Challenges and Solutions for Location of Healthcare Facilities

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Abstract

Healthcare infrastructure is essential for effective operations of healthcare systems. An efficient facility location can save cost and improve the facility utilization. It is important to update the knowledge of methods and applications to locate healthcare facilities for different purposes. This paper provides an overview of methods and challenges for decision-making of the healthcare facility location to ensure an optimal solution. This research suggests answers for defined questions. Challenges are discussed in detail for modeling and applications of healthcare facility location problems. It is noticed that many existing location models were developed to cover the need of special cases. Cost and efficiency are two important criteria for healthcare services to minimize total traveling distance between patients and the healthcare facility. Uncertainty is recognized as an inevitable part of healthcare location problems. Reliability studies and sustainability should be considered in the location modeling. It is necessary to extend dynamic models to meet the trend of parameter changes over the time for decision-making. Considering the level of complexity and trend of needs for the healthcare facility, more research is required on the operation efficiency, patient safety and cost-effective solutions for the better resource utilization in the human-centered healthcare environment. The contribution of this paper is an overview of challenges and methods in the area to provide guidance for performance measures and improvements of healthcare facility location problems. This paper can be used as a guide of methods for the location or relocation of healthcare facilities.

Introduction

Healthcare infrastructure provides the basic support for healthcare operations and services. A study indicated that for every $10 billion investment in the infrastructure, 115,000 new jobs were created and GDP grew by 1.3% [1]. According to a study, each dollar spent on the healthcare infrastructure has led to tangible gains of $2.40 to $3 [2]. In Canada, healthcare infrastructure takes the largest portion of healthcare spending compared to drugs and physicians, which reached $60.5 billion, reflecting 29.2% of the total health expenditure and 11.6% of GDP (Gross Domestic Product) in 2012 [3].

Facility location is a critical factor in strategic planning of healthcare programs [4]. For the accessibility of healthcare facilities, a survey showed that the distance to hospitals is a key factor when patients choose the healthcare service [5]. Various research and applications have been conducted since the method of facility locations was introduced by Weber [6]. In the 1960s, the first facility location model for healthcare systems was proposed by Hakimi [7] followed by many innovative efforts of other researchers.

There are different review publications in this field. Table 1 summarizes the existing review papers based on contents, specifications and numbers of papers included. A comprehensive review in healthcare (HC) facility location models was done by Eiselt [8], Daskin and Dean [9], and Rahman and Smith [10]. Farahani et al. [11] reviewed covering problems of the facility location. A review of operation research in healthcare is presented by Rais and Vianaa [12]. Altay and Green [13] provided a holistic review for Operations Research and Management Sciences (OR/MS) methods used in the disaster operation management.

Other authors reviewed different topics of the healthcare location problems. ReVelle et al. [14] described an annotated bibliography in two branches of the discrete location theory and modeling. A review presented congestion models of the facility location with immobile servers [15]. Li et al. [16] reviewed optimization techniques for facility locations and planning of the emergency response. Optimization models in emergency logistics were reviewed by Caunhye et al. [17]. A review of probabilistic and deterministic location problems was conducted by Owen and Daskin [18] and Brotcorne et al. [19]. For extensive reviews on the facility location research under uncertainty, readers can refer to Baron et al. [20], Snyder [21], and Louveaux [22].

However, there is a lack of review on general methods and applications for healthcare facility location problems in the existing literature. Most papers focused on some specific types of location problems (Table 1). A general guideline is missed for readers to select and apply the methods for the healthcare facility location. This paper is to provide an updated and comprehensive overview for methods and criteria to locate healthcare facilities.

Proposed method of the review

This research investigates methods and applications in healthcare facility location decision-making. The objectives of the research are as follows:

- Identify key decisions, characteristics, and challenges in healthcare facility location problems,

- Explore models to formulate challenges and problems in this field, and

- Classify measures and solutions for proposed models based on theoretical and practical studies.

In order to achieve these objectives, questions are designed to

Author(s)	Content	Specification	Reviewed papers
Caunhye et al. [17]	Optimization models in emergency logistics	Detailed classification with some papers in HC facility location	74
Farahani et al. [11]	Covering models in facility location	Detailed presentation of covering models with some application in HC facility location	176
Li et al. [16]	Covering models and optimization techniques	Emergency response facility location and planning	112
Rias and Vianaa et al. [12]	Application of main operations research techniques in HC	General presentation of papers classified by OR techniques and applications	250
ReVelle et al. [14]	Discrete facility location	General bibliographical review including some HC models	113
Eiselt et al. [8]	Main facility location models	General review of the models with emphasis on Canadian contributions	136
Boffey et al. [15]	Congestion models in facility location	Detailed presentation of models with immobile servers with some applications in HC	73
Altay and Green et al. [13]	OR/MS in disaster operations management	Detailed classification including some of the HC facility location models	152
Snyder et al. [21]	Facility location under uncertainty	Detailed classification of tools and techniques	154
Daskin and Dean et al. [9]	Location models in HC	Detailed classification of models with application in HC	74
Brotcorne et al. [19]	Ambulance location & relocation models	Detailed classification	48
Rahman and Smith et al. [10]	Location models in HC	General facility location models with application in developing nations	22
Owen and Daskin et al. [18]	Main Facility location models	General presentation with some applications in HC	97
Louveaux et al. [22]	Discrete stochastic location models	Detailed presentation of models	19

Table 1: Previous review papers related to healthcare facility location problems

No.	Research Questions
1	What are the key healthcare services? What are the characteristics/specifications/ important factors of each facility service?
2	What are the main challenges of the facility location for healthcare services? What solutions are provided for those challenges?
3	What are measures and criteria applied to address the characteristics of healthcare facility location?
4	What are the mathematical technique and optimization methods applied to resolve HC location challenges?
5	What are the major solution methods applied in healthcare facility location and their implementation for real data?

Table 2: Research questions.

address problems in each step of the healthcare facility location. Based on the nature and challenges of healthcare services, metrics, methods and solutions are discussed in following sections (Table 2).

