Review Article

Multiple criteria facility location problems: A survey

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ABSTRACT

This paper provides a review on recent efforts and development in multi-criteria location problems in three categories including bi-objective, multi-objective and multi-attribute problems and their solution methods. Also, it provides an overview on various criteria used. While there are a few chapters or sections in different location books related to this topic, we have not seen any comprehensive review papers or book chapter that can cover it. We believe this paper can be used as a complementary and updated version.

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Contents

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1. Introduction

Decision making is one of the main abilities of human being that differs them from other creatures. Now, decision making and analysis is an important part of management sciences, and it is perhaps as old as history of mankind. In many real-world problems, the decision maker likes to pursue more than one target or consider more than one factor or measure. Such a desire transforms the decision making problem to a multi-objective decision making (MODM) problem or a multi-attribute decision making (MADM) problem. These groups of problems all come together in one category, named multi-criteria decision making (MCDM) problems.

There are many decision making problems whose information is spatial (geographical). These kinds of decisions are called location decisions. Location decisions are now a major part of operations research and management science (named location science). Facility location, location science and location models are terms that can be used instead. Facility location is a branch of operations research related to locating or positioning at least a new facility among several existing facilities in order to optimize (minimize or maximize) at least one objective function (like cost, profit, revenue, travel distance, service, waiting time, coverage and market shares).

From an application point of view there is no limitation for location science. Many application areas including public facilities, private facilities, military environment, business areas and national and international scopes can be seen in the related literature.

1.1. Location history

Now facility location can be considered a one-hundred year old science. Even though it is old, we believe that applications of these models are getting more attractive. Some experts believe that facility location as a classic science, has originated from Pierre de Fermat, Evagelistica Torricelli (a student of Galileo), and Battista Cavallieri. It is said that these people independently proposed the basic Euclidean spatial median problem early in the seventeenth century [1]; but formally it is accepted by all scientists that Alfred Weber's book [2] is the most important starting point in the history of location science. However, during the last 35 years, several comprehensive books in this area have been written. Interested readers can refer to these books to find out more about usual facility location models: Handler and Mirchandani [3], Love et al. [4], Mirchandani and Francis [5], Francis et al. [6], Daskin [7], Drezner [8], Drezner [9], Drezner and Hamacher [10], Nickel and Puerto [11], Church and Murray [12] and, Farahani and Hekmatfar [13].

1.2. MCDM

Although location science has a long history in single criterion location problems, it seems that since the introduction of multi-criteria decision making to management sciences, this concept has been implemented in location problems.

Since this paper is focusing on multi-criteria location models we also present a very short description of MCDM concepts. We consider the MCDM techniques as a combination of the MADM and the MODM techniques.

In the MADM there is usually a limited number of predetermined alternatives. These alternatives satisfy each objective in a specified level and the decision maker (DM) selects the best solution (or solutions) among all alternatives, according to the priority of each objective and the interaction between them. There are many techniques which are used to tackle the MADM problems. The most popular ones are as follows: dominant, maximin, maximax, conjunctive method, disjunctive method, lexicographic method, elimination by aspects, permutation method, linear assignment method, simple additive weighting (SAW), hierarchical additive weighting, elimination and choice expressing reality (ELECTRE), technique for order preference by similarity to ideal solution) (TOPSIS), hierarchical tradeoffs, linear programming techniques for multidimensional analysis of preference (LINMAP), interactive SAW method and MDS with the ideal point [14].

The MODM techniques are trying to design the best alternative by considering the various interactions within the design constraints which best satisfy the DM by way of attaining some acceptable levels of a set of objectives. The MODM problems have various components, but the common characteristics of them are as follows:

- A set of quantifiable objectives.
- A set of well defined constraints.
- A process of obtaining some trade-off information.

There are many techniques which are used to tackle the MODM problems. The most popular ones are as follows: global criterion method, utility function, metric L-P methods, bounded objective method, lexicographic method, goal programming

(GP), goal attainment method, method of Geoffrion, interactive GP, surrogate worth trade-off, method of satisfactory goals, method of Zionts–Wallenius, the methods as step method (STEM) and related method, sequential multi-objective problem solving (SEMOPS) and sequential information generator for multi-objective problems (SIGMOP) method, method of displaced ideal, goal programming STEM (GPSTEM), method of Steuer, parametric method, C-constraint method and adaptive search method [15–19].

However, in solving the MODM problems, without considering the used technique, investigating the following general steps are needed:

- *Conflicting objectives:* It is in the nature of the MODM problems to have conflicting objectives.
- *Efficient solution:* An ideal solution to a MODM problem is one that results in the optimum value of each of the objective functions simultaneously. An efficient solution (also known as non-inferior solution or non-dominated solution) is one, in which no one objective function can be improved without a simultaneous detriment to the other objectives [19].
- *A preferred solution:* A preferred solution (also known as the best solution) is an efficient solution, which is chosen by the decision maker (DM) as the final decision. We have used some of simple MODM methods and some sensibility analysis to choose a preferred solution.

There are different approaches to solve multi-objective optimization problems. These approaches can be divided into three categories:

- "Classical approaches" try to convert the multi-objective problem into a single objective problem and optimize new single objective problem.
- In "Pareto optimal approaches" a set of solutions will be resulted when the problem is solved.
- If the problem in the first and the second category are complex then those can be solved using evolutionary algorithms. Some of these approaches are multi-objective genetic algorithm (MOGA) [20], (non-dominate sorting genetic algorithm) (NSGA I[1]) [21] and fast non-dominate sorting genetic algorithm (NSGA II[2]) [22]. There are other special purpose approaches for solving complex MODM problems like: vector evaluated genetic algorithm (VEGA) [23], lexicographic ordering, weight min-max method and distance method. During the last decade, *multi-objective combinatorial optimization* (MOCO) (e.g. [24,19] provides an adequate framework to tackle various multi-criteria problems.

