sum_i y_{ij} = \sum_{j'} w_{jj'1k'} \;\; \forall (j,k') \in K, \tag{18}$$

$$t_{k'k''} * \sum_{jk} w_{jj'kk'} = \sum_{j''} w_{j'j''k'k''} \;\; \forall (j'j'') \in J, (k',k'') \in K, \neq 1), \tag{19}$$

$$y_{ij} \leq z_{ij} c_{jk} x_{jk} \;\; \forall i \in I, j \in J, k = 1, \tag{20}$$

$$y_{ij} \leq zij * \sum_i h_i \;\; \forall i \in I, j \in J, \tag{21}$$

$$y_{ij} \geq (zij - 0.999) * \sum_i h_i \;\; \forall i \in I, j \in J, \tag{22}$$

$$w_{jj'kk'} \geq v_{jj'kk'} * \sum_i h_i \;\; \forall (jj') \in J, (kk') \in K, \tag{23}$$

$$w_{jj'kk'} \geq (v_{jj'kk'} - 0.999) * \sum_i h_i \;\; \forall (jj') \in J, (kk') \in K, \tag{24}$$

$$y_{ij} \geq 0 \;\; \forall i \in I, j \in J, \tag{25}$$

$$z_{ij} \in (0,1) \;\; \forall i \in I, j \in J, \tag{26}$$

$$w_{jj'kk'} \geq 0 \ \ \forall (j, j') \in J, (k, k') \in K, \tag{27}$$

$$v_{jj'kk'} \in (0, 1) \ \ \forall (j, j') \in J, (k, k') \in K, \tag{28}$$

$$x_{jk} \geq 0 \ \ \forall j \in J, k \in K \tag{29}$$

The proposed model is formulated with two objective functions. Equation 9 sets the objective for maximizing the system accessibility and Eq. 10 minimizes the sum of traveling costs for patients, referral cost between servers and the fixed costs of servers at facilities.

Equation 11 ensures that every user must receive attention and Eq. 12 states that there can be a flow of patients from i to j if and only if the facility at j covers patients from i. Similarly, Eq. 13 allows referrals of patients from j to j' if and only if there is coverage between facilities at j and j'. Equations 14 and 15 verify the fulfillment of servers capacity requirements. Service level for patients is considered in Eq. 16 where the minimum number of available facilities is represented by q_i. The maximum number of servers for every facility is stated by Eq. 17.

The flow of patients across general practitioners and specialists is modeled by Eqs. 18 and 19, respectively. The activation of links in the network is constrained by Eqs. 21, 22, 23 24. Equations 25 to 29 define the mathematical nature of every variable in the model.

4 Computational Experiments

An implementation of the mathematical model for HFLNDP was coded in Python programming language supported by the Pyomo optimization modeling language [7] and solved using commercial optimization solver (Gurobi) [6] with a randomly generated instance. Table 2 presents parameter values for the constructed instance.

Table 2. Values of parameters for random instance

Param.	Values
$\lvert I\rvert$	8
$\lvert J\rvert$	14
$\lvert K\rvert$	5
d_{ij}	Euclidean distances between nodes i, j with random positions $\sim$ U(0,1)
$e_{jj'}$	Uniform random values for each pair i, j with random positions $\sim$ U(0,1)
f_{jk}	$\sim$ U(1,2)
h_i	$\sim$ U(5,8)
a_{ij}	Defined according to covering distances of 1.4, 1.0, 0.8, 0.6, 0.5 and 0.4
b_{ij}	Defined as 1.4
c_{jk}	$\sim$ U(40,100)
s_{jk}	$\sim$ U(8,12)
$t_{kk'}$	Randomly generated for each level k and considering that $t_{k,k'} \geq t_{k+1,k'+1}$

Experiments considered two factors: (i) covering distance for first appointment (a_{ij}), and (ii) service level (represented by the sum of available facilities for first appointments: $\sum_i q_i$). Covering distance was included with six levels: of 1.4, 1.0, 0.8, 0.6, 0.5 and 0.4. Second factor was explored defining levels for available facilities ranging from 13 to 21. This quantity was distributed among demand regions according to its population size.