In the remaining parts of this paper, after introducing natures of health services, challenges of the healthcare facility location are discussed and mathematical methods to model HC location problems are explained. Then reviewed methods are categorized for performance measures and metrics with objectives and constraints. Analysis of solutions and applications of the models is conducted in detail. Finally, the conclusion is summarized followed by recommendations for the future research.

Healthcare services, importance and specifications

Healthcare services are categorized into three comprehensive groups: preventive, emergency, and health center services or other normal services in this paper.

Preventive health services

Zhang et al. [23] categorized preventive healthcare programs into three groups based on following objectives:

- Primary prevention, e.g., immunizations of healthy children

- Secondary prevention, e.g., detection of early forms of cervical cancer

- Tertiary prevention, e.g., the sugar control in a diabetic, blood tests or mammograms

As a common characteristic among preventive health services, people may not seek services from the closest location for preventive health services as the quality of services can convince the people to not necessarily select the nearest facility. In other words, people have more flexibility to select service locations. The second characteristic

is that the preventive health services need a minimum number of clients to maintain their activities [24]. Exception is allowed if a policy decision obliges to provide preventive services for sparsely populated neighborhoods.

Emergency healthcare services

Emergency services such as ambulance systems must provide a high service level to ensure the public safety. A major specification of emergency services is unpredictability in terms of time and venue. These services are typically provided by vehicles based on fixed locations so that the number and position of vehicles are known as the vital factors to the quality of services [25]. Therefore, the challenge of ambulance services is to locate ambulances to minimize response time (i.e., the time from an emergency call receipt to the ambulance arrival on the scene). For the Emergency Medical Services (EMS), response time is a critical factor that affects life or death [16]. Studies have reported the correlation between improved survivals of high risk patients and decreased response time. In another study, ambulance response time is recognized as an important benchmark measure of the pre-hospital (EMS) quality [26]. There may be different standards and regulations in different countries; for example, in the USA, the crucial response time is defined less than 4 to 5 minutes [4,27]. In BC, Canada, the standard is 9 minutes or less [28].

Health center services or other normal services

Healthcare services which are not categorized as preventive or emergency services are classified in this group of services. Due to a wide range of health services provided in this category, comprehensive resources are needed to establish hospitals and professional clinical centers. Much research shows the easy access to healthcare center services as an important factor for success in healthcare programs. A survey found that the convenience of access to a facility is a very important factor in patient's decision to visit healthcare facilities [29].

Another study found that the efficacy of reducing structural barriers (including the distance required traveling) increases the community access to healthcare facilities [30]. Other studies on the structure of rural healthcare facilities in developing countries showed that accessibility is an important factor for success in health plans [31,32].

In summary, to fulfill patients' need for each type of healthcare services; specifications of each health service should be studied. Response time is essential for emergency service which is normally served by mobile facilities. Accessibility is vital for success in locating hospitals and clinical services. For preventive or long-term treatments, qualitative measures should be considered, e.g., trends of specific diseases in each regions.

Challenges and solutions of facility location for healthcare services

Challenges of locating healthcare facilities have been widely discussed in literature. One of the researchers, Nelson [33], highlighted the link between health needs and facility location. He addressed some errors in optimizing resources for healthcare including: errors in definition of needs, errors in measurement of need, and errors due to over-allocation (or under allocation) of services to those needs. Therefore, before decision-making for location, capacity and staffing, the current and future service needs of community should be investigated. Yatin and Paul [34] addressed a lack of access to trained staff as the biggest challenge after decisions such as size of facility and level of care needs. It indicates the importance of defining criteria for facility location problems.

Some studies discussed the challenges for specific type of healthcare locations. For example, Caunhye et al. [17] presented emergency facility location challenges including: uncertainty in demand and facility capacities, inaccessibility to accurate real-time demand information, difficulties to achieve timely and efficient deliveries, and limited resources. One big challenge for healthcare facility location models is how to deal with congestion incurred at the facility; another challenge is how to model the patient choice. The other challenge is to measure urgent health services where using estimation methods embeds uncertainty in modeling for the healthcare location problem. In this study, we focus on challenges related to modeling and optimization of healthcare location decisions.

Challenge 1-Difficulties for patients to access HC facilities: A fundamental challenge in location planning is minimizing the distance between facility and demand points (patients). Among different distance planning methods for a given number of facilities and locations, the P-median model seeks to minimize the total travelling distance from all clients to their closest serving facilities. This model, introduced by Hakimi [7], is one of the most popular models for facility location problems. P-median models have been extensively used in formulation of healthcare facility location problems. It has also been useful in planning control over disease [35]. ReVelle and Swain [36] formulated the P-median problem as a linear integer program. As noted by Church and ReVelle [37], one important way to measure the effectiveness of a facility location is to determine the average distance traveled by visitors. P-median is a basic model with the single objective; therefore, many other contributions have been made based on this model to cope with problems in healthcare facility location.

Challenge 2 Investigate the number of healthcare facilities required to cover all patients: For the number of facilities requested to fulfill healthcare service request, modeling for the location of a given number of facilities is to maximize the total clients covered by these facilities within a maximum acceptable distance. A common facility location model was the Location Set Covering Problem (LSCP) proposed by Toregas and Revelle [38]. The model allocates facilities by minimizing the average distance traveled. However, a full coverage is hard to achieve in reality due to the limited resources provided. Real facility location problems may require more features and objectives; other studies have been conducted to cover these needs.

Challenge 3- Difficulties to cover all patients' healthcare needs within specified number of HC facilities: The challenge stems from the limitation of resources to meet all requested facilities based on LSCP model. The aim is to maximize the healthcare service coverage for predefined number of facilities. As a solution for this challenge, a maximum deterministic model was proposed by Church and ReVelle [39] and extended by Daskin [40], named the Maximal Covering Location Problem (MCLP). When a facility is called for emergency services, both LSCP and MCLP are unable to provide reliable solutions. Other models were proposed to resolve this weakness. Daskin et al. [41] suggested approaches of an additional coverage and busy probabilities of facilities.