Interested readers are referred to Cohon [25], Szidarovszky et al. [18] and Hwang and Masud [17] to learn more about pure MODM and referred to Hwang and Yoon [14] to gain knowledge about pure MADM.

1.3. Location objectives

Apart from being single criterion or multi-criteria, maybe readers are interested to know about various objective functions in facility location problems. Eiselt and Laporte [26] is one of the best references in classifications of objectives in location models. On the other hand, the objectives that are usually considered in location problems can be different. Some of them can be as follows:

- Minimizing the total setup cost.
- Minimizing the longest distance from the existing facilities.
- Minimizing fixed cost.
- Minimizing total annual operating cost.
- Maximizing service.
- Minimizing average time/ distance traveled.
- Minimizing maximum time/ distance traveled.
- Minimizing the number of located facilities.
- Maximizing responsiveness.

Recently, environmental and social objectives based on energy cost, land use and construction cost, congestion, noise, quality of life, pollution, fossil fuel crisis and tourism are becoming customary. Consequently, one of the most important difficulties to tackle these problems is to find a way to measure these criteria.

1.4. Importance of multi-criteria location problems

The amount of papers on multi-criteria location problems were few for many years, but in the past decade, presenting and solving multi-criteria location problems have had a substantial growth, and have opened new windows to location science in

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[1] Non-dominate sorting genetic algorithm.
[2] Fast Non-dominate sorting genetic algorithm.

different businesses. In this paper, we review some of the recent efforts and developments of multi-criteria location problems.

However, since this paper is concentrating in a tighter scope of facility location (multi-criteria), we are interested to see whether this trend is still valid in this scope. In order to see this trend over recent years we used SCOPUS as the largest abstract and citation database on 28 July 2009. We used these keyword combinations: ("Facility Location" OR "Location Science" OR "Location Model" OR "Location Theory" OR "Location Problem" OR Siting OR Locating) AND (Multi OR Multiple OR Bi) AND (Criteria OR Criterion OR Objective OR Attribute). The results can be seen in Table 1.

In Table 1, we can see that:

- About 730 source titles were discovered.
- We can see the growing trend of this topic during recent years (available in a report 31.08.2009).
- About 89.04% of the sources are journal articles and conference papers. It means this topic is mostly of interest to researchers.
- The following journals have been the best sources in this area, respectively:
  ○ European Journal of Operational Research (48).
  ○ Computers and Operations Research (13).
  ○ Annals of Operations Research (12).
  ○ Computers and Industrial Engineering (11).
  ○ Journal of Environmental Management (9).
  ○ Journal of the Operational Research Society (8).

- With respect to the field "Subject Area" it became clear that this topic is of the interest in areas of Engineering, Decision Sciences, Computer Science, Mathematics, Social Sciences and Environmental Science, respectively. With the support of this section we have formed a part of future research in the last section of this paper.
- It seems that in this area, it started to attract most attention after 1990. Although we have found few sources that are not up to date. It was discovered that even some book chapters were found outdated:
  ○ Chapter 10 of Cohon [25] entitled "Multi-objective analysis of facility location problem". Cohon [25] presented two real-world applications of multi-objective facility location problems. One of them is related to a fire station location problem in Baltimore, Maryland. This problem includes six objective functions: maximizing property value covered by new fire stations, maximizing population coverage, maximizing the area coverage, maximizing expected fires coverage, maximizing property hazard coverage and maximizing population hazard coverage. Another application that was considered by Cohon [25] was on power plant siting and is of hypothetical nature. This model objective functions are minimizing facility cost, minimizing water transfer, maximizing equity of plant distribution and minimizing population safety impact.
  ○ Chapter 4 of Handler and Mirchandani [3] entitled "Multi-objective and other location problems on a network".
  ○ A sub-section of Chapter 8 of Daskin [7] entitled "Multi-objective problems". Daskin [7] considers multi-objective location problems as one of the extensions of location models. He gives two examples in location models, including locating landfills for non-hazardous materials and locating warehouses. In the first example he considers two objective functions: (a) maximizing location distance from population centers and (b) minimizing vehicle travel distances to waste transport. In the second example he wanted to find a location for a warehouse with respect to two objective functions: (a) minimizing total travel distance to demand points or customers and (b) maximizing the number of customers who receive services. Daskin [7] has allocated the rest of this section to explain about basic concepts for general bi-objective problems.
  ○ A very brief sub-section of Chapter 3 of Drezner and Hamacher [10] entitled "multi-objective models" which is written by Current et al. [27].
  ○ Larichev and Olson [28] in their book, focus on different applications of multi-criteria decision making in strategic siting like solid waste systems and pipeline location decisions.
  ○ Hekmatfar and SteadieSeifi [29] in a fairly comprehensive book chapter. tried to point out this topic from modeling, solution techniques and application point of view. They are adopting the core of their work from Eiselt and Laporte (1995).

- Take note that we are in the middle of 2009, it can be seen that the trend during recent years is increasing.

This paper is organized as follows: in the next section, we introduce the classification used in this review. We take a look at various bi-objective modeling approaches in Section 3, while in Section 4 we describe the problem with more than two objectives. In addition, as multi-attribute location problems are a concern of this paper as well, the Section 5 provides a survey on these location problems. Section 6 belongs to the solution methods proposed in the reviewed problems. Criteria are the most crucial properties of location problems, therefore we provide a review on different kinds of criteria used in the reviewed literature in Section 7. Future directions will be presented in Section 8 and the paper then ends with some concluding remarks in Section 8.