Experiments consisted in solving the mathematical model separately for the objective functions defined in Eqs. 9 and 10. Figure 2 illustrates the effect of minimizing costs and the corresponding accessibility of different scenarios. The lower the costs, the lower the accessibility. There is no evidence of an influence of service level in either of the objectives. Conversely, higher values of covering distance corresponded to lower values for costs and accessibility. From that point of view, the decision to decrease costs affects the accessibility of patients. Therefore, conflicts arise when reducing costs in a HN because that would cause a reduction of accessibility and a reduction of covering distances increases costs.

An additional set of experiments was done to maximize accessibility. Results indicate that the higher values of covering distances, the higher costs obtained (Fig. 3). The maximization of accessibility can be accompanied by lower costs with shorter covering distances. If covering distances are to be higher, accessibility is reduced and costs increase significantly. The optimization model seeks for increasing accessibility by allocating the maximum possible number of servers in facilities. Obviously, this strategy brings higher costs.

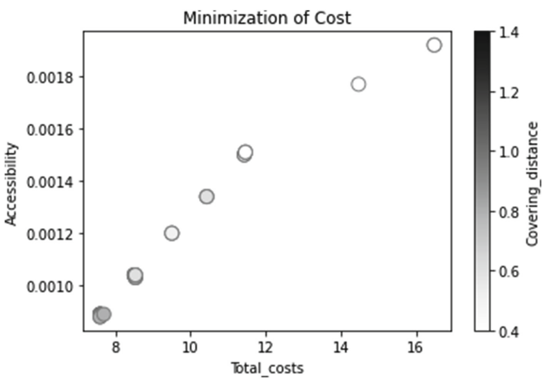

Fig. 2. Minimization of costs

Results guide towards the inclusion of covering distances as an influential parameter in network design. When minimizing costs, increasing covering distances allows a reduction of the costs in the system and a markdown on accessibility. On the contrary, when maximizing accessibility, increasing covering distances conveys an increase in costs. Consequently, decision-makers shall find balances among those measures that may preserve the access for patients and the cost efficiency for the system.

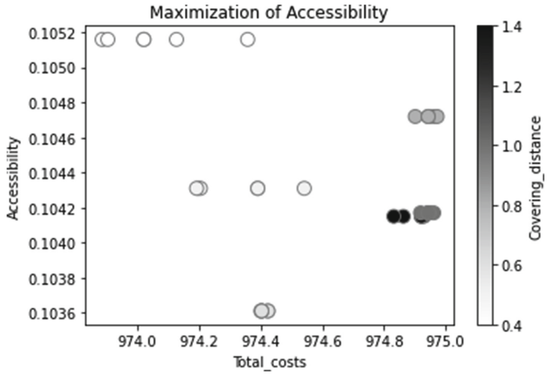

Fig. 3. Maximization of accessibility

Additional tests were performed with the comparison of optimal values for accessibility and costs on every scenario. Figure 4 represents the space of objective functions included in the experiments. This analysis suggests a conflicting nature between accessibility and cost-efficiency. In every scenario, a reduction in system cost resulted in an overall decrease of accessibility. This statement leads to the need of additional studies in order to find proper equilibrium among those objectives.

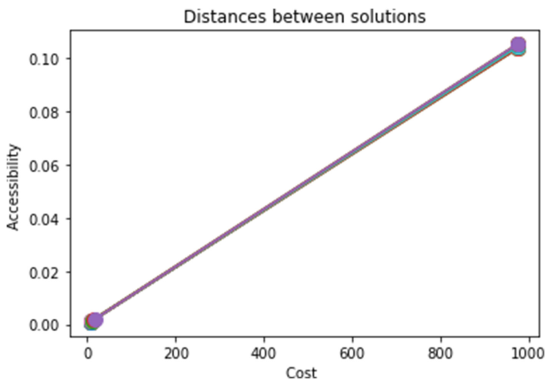

Fig. 4. Space of objective functions

5 Conclusions

A formulation for the Healthcare Facility Location Network Design Problem (HFLNDP) was proposed to analyze the relation among accessibility and cost efficiency. The scope of the study consisted in separately experiment with the minimization of network costs and the maximization of accessibility. Network costs included patient transportation, allocation of servers and transfer or referrals. Accessibility measurement consisted in the implementation of the Two Steps Floating Catchment Area method (2SFCA).