Gendreau [42] proposed Double Standard Model (DSM). The DSM aims to allocate facilities among potential sites to provide the full coverage within a longer distance standard while maximizing the coverage within a shorter distance standard. Doerner et al. [43] and Doerner and Hartl [44] developed models based on the DSM, in which penalty terms are embedded to the objective function to avoid unmet coverage requirements and uneven workload. The models proposed by Hogan and ReVelle [45] maximize the population coverage with more than two facilities while forcing all demand points to be covered once, known as Backup Coverage Problem (BACOP1 and BACOP2). Hierarchical version of the LSCP was developed by Daskin and Stern [46]. In these models the objective is to minimize the number of facilities for full location coverage within a distance standard, and then to maximize the number of demand points with multiple coverage.

In gradual covering models, it is assumed that a demand point can be covered more than one time by facilities within a predefined threshold. It uses mathematical functions for a gradual decline of the coverage along the distance increase. A partial coverage version of MCLP (MCLP-P) was developed by Karasakal and Karasakal [47] using Lagrangean Relaxation to optimize the solution. By applying a stochastic gradual coverage model, Drezner et al. [48] presented a new model using parameters such as short (r_1) and long (r_2) distance standards for random variables.

In cooperative covering models, it is assumed that the coverage can be reached not only by one facility (usually the nearest one) but also by other facilities, simultaneously. Berman et al. [49] defined that each facility emits a "signal" that decays over the distance based on a decay function. A demand point receives signals from all facilities. If the summation of all received signals exceeds a pre-defined threshold, demand points can be called covered. They formulated the Cooperative Location Set Covering Problem (CLSCP) and the Cooperative Maximum Covering Location Problem (CMCLP).

Challenge 4-Optimize access to healthcare services for patients with the longest distance: One concern in locating healthcare facilities is patients with the minimum coverage who are vulnerable to dismiss access to healthcare services. In case emergency facilities are located, improving the coverage of these patients is more critical. There are various methods proposed to resolve this challenge. For example, the *P*-center modeling specifies a location arrangement to minimize

the maximum distance while covering all clients required. Unlike the covering model which takes an input coverage distance, this model determines endogenously the minimal coverage distance associated with locating a given number of facilities [40]. The *P*-center problem has an obvious assumption that a facility located at a node can respond to all demands originating from the node; this assumption is not valid in case of large-scale emergencies where many of the facilities may be ruined. This model is useful when there are not enough facilities while the service has to cover all the clients within a target region [50-52].

Hochbaum and Pathria [53] proposed a model for stochastic *P*-center emergency facility location problems aimed to minimize the maximum distance on the network across all time periods. In another *P*-center model presented by Talwar [54], three emergency rescue helicopters are located to serve growing EMS demands in the north and south Alpine mountain ranges. The objective was to minimize the worst (maximum) response time. Other methods of P-center modeling can be referred to Handler [52], Brandeau and Chiu [55], Daskin [56], and Current et al. [57].

Challenge 5-Deal with uncertainties in covering patients with healthcare services: Uncertainty is inevitable in the location modeling when there is no information about the probabilities for decision makers to optimize the worst-case performance of the system [21]. The uncertainty can happen in stochastic problems or robust optimization problems. Probabilistic models acknowledge a probability for a lack of the access to a given facility when it is needed. This uncertainty has been modeled using queuing, simulation, or mathematical programming formulation. Berman et al. [58] combined the queuing theory and *P*-median model, called Stochastic Queue Median (SQM), to optimally allocate mobile servers such as emergency response units to the demand points to minimize the average cost of the response. ReVelle and Hogan [59] proposed a probabilistic covering location model named the Maximum Availability Location Problem (MALP) with two versions. The main assumption in MALP-I was that the facilities have the same busy fraction. However, in the MALP-II, the busy fraction associated with each demand point was computed as the ratio of the total duration of all calls generated from the demand point to the total availability of all facilities. Marianov and ReVelle [60] proposed the queuing Maximal Availability Location Problem (Q-MALP) to relax the assumption in the MALP-I. By integrating a hypercube queuing model into the MALP, Galvão et al. [61] proposed the model called EMALP to relax the assumption of identical servers in the MALP.

In the Maximum Expected Covering Location Problem (MEXCLP), all facilities are assumed to have the same busy probability and to operate independently. The objective of this model is to maximize the expected coverage with a limited number of facilities. Similar to the DSM, the MEXCLP also allows more than one facility at one site. The MEXCLP has two strong assumptions: independent facilities and same busy probabilities of facilities. Some extensions to the MEXCLP were presented by Repede and Bernardo [62] to incorporate temporal varying demands into the model named the TIMEXCLP. Sorensen and Church [63] modeled the Local Reliability based on MEXCLP (LR-MEXCLP) with the same objective as the MEXCLP using local reliability estimation. Queuing Probabilistic Location Set Covering Problem (QPLSCP) formulated by Marianov and Revelle [64] relaxed the assumption for servers operated independently. Later, Marianov and Serra [65] proposed a queuing version of MCLP named the Maximal Covering Location-Allocation Problem (MCLAP) with constraints on waiting time in queue.

The hypercube queuing model was designed to analyze behaviors of a multi-server queuing system with distinguishable servers [66]. The hypercube queuing theory was then embedded into the MEXCLP model by Batta et al. [67] called the Adjusted MEXCLP (AMEXCLP). Another hypercube queuing model was developed by McLay [68] (called MEXCLP2) to analyze the dependencies between facilities within the same type, and dependencies of facilities among different types. The Stochastic Hybrid Queuing Location Model (SHQLM) proposed by Geroliminis et al. [69] combined the MCLP and the hypercube queuing theory to minimize the mean response time and maximize a minimum predefined level of coverage.