Table 1
A statistical report from SCOPUS related to multi-criteria location problems.

Source title	Author name	Year	Document type	Subject area
European Journal of Operational Research (48)	Drezner, Z. (10)	2009 (53)	Article (482)	Engineering (295)
Computers and Operations Research (13)	Ogryczak, W. (9)	2008 (115)		Decision Sciences (153)
Annals of Operations Research (12)	Chang, N.B. (6)	2007 (76)		
Computers and Industrial Engineering (11)	Berman, O. (6)	2006 (66)	Conference Paper (168)	Computer Science (140)
Journal of Environmental Management (9)	ReVelle, C. (7)	2005 (51)		
Journal of the Operational Research Society (8)	Bogdan, M. (5)	2004 (37)		Mathematics (133)
Waste Management (8)	Drezner, T. (5)	2003 (17)		Social Sciences (130)
IEEE Conference on Intelligent Transportation Systems Proceedings ITSC (8)	Farmani, R. (4) Walters, G.A. (4)	2002 (29) 2001 (21)	Review (18)	Environmental Science (106)
Xitong Gongcheng Lilun Yu Shijian System Engineering Theory and Practice (7)	Aryanezhad, M.B. (3) Shahanaghi, K. (3)	2000 (15) 1999 (29)	Article in Press (7)	Earth and Planetary Sciences (62)
Proceedings of SPIE the International Society for Optical Engineering (6)	Storbeck, J.E. (3) Blatt, D. (3)	1998 (20) 1997 (29)		Medicine (55)
Location Science (6)	Daskin, M.S. (3)	1996 (12)		Business, Management and Accounting (42)
Lecture Notes in Computer Science Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics (6)	Studzinski, K. (3) He, B. (3) Kaboli, A. (3)	1995 (20) 1994 (22) 1993 (9)	Book (4)	Energy (26)
IIE Transactions Institute of Industrial Engineers (6)	Futschik, A. (3)	1992 (8)	Conference Review (3)	Agricultural and Biological Sciences (24)
Waste Management and Research (5)	Erkut, E. (3)	1991 (6)		
Proceedings IEEE International Conference on Robotics and Automation (5)	Savic, D.A. (3) Hero, A.O. (3)	1990 (12) 1989 (5)		
Transportation Research Record (5)	Malczewski, J. (3)	1988 (5)	Dissertation (2)	Biochemistry, Genetics and Molecular Biology (24)
8th Annual Water Distribution Systems Analysis Symposium 2006 (4)	Wesolowsky, G.O. (3) Smith, A.E. (3)	1987 (9) 1986 (3)		
IIE Annual Conference and Exhibition 2004 (4)	Love, R.F. (3)	1985 (8)		
Socio Economic Planning Sciences (4)	Zorychta, K. (3)	1984 (3)	Report (1)	Chemical Engineering (22)
Land Use Policy (4)	Brimberg, J. (3)	1983 (9)		Physics and Astronomy (22)
Environmental Monitoring and Assessment (4)	Tiwari, R.N. (3)	1982 (4)		
Computer Communications (4)	Sarker, B.R. (3)	1981 (6)	Short Survey (1)	Materials Science (17)
Omega (3)	Melachrinoudis, E. (3)	1980 (8)		
Fuzzy Sets and Systems (3)	Whitaker, R.M. (3)	1979 (3)		Economics, Econometrics and Finance (9)
Journal of the Operations Research Society of Japan (3)	Dozier, G. (3) Yapicioglu, H. (3)	1978 (6) 1977 (1)	Undefined (44)	
Computational Optimization and Applications (3)	Baierl, A. (3)	1976 (3)		Psychology (7)
Proceedings of the World Congress on Intelligent Control and Automation WCICA (3)	Zografos, K.G. (3) Raufer, R.K. (2)	1975 (3) 1974 (4)		Health Professions (6)
Proceedings IEEE INFOCOM (3)	Rao, J.R. (2)	1973 (2)		Chemistry (5)
Smart Materials and Structures (3)	Haynes, K.E. (2)	1965 (1)		Immunology and Microbiology (4)
Expert Systems with Applications (3)	Suh, K. (2)			
Progress in Biomedical Optics and Imaging Proceedings of SPIE (3)	Downs, P.W. (2) Raisanen, L. (2)			Arts and Humanities (4)
Genetics (3)	Williams, J.C. (2)			Multidisciplinary (3)
IEEE Vehicular Technology Conference (3)	Halvadakis, C.P. (2)			Nursing (3)
World Water Congress 2005 Impacts of Global Climate Change Proceedings of the 2005 World Water and Environmental Resources Congress (3)	Yang, X. (2) Snyder, L.V. (2) Benjamin, C.O. (2)			Neuroscience (2) Undefined (5)
Proceedings of the IEEE International Conference on Systems Man and Cybernetics (3)	Riordan, C.A. (2) Kurose, J. (2)			
Industrial and Engineering Chemistry Research (3)	Evans, G.W. (2)			
Water Science and Technology (3)	Espuna, A. (2)			

Table 1 (continued)

Source title	Author name	Year	Document type	Subject area
Engineering Optimization (2)	Yang, C. (2)			
International Journal of Industrial Engineering Theory Applications and Practice (2)	Revelle, C.S. (2) Ren, M.M. (2)			
Electric Power Systems Research (2)	Spea, S.R. (2) Bhattacharya, U. (2) Bhushan, M. (2) Xu, L. (2) Min, H. (2) Biecek, P. (2) Spengler, T. (2) Kotecha, P.R. (2) Ray, A.K. (2) Korman, T.M. (2)			

2. Our classification

There are different categorizations for these problems, but here, based on the background of their decision making approach, we divided them into 'multi-objective' and 'multi-attribute' location problem. Furthermore, as the 'bi-objective' location problems have become of particular consideration, we investigated them separately from other k-objective one ($k \geqslant 3$). Fig. 1 has illustrated our classification of multi-criteria location problems.