Experiments showed that the minimization of costs for the system conducted to a reduction of accessibility for patients. When maximizing accessibility, longer values of covering distances required higher costs for the system. Shorter covering distances produced lower costs and higher values of accessibility. This study considered service level as a factor and it was modeled as the number of available facilities for first appointments. Nevertheless, the results do not reflect its influence on accessibility. Additional experiments should be developed considering a wider range of options for its levels.

Finally, the analysis of the conflicting nature among accessibility and costs for the system supports the need for additional studies to explore the multi-objective dimension of healthcare network design. In addition to accessibility and costs, further objectives may be included in future studies: congestion, continuity and equity, among others.

References

1. Aboolian, R., Berman, O., Verter, V.: Maximal accessibility network design in the public sector. Transp. Sci. **50**(1), 336–347 (2016)
2. Ahmadi-Javid, A., Seyedi, P., Syam, S.S.: A survey of healthcare facility location. Comput. Oper. Res. **79**, 223–263 (2017)
3. Berman, O., Krass, D.: Stochastic location models with congestion. In: Laporte, G., Nickel, S., da Gama, F.S. (eds.) Location Science, pp. 443–486. Springer, Cham (2015). https://doi.org/10.1007/978-3-319-13111-5_17
4. Bhat, C., Handy, S., Kockelman, K., Mahmassani, H., Chen, Q., Weston, L., et al.: Accessibility measures: formulation considerations and current applications. Technical report, University of Texas at Austin. Center for Transportation Research (2000). https://ctr.utexas.edu/wp-content/uploads/pubs/4938_2.pdf
5. Gupta, D., Wang, W.Y.: Patient appointments in ambulatory care. In: Hall, R. (ed.) Handbook of Healthcare System Scheduling, vol. 168, pp. 65–104. Springer, US, Boston, MA (2012). https://doi.org/10.1007/978-1-4614-1734-7_4
6. Gurobi Optimization, LLC: Gurobi optimizer reference manual (2020)
7. Hart, W.E., et al.: Pyomo-Optimization Modeling in Python, vol. 67. Springer Science & Business Media, second edn. (2017). https://doi.org/10.1007/978-3-319-58821-6
8. Luo, J.: Analyzing potential spatial access to primary care services with an enhanced floating catchment area method. Cartographica **51**(1), 12–24 (2016)
9. Luo, W., Wang, F.: Measures of spatial accessibility to health care in a gis environment: synthesis and a case study in the chicago region. Environ. Plann. B Plann. Des. **30**(6), 865–884 (2003)
10. Mendes, E.V.: Las Redes de Atención de Salud. Organización Panamericana de la Salud, Brasilia (2013)
11. Paraskevopoulos, D., Gürel, S., Bektaş, T.: The congested multicommodity network design problem. Transp. Res. Part E Logistics Transp. Rev. **85**, 166–187 (2016)

12. Phillips, D.R.: Health and Health Care in the Third World. Longman Scientific & Technical, Harlow, Essex, England, Longman Development Studies (1990)
13. Pouraliakbari, M., Mohammadi, M., Mirzazadeh, A.: Analysis of maximal covering location-allocation model for congested healthcare systems in user choice environment. Int. J. Ind. Syst. Eng. **28**(2), 240–274 (2018)
14. Rahmaniani, R., Ghaderi, A.: A combined facility location and network design problem with multi-type of capacitated links. Appl. Math. Model. **37**(9), 6400–6414 (2013)
15. Vidyarthi, N., Kuzgunkaya, O.: The impact of directed choice on the design of preventive healthcare facility network under congestion. Health Care Manag. Sci. **18**(4), 459–474 (2015)
16. Wang, F.: Measurement, optimization, and impact of health care accessibility: a methodological review. Ann. Assoc. Am. Geogr. **102**(5), 1104–1112 (2012)
17. Zhou, X., Yu, Z., Yuan, L., Wang, L., Wu, C.: Measuring accessibility of healthcare facilities for populations with multiple transportation modes considering residential transportation mode choice. ISPRS Int. J. Geo-Inform. **9**(6), 394 (2020)