Challenge 6- Deal with varying demands for HC services: The epidemic and seasonal nature of some diseases brings difficulties to predict needs to healthcare services. One solution for the challenge is to study the seasonal trends of diseases. Dynamic models can maximize the coverage objective through the time horizon repeatedly for a time-varying demand to be covered efficiently. For example, a study of the dynamic ambulance positioning strategy for a campus emergency service led to another *P*-median model by Carson and Batta [70]. This is a scenario-based model to represent the demand conditions at different time. In a facility location model for emergency medical services (EMS), Gendreau et al. [71] introduced variables and parameters to reflect the dynamic nature of the model named DDSMt. Rajagopalan et al. [72] presented the Dynamically Available Coverage Location (DACL) model whereas the time horizon is divided into clusters based on a significant change of demands. Gendreau et al. [73] proposed a model named the Maximal Expected Coverage Relocation Problem (MECRP) to maximize the expected demand coverage with the number of relocated facilities not exceeding a predefined value. Others studies attempted to model the trend of varying demand and test the efficiency of proposed scenarios of improvement under demand trends.

Challenge 7-Design a network with various services, various levels and facility types: Communities require various types of healthcare services; therefore, a challenge is locating such versatile healthcare facilities to meet all patients' requirements. Another concern is the location of multiple level treatment facilities (e.g., emergency services, operation, after operation treatments, physiography service). Hierarchical location models deal with the location of facilities within a multi-level structure. For example in HC facility location problems, the structure may include regional clinical centers, general hospitals and specialized hospitals. Hierarchical location models are of growing importance in the design of telecommunications networks [74]. Calvo and Marks [75] proposed a multi-level healthcare facilities model based on *P*-median to locate central hospitals, community hospitals and local reception centers. The objective is to minimize the distance and user costs, and to maximize the demand and utilization. Due to difficulties in modeling such problems, limited research is observed in literature.

Challenge 8-The best order and location of HC facilities for a combination of challenges: Real problems in HC facility locations may be a combination of different challenges, it is necessary to construct a decision-making mechanism to overcome the combined challenges. (Table 3) summarizes efforts done in this area. In order to provide a solution mechanism, metrics and methods for HC facility location problems are addressed in following sections. The methods and models used for locating healthcare facilities are investigated in details.

Mathematical techniques and optimization methods

Optimization techniques are widely used in the search of solutions of HC location problems. Other techniques and methods include multi-criteria decision making methods, simulation, gravity model, and GIS

Models	Authors	Resolved challenges						
		CH1	CH2	CH3	CH4	CH5	CH6	CH7
Hierarchical Objective Set Covering (HOSC)	Daskin and Stern et al. [46]			✓				✓
Dynamic Double Standard Model (DDSMt)	Gendreau et al. [71]			✓			✓	
Maximum Expected Covering Location Problem (MEXCLP)	Daskin et al. [40]			✓		✓		
Maximum Availability Location Problem (MALP I & II)	ReVelle and Hogan et al. [59]			✓		✓		
Adjusted MEXCLP (AMEXCLP)	Batta et al. [67]			✓		✓		
Adjusted MEXCLP	Goldberg et al. [76]			✓		✓		
Modified LSCM (Rel-P)	Ball and Lin et al. [77]		✓			✓		
Time dependent MEXCLP (TIMEXCLP)	Repede and Bernardo et al. [62]			✓		✓		
Queuing Probabilistic Location Set Covering Problem (QPLSCP)	Marianov and ReVelle et al. [64]		✓			✓		
Two-Tiered Model (TTM)	Mandell et al. [78]			✓		✓		
Dynamically Available Coverage Location (DACL)	Rajagopalan et al. [72]			✓			✓	
Backup Double Covering Model (BDCM)	Başar et al. [79]			✓				✓
MCLP in multi-period context	Schilling et al. [80]			✓			✓	
Maximal Covering Location-Allocation Problem (MCLAP)	Marianov and Serra et al. [65]			✓		✓		
Local Reliability based MEXCLP (LR-MEXCLP)	Sorensen and Church et al. [63]			✓		✓		
MEXCLP2	McLay et al. [68]			✓		✓		
Stochastic Hybrid Queuing Location Model (SHQLM)	Geroliminis et al. [69]			✓		✓		
Spatial Queuing Model (SQM)	Geroliminis et al. [81]			✓		✓		
Extended Maximum Availability Location Problem (EMALP)	Galvão et al. [61]			✓		✓		
MCLP with partial coverage (MCLP-P)	Karasakal and Karasakal et al. [47]			✓		✓		
Stochastic Gradual Coverage Model	Drezner et al. [48]			✓		✓		
Cooperative Location Set Covering Problem (CLSCP)	Berman et al. [49]			✓		✓		
Cooperative Maximum Covering Location Problem (CMCLP)	Berman et al. [49]			✓		✓		
chance-constrained P-median	Carbone et al. [82]	✓				✓		
hierarchical P-median	Calvo and Marks et al. [75]	✓						✓
Dynamic P-median model	Carson and Batta et al. [70]	✓					✓	
Stochastic Queue Median (SQM)	Berman et al. [58]	✓				✓		
α reliability P-center problem	Revelle and Hogan et al. [83]				✓	✓		
Stochastic P-center	Hochbaum and Pathria et al. [53]				✓	✓		

Table 3: Extended models to resolve combined challenges in HC facility location (CH: Challenge).

based approaches. This section discusses methods used to analyze problems of the HC facility location, followed by an overview of the optimization technique for HC facility locations.

Sasaki et al. [84] used a genetic algorithm to optimize health planning for ambulances. They applied a prediction method to generate data for analysis. Schuurman et al. [85] developed a location optimization model to identify the suggested points for covering the greatest underserved population. This protocol was developed using Geographic Information Systems (GIS) to measure factors such as populations, distances and accessibility to services. Murphy and Killen [86] presented a model based on the accessibility concept to locate a single facility in Dublin, Ireland. They concluded importance of accessibility as the minimization of travel time.

Various Operations Research techniques are used in the research of HC facility location. Mixed Integer Programming (MIP) is the basis of all models for location selection decisions. Researchers in their studies mostly apply linear models rather than non-linear models. Zhang et al. [87] introduced a non-linear optimization model for a preventive health network. Before this work, Zhang et al. [23] formulated a non-linear programming model for the preventive health facility network design. In their model, the objective function and some of constraints are non-linear. Marianov et al. [88] proposed a competitive facility location problem for solving a set of non-linear equations. Other non-linear models can refer to Hsia et al. [89], Mahar et al. [90], Dokmeci [91], and Cho [92].