Based on such categorization, Table 2 gives an overview of what we are looking at in this paper.

However, MCDM techniques, whenever applicable, can be used. In other words, MCDM techniques can be used for all types of facility location models including single facility location, multiple facility location, location–allocation, quadratic assignment problems, covering problems, median problems, center problems, hierarchical facility location problem, hub location problems, competitive facility location, warehouse location problems, dynamic facility location problems, location-routing, location-inventory, location-reliability and especially location in supply chain.

3. Bi-objective location problems

In this section, we reviewed recent literature on bi-objective location problems. As seen, these problems are an extension of classic location problems. These problems are bi-objective median, knapsack, quadratic, covering, unconstrained, location–allocation, hub, hierarchical, competitive, network, undesirable and semi-desirable location problems which will be investigated here.

As for the most well known basic ones, Ohsawa [30] has focused on a single facility, quadratic Euclidean distance bi-criteria model defined in the continuous space, with convex combination of the minisum and minimax objectives (efficiency and equity). Nickel [31] has extended the classic 2-facility Weber problems to bi-objective ones with regional restrictions. Bhattacharya et al. [32] developed a fuzzy goal programming for their convex multi-facility location problem with minisum (transportation cost) and minimax (distance) objectives with rectilinear distances. Klamroth and Wiecek [33] have developed the median location problem with a line barrier (like rivers, highways, borders, mountain ranges, etc.) which is non-convex and can have different measures of distance in its minisum objectives. Skriver et al. [34] has also introduced a generalization of the bi-criteria convex median problem with minisum objectives and criteria dependent edge lengths. Ohsawa et al. [35] too, has developed ordered median problem of two desirable and undesirable facilities (minisum and maxisum objectives) in continuous spaces with Euclidean distances.
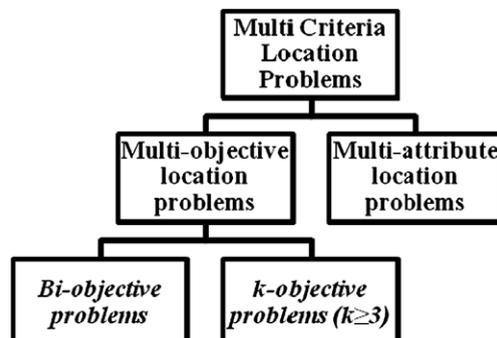

Fig. 1. The classification of multi-criteria location problems.

Table 2
Literature classification.

Category	References	
Bi-objective	Bhaskaran and Turnquist [45]	Klimberg and Ratick [44]
	Bhattacharya et al. [32]	Kozanidis [36]
	Brimberg and Juel [52]	Medaglia et al. [62]
	Blanquero and Carrizosa [46]	Melachrinoudis [53]
	Carrano et al. [63]	Melachrinoudis and Xanthopulos [58]
	Costa et al. [43]	Myung et al. [40]
	Current et al. [51]	Nickel [31]
	Du and Evans [49]	Ohsawa [30]
	Fernández et al. [47]	Ohsawa et al. [38]
	Fonseca et al. [50]	Ohsawa et al. [35]
	Galvão et al. [42]	Plastria and Carrizosa [54]
	George and ReVelle [48]	Rakas et al. [59]
	Hamacher et al. [56]	Skriver et al. [34]
	Harewood [37]	Skriver and Andersen [57]
	Johnson [39]	Villegas et al. [41]
	Karasakal and Nadirler [61]	Yapicioglu et al. [60]
	Karkazis [134]	Zhang and Melachrinoudis [55]
	Klamroth and Wiecek [33]	
k-objective	Alumur and Kara [89]	Klose and Drexl [142]
	Araz et al. [73]	Leung et al. [85]
	Badri et al. [72]	Lin and Kwok [86]
	Bhattacharya et al. [68]	Malczewski and Ogryczak [133]
	Buhl [65]	Maniezzo et al. [104]
	Cantarella and Vitetta [96]	Melachrinoudis and Min [91]
	Chan et al. [76]	Melachrinoudis et al. [79]
	Cho [81]	Nema and Gupta [105]
	Colebrook and Sicilia [100]	Nickel et al. [69]
	Current et al. [64]	Nijkamp and Spronk [66]
	Dias et al. [92]	Ogryczak [70]
	Doerner et al. [88]	Ogryczak [71]
	Doerner et al. [74]	Ogryczak et al. [131]
	Drezner et al. [106]	Ogryczak et al. [132]
	Erkut et al. [83]	Pati et al. [99]
	Farhan and Murray [75]	Puerto and Fernández [67]
	Fernández and Puerto [80]	Puerto and Rodríguez-Chía [77]
	Giannikos [103]	Raisanen and Whitaker [94]
	Hong et al. [95]	Selim and Ozkarahan [101]
	Kerbache and Smith [84]	Stummer et al. [93]
	Klimberg and Bennekom [82]	Uno and Katagiri [98]
	Leung [97]	Villegas et al. [41]
		Xu et al. [102]
		Yang et al. [78]
		Zhang and Armstrong [90]
Multi-attribute	Aras et al. [109]	Kahraman et al. [118]
	Badri [113]	Kinra and Kotzab [111]
	Canbolat et al. [122]	Lahdelma et al. [127]
	Cáceres et al. [128]	Norese [121]
	Chan and Chung [115]	Shen and Yu [117]
	Chou et al. [116]	Tabari et al. [119]
	Ertuğrul and Karakaşoğlu [126]	Turetken [129]
	Fernández and Ruiz [112]	Tuzkaya et al. [108]
	Guimarães Pereira et al. [130]	Tzeng et al. [110]
	Guo and He [114]	Yong [124]
	Higgs [107]	Farahani and Asgari [123]

Kozanidis [36] has introduced the convex Linear Multiple Choice Knapsack Problem that incorporates a second objective to allocate the available resource among a group of disjoint sets of activities, equitably. The objectives of this problem are in the form of maxisum and minimax functions (profit and equity).

Many papers utilize the classic covering problems in the way of multi-objectivity. Giving examples on bi-objective problems, Harewood [37] applied the queueing probabilistic location set covering problem ambulances with Euclidean distances and maxisum and minisum objectives (coverage and cost) for locating emergencies. Ohsawa et al. [38] developed new bi-criteria location problems with partial covering to model siting a semi- obnoxious facility within a convex polygon. Their model considers minimax and maximin objectives in Euclidean distances. Johnson [39] has modeled a subsidized housing project into a bi-objective single-period integer program with maxisum (difference between cost and variable net profit) and maximin (dispersion) objectives.

Considering capacities in location problems, there are capacitated and uncapacitated problems in the literature. For instance, Myung et al. [40] have considered an uncapacitated facility location problem with two maxisum objectives (net profit and profitability of the investment) and modeled it as a parametric integer program with fractional and linear objectives. Villegas et al. [41] has modeled a supply network as a bi-objective uncapacitated facility location problem, with minisum and maxisum objectives (cost and coverage). In contrast, Galvão et al. [42] developed an extension of the capacitated model to deal with locating maternity facilities with minisum objective (distance traveled and load imbalance).

In some cases, location problems come to simultaneous allocation issues. For example, Costa et al. [43] has presented a bi-criteria approach to the single allocation hub location problem. The first objective is a minisum form (cost), while the second objective (process time) has two alternative forms: minisum or minimax. Klimberg and Ratick [44] have utilized a different concept in order to formulate and find optimal and efficient facility location/allocation patterns. This concept is called Data Envelopment Analysis (DEA) which defines relative efficiency as the ratio of the sum of weighted output to the sum of weighted input: DEA efficiency = sum of weighted output/sum of weighted input. The more output produced for a given amount of resources, the more efficient (i.e., less wasteful) the process is. Therefore, the purpose in their model is to simultaneously minimize cost and maximize DEA objectives.

One of the most famous categories of location problems is facility location on a network, especially in supply chain context. One examples is Bhaskaran and Turnquist [45] which has studied the relation between transportation cost and coverage objectives in a network multi-facility location in both ordinary and ordered problems. Another example is Blanquero and Carrizosa [46] work in which they dealt with a bi-objective semi-obnoxious location problem with minisum and minimax objectives (cost and negative effect). Fernández et al. [47] presented a bi-objective supply chain design and facility location problem of supermarkets on the plane in which the main objective was to maximize the profit obtained by the chain, and the secondary objective was to minimize the cannibalization suffered by the existing chain-owned facilities. The cannibalization suffered, is the difference between market shares before and after entering a new facility. These are not the only applications of facility location on a network. For example, when you are about to locate a regional rail road or subway network, you will have subtree location problems. George and ReVelle [48] have focused on Median Subtree Location Problems (MSLP) in which they minimized the cost of the subtree as well as minimized travel distance from unconnected nodes as an integer program. There is another famous sub-category for facility location on a network, named reverse logistics. Du and Evans [49] have modeled a reverse logistic network for repair service as a bi-objective optimization problem with minisum objectives (cost and tardiness of cycle time). Fonseca et al. [50] have studied stochastic reverse logistics with several facility echelon, multi-commodities, and technology choices. They model these problems as a two-stage (strategic and tactical) mixed integer program with two minisum objectives (cost and undesirable effect) with Euclidean distances. Some network location problems are combined with routing problems. Current et al. [51] have considered maximum covering/shortest path problems as bi-objective integer programs with cost (minisum) and coverage (maxisum) objectives.

Undesirable and semi-desirable facility location problems, because of the contrasting nature of their models, have seen most efforts among bi-objective facility location problems. And in most cases, the objectives are reducing cost as well as the undesirable effects. For example, Brimberg and Juel [52] have modeled the problem of locating a semi-desirable facility in the plane with Euclidean distances and minisum objectives. Melachrinoudis [53] has developed a bi-criteria location problem with rectilinear distances and maximin and minisum objectives. Plastria and Carrizosa [54] have also investigated locating an undesirable facility within limited region in the plane as well as on a planar network. Their approach was based on locating disks in order to minimize the coverage and maximize the radius of those disks. Zhang and Melachrinoudis [55] have studied the maximin–maxisum location problems for locating an obnoxious facility and investigated their properties in both decision and objective spaces. Hamacher et al. [56] have set up a weighted anti-median and median facility location model on a network with the maxisum and minisum objectives. In Skriver and Andersen [57], to locate an airport (a semi-desirable facility), two bi-criteria location models with minisum objectives, one for the planar case and one for the network case have been presented. In Melachrinoudis and Xanthopulos [58], a new model to locate a new facility within a bounded region with maximin and minisum objective has been introduced. Rakas et al. [59] investigated locating undesirable facilities with minisum functions (cost and distance) in an uncertain environment, while the model of semi-obnoxious facility location problem introduced by Yapicioglu et al. [60], was composed of a weighted minisum function (cost and distance) with rectilinear metrics of distance. Another single facility location problem with maximin and minisum objectives (distance and cost) in a planar region with rectilinear measure of distance, has been introduced by Karasakal and Nadirler [61] and Medaglia et al. [62] have proposed a facility location model for a hospital waste management system with minisum objective (cost and distance). The Joint Facility Location and Network Design problems (JFLND) were considered by Carrano et al. [63] as bi-objective hierarchical models.