Goal programming is a type of multi-objective optimizations to handle multiple, normally conflicting objective measures. A goal is assigned to each objective to minimize unwanted deviations from the set goal. Araz et al. [25] used a Fuzzy Goal Programming (FGP) to model the problem. Their problem includes multiple objectives in an emergency service network design. The multi-objective model for an extension of the emergency vehicle location model was formulated in goal programming by Alsalloum and Rand [93]. Chu and Chu [94] proposed a model for the location of hospitals and allocation of the services with goal programming. In another classification of the models, Hierarchical models, Dynamic models, and Joint models are discussed (Table 4).

There are two types of hierarchy in existing models: multi-services and multi-level networks. For strategic planning of healthcare services, hierarchical models are efficient as a variety of required services to locate. Dynamic models are usually used to solve complex problems by breaking the problem into a sequence of decision steps over the course of time. Some of the dynamic models can be easily formulated and solved using mathematical programming while some of the models need specific formulations and solutions.

Joint models seek more than one decision through modeling and solving process. A common type of joint models is location-allocation

Hierarchical models	
(a). Service variety	Griffin et al. [95], Cho [92], Teixeira and Antunes [96], Mahar et al. [90], Chu and Chu [94], Galvão et al. [74], Mandell [78], Benneyan et al. [97], Knight et al. [98], Cheu et al. [99], Schmid [100], Mestre et al. [101], Côté et al. [105]
(b). Service level	Griffin et al. [95], Teixeira and Antunes [96], Galvão et al. [74], Mitropoulos et al. [117], Şahin et al. [103], Smith et al. [104], Mestre et al. [101], Dokmeci [91], Galvão et al. [102], Marianov and Taborga [106]
Dynamic Models	Ndiaye and Alfares [107], Sasaki et al. [84], Benneyan et al. [97], Schmid [100]
Joint Models	Mahar et al. [90], Chu and Chu [94], Kim and Kim [108], Shariff et al. [109], Doerner et al. [110], Erdemir et al. [111], Branas et al. [112], Stummer et al. [113], Jacobs et al. [114], Shen et al. [115], Or and Pierskalla [116]

Table 4: Type of models proposed for healthcare facility location problems.

Uncertainty Type	Reviewed papers
Capacity	Mahar et al. [90], Rajagopalan and Saydam [118], Shiah and Chen [119]
Demand	Beraldi and Bruni [120], Mitropoulos et al. [117], Beraldi et al. [121], Alsalloum and Rand [93], Schmid [100], Harewood [122], Jia et al. [123], Chu and Chu [94], Zhang et al. [23], Shariff et al. [109], Şahin et al. [103], Mandell [78], Daskin [40], Galvão et al. [102], Côté et al. [105]
Time	Ingolfsson et al. [124], Knight et al. [98], Cheu et al. [99], Sasaki et al. [84], Alsalloum and Rand [93].

Table 5: Type of uncertainty reviewed in healthcare facility location problems.

Measures	Healthcare services		
	Emergency	Health center	Preventive
Coverage	Erkut et al. [134], Araz et al. [25], Yin and Mu [129], Smith et al. [104], Mandell [78], Knight et al. [98], Cheu et al. [99], Shiah and Chen [119], Harewood [122], Jia et al. [123], Erdemir et al. [111]	Cho [92], Murawski and Church [125], Shariff et al. [109], Doerner et al. [110], Stummer et al. [113], Marianov and Taborga [106]	Griffin et al. [95], Gu et al. [24], Verter and Lapierre [133], Zhang et al. [87], Zhang et al. [23]
Cost	Beraldi and Bruni [120], Beraldi et al. [121], Harewood [122], Erdemir et al. [111]	Cho [92], Mahar et al. [90], Malczewski and Ogryczak [130], Syam and Côté [127], Cocking et al. [126], Benneyan et al. [97], Dokmeci [91], Stummer et al. [113], Côté et al. [105]	Ndiaye and Alfares [107]
Distance	Sasaki et al. [84], Hsia et al. [89], Araz et al. [25], Rajagopalan and Saydam [118], Huang et al. [128], Yin and Mu [129]	Bruni and Conforti [132], Mitropoulos et al. [117], Mitropoulos et al. [131], Galvão et al. [102]	Galvão et al. [74], Şahin et al. [103], Jacobs et al. [114]
Efficiency	Hsia et al. [89]	Malczewski and Ogryczak [130], Bruni and Conforti [132], Mitropoulos et al. [117], Mitropoulos et al. [131], Doerner et al. [110], Galvão et al. [102], Stummer et al. [113],	Gu et al. [24]
Time	Schmid [100]	Mestre et al. [101]	
Other metrics	Alsalloum and Rand [93]	Teixeira and Antunes [96], Murphy and Killen [86], Chu and Chu [94], Malczewski and Ogryczak [130], Kim and Kim [108], Mitropoulos et al. [131], Doerner et al. [110], Rahman and Smith [31]	Smith et al. [104]

Table 6: Measures used in reviewed healthcare facility location problems.

models that are widely applied in HC facility location models [94]. Capacity is another parallel decision measure joined with locations [113]. Other decision methods such as location–allocation and routing [116] and location-inventory [115] are shown in (Table 4).

Stochastic optimization models are used when model parameters are uncertain. In this case, the value of parameters is defined through probability distributions by decision makers. Such approaches may include queuing-based, stochastic programs, stochastic processes, etc. Mahar et al. [90] coped with the probabilistic demand and capacity. Schmid [100] suggested a model for the dynamic ambulance relocation with the stochastic demand and time parameters. Rajagopalan and Saydam [118] presented a model to minimize the expected response time in an emergency service network. They used probabilistic coverage constraints and expected distance traveled expressions.

Uncertainty can be investigated in terms of models and data. In case of uncertainty in the models, some parameters or variables are embedded in the models to reflect the uncertainty. When uncertainty is within data, various methods such as prediction methods may be applied to generate data for parameters of the models. In all of these cases, validation is necessary to ensure the accuracy of models for solutions. (Table 5) presents types of uncertainty discussed in the existing research.