In brief, bi-objective location problems are getting more attention, especially in relation to semi-desirable and undesirable problems, as well as location problems on network. The purpose in most of these problems is minimizing cost, but this objective is in conflict with the other one, which is in most cases, maximizing the distance, or coverage.

4. *k*-Objective location problems

In this section, we evaluated that part of literature in which there is more than two objectives. We call them multi-objective location problems.

Current et al. [64] is a survey on these problems which classified the literature into four categories based on their types of objectives: dealing costs, demand coverage, profit maximization, and environmental issues. We discuss multi-objective location literature based on their classic operational research families: Weber, median, covering, constrained, uncapacitated, location–allocation, location-routing, dynamic, competitive, network and undesirable location problems. Before looking at these works, we would like to mention a different paper. Buhl [65] has studied the adequacy of the objective used in the location science from a theoretical point of view and proved economy and value judgment of each one of the objectives pointed out.

Now, as for classic location problems, Nijkamp and Spronk [66] considered an extension to the Weber problems in which the solution space is discrete and instead of the traditional single cost function, there are multiple objectives. Puerto and Fernández [67] have brought up the issue of the multi-criteria Weber problem with strict norms in a convex set with Euclidean distances. Bhattacharya et al. [68] have modeled location a single facility on a plane with maximin, minimax and minisum objectives and rectilinear measure of distance. Nickel et al. [69] has presented the ordered median problems for modeling multi-criteria location problems on the plane within any polyhedral gauge with Q general criteria. Ogryczak [70] has considered not only minimizing the largest distance (center) objective, but minimizing the second largest distance, minimizing the third largest distance and so on, to bring more efficiency and equity to the solution of the problem. This author has another interesting development to the classic problems. Ogryczak [71], instead of the traditional implementation of only center or median problems, considers all kinds of distances as a set of multiple uniform criteria and develop a multi-objective location problem.

From the family of covering location problems, Badri et al. [72] have proposed a multi-objective model for a set covering problem of locating fire stations. In Araz et al. [73], a fuzzy multi-objective covering-based model has been developed for emergency service location problems with Euclidean distances in which in addition to coverage and backup coverage objectives, service level was a target too. Considering Tsunami phenomenon, locating public facilities has been presented by Doerner et al. [74] with coverage and risk objectives and Euclidean measure of distance. Farhan and Murray [75] have developed a multi-objective spatial optimization model in which travel time and coverage standards are considered. The Generalized Search-And-Rescue (GSAR) problem which is a fourfold extension of the CMC (capacitated Maximum Coverage) facility location/allocation problem has been investigated by Chan et al. [76].

Some location problems include limitations, like in Puerto and Rodríguez-Chía [77], in which they have developed a general constrained multi-criteria location problem in two-dimensional and convex spaces. Yang et al. [78] have developed a fuzzy multi-objective model to locate fire stations where there are a number of physical limitations.

With reference to capacity in location problems, Melachrinoudis et al. [79] modeled their multi-period, capacitated discrete location problem of siting landfills into a dynamic multi-objective mix integer program. In contrast, Fernández and Puerto [80] have brought up the discrete multi-objective uncapacitated plant location problem.

In the location/allocation type of problems, a new location/allocation structure, referred to as the equity-efficiency trade-off model to locate medical facilities has been suggested by Cho [81]. In addition to cho, Klimberg and Bennekom [82] have presented four models, three of which are multi-objective location/allocation problems for after-sales repair service, based on an extension to set covering problems. Erkut et al. [83] have presented a new multi-objective model to solve the location/allocation problem of waste treatment facilities.

Routing problems are one of the major means of attention for multi-objective location problems. For example, in Kerbache and Smith [84], a multi-objective routing problem within a large scale manufacturing facilities has been modeled as open finite queuing networks with a multi-objective set of performance measures. Leung et al. [85] have proposed a cross-border logistics problem with three major objectives. Sometimes we have location issues combined with routing problems. An example is the multi-objective problem with multiple usages of vehicles, developed by Lin and Kwok [86]. Caballero et al. [87] have also presented a multi-objective location-routing problem for disposal of animal waste. Doerner et al. [88] have introduced a multi-objective formulation for a mobile medical facility location-routing problem, to find a closed tour and stops on a suitable selected subset of a given set of population nodes. Alumur and Kara [89] have also modeled a hazardous waste management as a multi-objective location-routing model. Zhang and Armstrong [90] studied corridor location problems through a multi-objective decision approach.

Some location problems try to model a multi-period or dynamic environment. Melachrinoudis and Min [91] have developed a dynamic two-echelon, multi-objective model for relocation and phase-out of a home improvement hardware manufacturing plant and warehousing. In Dias et al. [92], we also found the capacitated and uncapacitated multi-objective single- and multi-level dynamic location problems have been investigated.

Again, many network facility location problems utilize multi-objective optimization concepts. Stummer et al. [93] have determined the location and size of medical facilities in a hospital network. In Raisanen and Whitaker [94], locating and configuring infrastructure of cellular wireless networks have been proposed. Another example is Hong et al. [95] which has formulated the problem of locating static transfer switches as a fuzzy multi-objective program. In Cantarella and Vitetta [96], an urban network layout and link capacity has been introduced through a multi-objective Road Network Design Problem (RNDP). Leung [97] utilized a multiple objective nonlinear mathematical model for a trip distribution problem. Uno and Katagiri [98] have proposed the defensive location problem (DLP) which is an optimal location problem on a network and extended the DLPs to the multi-objective DLPs (formulated as bi-level 0–1 programming problems). As for reverse logistics, Pati et al. [99] proposed a multi-objective model for a paper recycling network system in determining the facility location, route and flow of different varieties of recyclable wastepaper in a multi-item, multi-echelon and multi-facility environment.

Most of the literature on network location analysis focuses on problems considering only one node weight and/or one single edge length. However, it might be needed to model problems in which several node weights represent different demands, and several edge lengths denote different measures as distance, time, travel costs, etc. Colebrook and Sicilia [100] have addressed the *k*-cent-dian problem on multi-criteria networks.

Selim and Ozkarahan [101] have presented a supply chain distribution network design model that utilizes maximal covering approach in the reporting of the service level and with multiple capacity levels, through a fuzzy multi-objective model. Note, Xu et al. [102] have developed a random fuzzy multi-objective model for design problem of a liquor supply chain network.

Regarding modeling undesirable/semi-desirable facility location problems, the literature in multi-objective is less than bi-objective. One example is Giannikos [103], in which locating and routing hazardous wastes through a disposal network has been presented. Another is Maniezzo et al. [104] which for locating an industrial waste facility, they designed a hierarchical multi-objective decision model. Nema and Gupta [105] have also presented an improved multi-objective approach for a hazardous waste location/allocation/routing problem.

Hamacher et al. [56], in addition to bi-objective model, they have investigated the weighted anti-median and median multi-objective facility location model on a network as well.

Drezner et al. [106] have incorporated five objectives of *p*-median, *p*-center, two maximum covering and the minimum variance in order to minimize the maximum percent deviation from the optimum of each of these objectives for a casualty collection point location problem just like compromise programming (CP).

Having taken a second look at the paper reviewed in this section, we saw that whenever it comes to routing problems, solely or combined with location/allocation problems, the multi-objective optimization concept shows a major advantage to deal with such problems. Like bi-objective problems, network problems are getting more complex, multi-objective versions of location problems become more apparent. In addition, the larger and more complicated the problems get, the more the use of fuzzy set theory increases, like in the work of Araz et al. [73], Yang et al. [78], Hong et al. [95], Selim and Ozkarahan [101] and Xu et al. [102].

5. Multi-attribute location problems

As multi-attribute location problems is a concern of this review as well, we present some of the literature in which some well known multi-attribute decision making such as ANP, AHP, ELECTRE, MAUT, TOPSIS, SMAA are utilized for solving siting problems. Sometimes geographical information systems (GIS) come to the help of location problems. Higgs [107] has reviewed some efforts in waste management siting in which multi-criteria analysis and evaluation have been combined with GIS to take into account the role of public decision making.

Tuzkaya et al. [108] used the analytic network process (ANP) technique, which includes qualitative and quantitative factors, and tangible and intangible criteria, without sacrificing their dependence, to evaluate and select suitable undesirable facility locations based on four main factors, namely, benefits, cost, opportunities and risks.

Analytic Hierarchical Process (AHP) which is a special case of the ANP, has been widely used for location problems, including in Aras et al. [109], in which a considerable number of criteria were taken into account for a wind observation station location problem. Another example of AHP location problems is Tzeng et al. [110] in which five aspects and 11 criteria were used for a location evaluation hierarchy of a restaurant. In this paper, the compromise ranking method (named VIKOR) has been introduced as one applicable technique. The VIKOR algorithm determines the weight stability intervals, for the obtained compromise solution with the "input" weights, indicating the preference stability of obtained compromise solution. Kinra and Kotzab [111] have applied AHP to investigate the relation of environmental terms in their supply chain as a multi-level multi-attribute decision problem as well. Fernández and Ruiz [112] considered the selection of a location for an industrial park. In their paper, they have proposed a three-level hierarchical decision process in which each level has its own geographical decision criteria. They then used AHP to find the location.

It is not too long since goal programming has been utilized to improve the problems solved by AHP. For example, Badri [113] offered a combined AHP and goal program modeling approach for international facility location/allocation problem; the role of AHP was to prioritize the set of location alternatives at first. Another paper, in which these combined approaches were presented, is Guo and He [114]. They introduced an approach for the location/allocation problem of a grain post-harvest system, which was solved by Multiple-Phase Simplex Algorithm for GP (MPGP).

Chan and Chung [115] developed a GA + AHP (a combination of Genetic Algorithm and AHP) model for solving distribution network problems in supply chain management. The optimization results showed them that GA + AHP was reliable and robust.

Under many situations, the values of the qualitative criteria are often imprecise or vague, therefore fuzzy multi-attribute group decision making is becoming a handy approach, like Chou et al. [116] which presented a fuzzy multi-criteria decision model for selecting a location for an international tourist hotel and used the methods of fuzzy set theory, linguistic value, hierarchical structure analysis, and fuzzy analytic hierarchy processes to consolidate decision-makers' assessments about criteria weightings. Another example is Shen and Yu [117] in which to select a location for an international company, implemented fuzzy set theory and a risk judgmental procedure for their fuzzy multi-attribute group decision making.