Measures and Criteria of the Facility Location for Healthcare Services

Measures and criteria are required for the evaluation of healthcare facility locations based on objectives and constraints.

Objective functions

Various objectives have been applied to address the purpose of HC facilities location optimizations. The HC system performance can be measured by six main categories including coverage, cost, distance, time, efficiency and others (such as accessibility). An overview of the criteria used is illustrated in (Table 6).

Coverage: Coverage objective is the most used measure in HC facility location modeling. Different maximization models of coverage have been addressed. Knight et al. [98] introduced the Maximal Expected Survival Location Model for Heterogeneous Patients (MESLMHP) to maximize the overall expected survival probability of multiple-classes of patients. The objective function presented by Shariff et al. [109] maximized the population assigned to a facility within the specified coverage distance. The model designed by Zhang et al. [87] aimed to improve the accessibility of preventive healthcare facilities for potential clients with the maximal participation. Murawski and Church [125] introduced a model called Maximal Covering Network

Improvement Problem (MC-NIP) to maximize the number of people with the access-coverage. Many other models apply the coverage concept as a criterion [85,99,124].

Cost: Using the minimized cost as the objective, Benneyan et al. [97] measured the total cost of procedure, travel, non-coverage, and start-up for the network capacity with accessible constraints. Mahar et al. [90] suggested a model to minimize expected total cost for the hospital network including the fixed and variable cost in maintaining the capacity across the sites, the penalty cost of not being able to meet the demand at a location in each period, the transportation cost of re-routing patients with flexible and non-flexible demand, and the transportation cost of unmet flexible and non-flexible demand. Cocking et al. [126] applied a model to minimize the total travel cost. The objective function presented by Syam and Côté [127] minimized the sum of fixed, overhead, and labor costs, variable patient treatment costs, travel, lodging, labor costs, and the cost of lost service.

Distance: The minimized distance is used in different methods. Huang et al. [128] proposed a model to minimize the maximum weighted distance between a node and the nearest available facility for emergency evacuation while trying to locate p facilities. Rajagopalan and Saydam [118] introduced a model to minimize expected sum of distances traveled to cover the demand in each node for a given fleet size and set of server locations. The hierarchical model for designing a network of blood services presented by Şahin et al. [103] minimized the total referral demand-weighted distances from blood centers to regional blood centers, and the total demand-weighted distances from demand points to blood centers. Other contributions in distance objective functions can refer to Galvão et al. [74] and Jacobs et al. [114].

Time: Time measures include traveling time, waiting time, etc. A model was proposed by Schmid [100] for dynamic ambulance relocation and dispatching problems to minimize the expected sum of response time over the given planning horizon. Mestre et al. [101] applied a geographical access objective function interpreted as the minimization of total travelling time.

Other metrics: There are other measures for the healthcare facility location. Kim and Kim [108] suggested a model to minimize the maximum load of established facilities for load balancing. Smith et al. [104] presented a model for the location of the maximal number

of sustainable facilities. Teixeira and Antunes [96] introduced an extension of the *P*-median model to maximize the accessibility of users to facilities. Murphy and Killen [86] presented a model to maximize accessibility where accessibility interpreted as minimization of travel time. Other measures include work by Alsalloum and Rand [93], Chu and Chu [94], and Rahman and Smith [31] (Table 6).

Multiple objectives: Multi-objective models are used to optimize different measures in HC facility locations. Efficiency, coverage and distance are the most common measures. Mitropoulos et al. [131] proposed a method to consider efficiency of the healthcare service provider based on three objectives: minimization of total distance travelled by patients, minimization of under achievement in the constraint that concerns the number of patients served, and maximization of the mean efficiency of healthcare centers. Yin and Mu [129] presented a model to maximize the covered allocated demand while simultaneously minimizing the total distance between the uncovered allocated demand and the sites assigned. Hsia et al. [89] applied a bi-criteria model, first to minimize the maximum weighted sum of distances, and then to maximize the preference function of facility sites. Araz et al. [25] introduced a multi-objective model for maximization of the population covered by one vehicle, maximization of the population with backup coverage and minimizing the total travel distance from locations at a distance bigger than a pre-specified distance standard for all zones to increase the service level. Doerner et al. [110] suggested a multi-criteria tour planning for mobile healthcare facilities. Tours were measured based on three criteria; economic efficiency criterion related to the tour length, the average distances to the nearest tour stop, and the percentage of the population that are unable to reach a tour stop within a predefined maximum distance. Bruni and Conforti [132] suggested a model for the organ transplantation to minimize the total distance between explanation-performing centers and transplant centers, to minimize the total distance traveled by patients to the transplant center, and to minimize the maximum size of waiting list of the patients. Mitropoulos et al. [117] presented a bi-objective model to minimize the distance between patients and facilities with equitable distributions of facilities among citizens. Cho [92] presented an equity-efficiency trade-off model with the objective of systems equity measured by the opportunity to receive medical services, and the objective of efficiency represented by consumer and producer welfare. Malczewski and Ogryczak [130] presented an interactive

Constraints	Healthcare services		
	Emergency	**Health center**	**Preventive**
Demand	Araz et al. [25], Rajagopalan and Saydam [118], Alsalloum and Rand [93], Yin and Mu [129], Cheu et al. [99], Schmid [100], Erdemir et al. [111]	Cho [92], Teixeira and Antunes [96], Mahar et al. [90], Murphy and Killen [86], Chu and Chu [94], Malczewski and Ogryczak [130], Kim and Kim [108], Syam and Côté [127], Mitropoulos et al. [117], Mitropoulos et al. [131], Cocking et al. [126], Doerner et al. [110], Benneyan et al. [97], Mestre et al. [101], Marianov and Taborga [106]	Zhang et al. [87], Gu et al. [24], Ndiaye and Alfares [107], Griffin et al. [95], Verter and Lapierre [133]
Efficiency	Rajagopalan and Saydam [118], Beraldi and Bruni [120], Beraldi et al. [121], Alsalloum and Rand [93], Mandell [78], Cheu et al. [99], Schmid [100], Harewood [122], Jia et al. [123], Erdemir et al. [111]	Cho [92], Mahar et al. [90], Kim and Kim [108], Syam and Côté [127], Mestre et al. [101], Galvão et al. [102], Stummer et al. [113], Marianov and Taborga [106], Côté et al. [105]	Zhang et al. [87], Zhang et al. [23], Smith et al. [104], Ndiaye and Alfares [107], Verter and Lapierre [133], Galvão et al. [74], Jacobs et al. [114],
Capacity	Araz et al. [25], Yin and Mu [129] , Cheu et al. [99], Shiah and Chen [119],	Teixeira and Antunes [96], Mahar et al. [90], Chu and Chu [94], Malczewski and Ogryczak [130], Syam and Côté [127], Mitropoulos et al. [117], Mitropoulos et al. [131], Shariff et al. [109], Benneyan et al. [97], Mestre et al. [101], Dokmeci [91], Galvão et al. [102], Stummer et al. [113], Côté et al. [105]	Zhang et al. [23], Jacobs et al. [114]
Distance	Hsia et al. [89], Beraldi and Bruni [120], Huang et al. [128]	Teixeira and Antunes [96], Chu and Chu [94], Kim and Kim [108], Syam and Côté [127], Mitropoulos et al. [131], Murawski and Church [125], Doerner et al. [110], Mestre et al. [101]	Griffin et al. [95], Verter and Lapierre [133], Galvão et al. [74]
Cost	Ingolfsson et al. [124], Erdemir et al. [111]	Cocking et al. [126], Murawski and Church [125], Mestre et al. [101], Galvão et al. [102]	Griffin et al. [95], Galvão et al. [74]

Table 7: Type of Constraints used in reviewed healthcare facility location problems.

multi-objective optimization approach to the central facility location problem. Their model minimized the aggregate travel cost for the population and maximized the level of users' satisfaction for a location pattern of hospitals.

Constraints

Another important factor in HC facility location problems is the constraint to achieve the objective. Constraints are normally resource limitations. In Table 7, constraints are sorted based on the type of health facilities. Constraints for demand, efficiency, capacity, distance, and cost are commonly used in the problems (Table 7).

Solution methods: Since the late 1970s it has been known that most complex location models are NP-hard [50]. The search for a solution may consume a large amount of computational resources. Solution methods are divided into three main classes: Exact, Heuristic, and Meta-heuristic methods. Exact methods can guarantee the optimized solution. According to the techniques used in these methods, they are efficient for small-size problems, normally in linear environments. If the size or any other feature of the problem leads to more complexity, exact methods would lose efficiency and other methods should be applied. Most of the models using in existing research were solved by the exact methods such as branch-and-bound. Some of the software packages in mathematical programming such as CPLEX, LINDO, and GAMS are widely used to solve the models. Solution methods used in the existing research are listed in Table 8.

One of the applications of heuristic methods is for the case with the time-consuming solution search process. Other applications are for complex models when the exact methods do not guarantee a global optimum solution. To accelerate the solving process, Gu et al. [24] implemented the Interchange algorithm by building two data structures. Galvão et al. [102] solved their model using a Lagrangean heuristic. The solution method used by Cho [92] combined the Monte Carlo integer programming technique with the augmented Lagrangean algorithm. Other applications of heuristic methods are addressed in Table 8.

Application of meta-heuristic methods to solve optimization problems is increasing. Although these methods do not guarantee the optimum solution, their efficiency is trusted when the models are complex. Especially in non-linear environments when a global optimum solution is hard to find among local optimums, meta-heuristic methods are widely used to present optimum or near optimum solutions. Tabu search (TS) is one of the most applied meta-heuristic methods in HC facility location models [87,113,118]. Other methods used to solve the problems include Genetic Algorithm (GA) [109], Simulated Annealing (SA) [127], and Pareto Ant Colony Optimization (P-ACO) [110]. Rajagopalan et al. [135] developed several heuristic algorithms, including GA, TS, SA and hybridized hill climbing, to optimize the MEXCLP. Other solutions presented for the general purpose of facility location models such as covering models can refer work done by Li et al. [16].

Applicability of the research: Most of the existing research used a testing step to show the application after the model presentation. Data are required to verify the location solution. As shown in Table 9, most of the research test their models based on the case study while some were measured by assumed data (Table 9).

Exact methods	Griffin et al. [95], Verter and Lapierre [133], Ndiaye and Alfares [107], Teixeira and Antunes [96], Murphy and Killen [86], Chu and Chu [94], Erkut et al. [134], Malczewski and Ogryczak [130], Araz et al. [25], Bruni and Conforti [132], Beraldi and Bruni [120], Mitropoulos et al. [117], Mitropoulos et al. [131], Beraldi et al. [121], Alsalloum and Rand [93], Huang et al. [128], Cocking et al. [126], Murawski and Church [125], Shariff et al. [109], Şahin et al. [103], Yin and Mu [129], Ingolfsson et al. [124], Smith et al. [104], Benneyan et al. [97], Rahman and Smith [31], Knight et al. [98], Cheu et al. [99], Shiah and Chen [119], Schmid [100], Mestre et al. [101], Harewood [122], Jia et al. [123], Erdemir et al. [111], Galvão et al. [102], Côté et al. [105], Mandell [78], Jacobs et al. [114]
Heuristic methods	Erdemir et al. [111], Gu et al. [24] , Kim and Kim [108], Hsia et al. [89], Beraldi and Bruni [120], Zhang et al. [23], Galvão et al. [102], Galvão et al. [74], Marianov and Taborga [106], Cho [92], Dokmeci [91]
Meta-heuristic methods	Shariff et al. [109], Sasaki et al. [84], Zhang et al. [87], Syam and Côté [127], Rajagopalan and Saydam [118], Zhang et al. [23], Doerner et al. [110], Stummer et al. [113]

Table 8: Solution methods for reviewed healthcare facility location problems.

Case study	Griffin et al. [95], Gu et al. [24], Verter and Lapierre [133], Ndiaye and Alfares [107], Cho [92], Teixeira and Antunes [96], Schuurman et al. [85], Mahar et al. [90], Murphy and Killen [86], Chu and Chu [94], Malczewski and Ogryczak [130], Zhang et al. [87], Kim and Kim [108], Galvão et al. [74], Syam and Côté [127], Rajagopalan and Saydam [118], Bruni and Conforti [132], Mitropoulos et al. [117], Mitropoulos et al. [131], Alsalloum and Rand [93], Cocking et al. [126], Murawski and Church [125], Zhang et al. [23], Shariff et al. [109], Şahin et al.(2007), Yin and Mu [129], Doerner et al. [110], Ingolfsson et al. [124], Mandell [78], Smith et al. [104], Benneyan et al. [97], Rahman and Smith [31], Cheu et al. [99], Shiah and Chen [119], Schmid [100], Mestre et al. [101], Harewood [122], Jia et al. [123], Erdemir et al. [111], Dokmeci [91], Galvão et al. [102], Stummer et al. [113], Marianov and Taborga [106], Côté et al. [105], Jacobs et al. [114]
Assumed data	Sasaki et al. [84], Hsia et al. [89], Erkut et al. [134], Araz et al. [25], Beraldi and Bruni [120], Beraldi et al. [121], Huang et al. [128], Erdemir et al. [111], Galvão et al.(2006)

Table 9: Applications of existing models for healthcare facility location problems.

Type of application	Healthcare services		
	Emergency	**Health Center**	**Preventive**
Location	Rajagopalan and Saydam [118], Alsalloum and Rand [93], Ingolfsson et al. [124], Mandell [78], Schmid [100], Harewood [122], Jia et al. [123], Erdemir et al. [111]	Araz et al. [25], Mitropoulos et al. [117], Mitropoulos et al. [131], Doerner et al. [110], Marianov and Taborga [106]	Gu et al. [24], Verter and Lapierre [133], Galvão et al. [74], Jacobs et al. [114]
Location-Allocation	Knight et al. [98], Cheu et al. [99]	Cho [92], Mahar et al. [90], Malczewski and Ogryczak [130], Syam and Côté [127], Bruni and Conforti [132], Benneyan et al. [97], Côté et al. [105]	Griffin et al. [95], Ndiaye and Alfares [107], Zhang et al. [23], Şahin et al. [103], Smith et al. [104]
Capacity	Yin and Mu [129], Shiah and Chen [119]	Chu and Chu [94], Galvão et al. [102], Stummer et al. [113]	Zhang et al. [87]

Table 10: Type of applied location decisions in reviewed healthcare location problems.

Applications listed in Table 10 are segmented into location, location-allocation, and capacity models to have details on related research. Considerable numbers of the studies have been applied in the USA and Canada (Table 10).

To review recent cases in emergency facility locations, Yin and Mu [129] used a modular capacitated maximal covering location model to optimize site ambulances for Emergency Medical Services (EMS) in Georgia, USA. Knight et al. [98] solved their maximal expected survival location model for allocation of ambulances in Wales, UK. Erdemir et al. [111] suggested joint ground and air emergency medical services coverage models based on the crash data from New Mexico, USA.

In a hierarchical and multiservice model for the health center type of facilities, Mestre et al. [101] illustrated an application to the south region of the Portuguese to define location, supply, and referrals in planned hospital systems. Mitropoulos et al. [131] implemented their model for location and relocation of a healthcare centre in Greece. This model combined data envelopment analysis (DEA) with a location analysis for the effective consolidation of services. Benneyan et al. [97] applied models in a special care for the single and multi-period location-allocation.

Gu et al. [24] developed an application of the facility location model for the Alberta breast cancer screening program in Canada to increase the accessibility of breast cancer screening services. Zhang et al. [87] applied their bi-level congestion-based model in a network of mammography centers in Montreal, Canada. Şahin et al. [103] used real data to organize Turkish Red Crescent blood services with hierarchical location-allocation model.

Conclusions and Further Work

The existing research on healthcare facility location problems is reviewed in this paper. The methods and applications are summarized for the healthcare facility location to provide a general guide for researchers. During the review, it is noticed that many existing location models were developed to cover the need of special cases, such as the capability of covering models for the need of emergency facility locations. Another found is that cost and efficiency are two important criteria for healthcare services to minimize total traveling distance between patients and the healthcare facility. In healthcare planning such as the location of specialized services accompanied with a budget limitation, *P*-median models are common applied with expected results. In order to establish or improve a network of preventive healthcare services, coverage and distance are essential measures for the optimal solution. Many case studies show different applications. Specifications of the each case have to be identified to decide the best fit model. Different performance metrics may be used for the model evaluation as reviewed in this paper.

Uncertainty is recognized as an inevitable part of healthcare location problems. Many methods considered uncertainties in data and models. Combination of techniques such as DEA in facility location models can improve modeling for more acceptable solutions. Considering the level of complexity and trend of needs for the healthcare facility, more research is required on the operation efficiency, patient safety and cost-effective solutions for the better resource utilization in the human-centered healthcare environment.

Reliability studies for HC facility locations should also be developed to trace out-of-service situations. The optimization of both service reliability and resource utilization is expected. Sustainability should be considered in the location modeling. Sustainable healthcare facilities are essential for the long-term facility location planning to minimize negative impacts for the future. It is necessary to extend dynamic models to meet the trend of parameter changes over the time for decision-making. Some techniques and package tools such as GIS can be embedded in facility location modeling for more accurate solutions.

There is a lack of comprehensive models in literature for decision-making of multiple healthcare services. For the comprehensive healthcare services, it is recommended to develop models for integrated locating (or re-locating) problems of healthcare facilities and services. Another recommendation is to integrate fixed and mobile healthcare facilities to empower the healthcare network for the safe and fast response to patients' requests. An example is to search the optimal location of ambulances, helicopters, and hospitals for emergency requests.

One of the suggested research areas is the integration of facility location decision-making with other tactical/operation considerations to provide a comprehensive solution for the healthcare facility location problems. These considerations include but not limit to the resource management, facility recycling, service upgrading for emergency or disasters, etc.

It is expected that this paper will provide a guideline for the improvement of healthcare facility locations and the patient accessibility to the healthcare facilities.

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