In Kahraman et al. [118] four different fuzzy multi-attribute group decision making approaches for facility location selection were implemented and compared from a different point of view (including the amount of data and time needed). These approaches were: fuzzy AHP, fuzzy model of group decision proposed by Blin, fuzzy synthetic evaluation and Yager's

weighted goals method. Tabari et al. [119] also have utilized fuzzy AHP with objective, subjective and critical factors to select a location for a new facility.

In addition to AHP, other multi-attribute methods have been used in the literature. Barda et al. [120] have modeled their thermal plant location problem in a hierarchical decision process in which they have utilized ELECTRE III to finally choose the best sites for each region they were studying. Another example is Norese [121] who presented an ELECTRE III method to select the best sites for a waste-disposal plant and for the incinerator. The ELECTRE III method was chosen from its family methods, because of the imprecision and uncertainty of some available data. The ELECTRE III uses the concept of pseudo criteria 3 and fuzzy outranking procedure.

Canbolat et al. [122] developed a three-phase methodology to deal with the international location problem of a manufacturing facility. In the first phase, they used an influence diagram to probe factors and uncertainties. Then, the decision tree was used to analyze the uncertainties, and gain a cumulative risk profile. In the last phase, this cumulative risk profile was incorporated as one of the measures for the Multi-Attribute Utility Theory (MAUT) model, that evaluated the alternative countries.

Sometimes, different multi-attribute is combined together or combined with multi-objective approaches to gain better results. Farahani and Asgari [123] have presented a five-stage procedure that was based on the situation where they used different tools and models like MADM, covering, districting, MODM, binary programming and quadratic programming. The case of this research is a hybrid multi-attribute and multi-objective set covering problem for locating military warehouses. They used TOPSIS and utility function (from global criterion method) to solve their hierarchical mode.

Like AHP, TOPSIS approach can apply fuzzy numbers to solve problems in which criteria or their weights are inaccurate. The example can be Yong [124] in which a new fuzzy TOPSIS was presented for selecting a plant location under linguistic terms, as triangular fuzzy numbers. Another example for the utilization of fuzzy TOPSIS, is Wadhwa et al. [125] in which the target was a reverse manufacturing chain. The proposed method claims to be very flexible and provides more objective information for alternative selection in a Reverse Logistics Systems (RLS).

A comparison of fuzzy AHP and fuzzy TOPSIS methods was developed by Ertuğrul and Karakaşoğlu [126] and implemented in a facility location of a textile company. It can be said that the results of this work are general, but based on the desires of the decision-makers, each of them can give a better answer.

As for less recognised multi-attribute approaches, Lahdelma et al. [127] has applied an Environmental Impact Assessment (EIA) process to process the data and the Stochastic Multi-criteria Acceptability Analysis with Ordinal criteria (SMAA-O) to evaluate criteria in a location problem of a waste treatment plant.

Cáceres et al. [128] presented the new integral analysis method (IAM) to a facility location problem of retail stores. This methodology integrates the cardinal and ordinal criteria of combinatorial stochastic optimization problems in four stages: the first one establishes the type of problem (cardinal and/or ordinal) and its stochastic or deterministic nature. In the second stage, the alternatives are selected considering optimization criteria and variability of the cardinal variables, an analysis in which Monte Carlo simulation and probability elements are employed as optimization techniques. In the third stage, the alternatives are further analyzed by means of SMAA-O and probability elements. In the final stage, the alternatives are analyzed again in both ordinal and cardinal aspects using a transformed version of deterministic SMAA and probability elements.

Turetken [129] has focused on locating IT infrastructures, especially for an international banking group, and proposed a qualitative discriminatory process (QDP) to tackle with both subjective and objective criteria by allowing decision makers to determine their preferences in relatively vague terms, then deriving numerical estimates for these ratings based on the minimum absolute deviation regression method.

The instances in the literature which have utilized heuristics and meta-heuristics in multi-attribute location problems are few. An example is Guimarães Pereira et al. [130] which for locating a retail facilities, have applied Genetic Algorithm (GA) to their multi-criteria location problem by defining degrees of membership to a group of solutions called suitable sites for each solution.

Sometimes in location problems, we are not dealing with numbers and mathematical findings but our decision is based on human judgment. Therefore, multi-attribute decision making is an important part of location science and based on the data type which is sometimes vague, fuzzy multi-attribute models are used more and more.

6. Solution methods

There has been a vast variety of solution methods – exact or approximate – used to find the Pareto-set of each investigated multi-criteria location problem. In this section, we explored with the paper's publishing time in mind.

Current et al. [51] have solved their bi-objective location problem with relaxing integer terms and then used branch-and-bound procedure when necessary.

Bhattacharya et al. [68] solved a fuzzy goal program for their multi-objective location problem.

Puerto and Fernández [67] provided a new way to apply polyhedral norms to solve their multi-criteria Weber location problem and approximate the solution set.

For their transshipment location problem, Ogryczak et al. [131] have proposed a Dynamic Interactive Network Analysis System (DINAS) which is an extension of the classic reference point method and includes a branch-and-bound and a Simplex Special Ordered Network (SOP) algorithm, to solve their integer programming problem. They applied this DINAS approach to health service districts reorganization in Ogryczak et al. [132].

Melachrinoudis et al. [79] used weighting method to generate good solutions and a filtering method to reduce them for their dynamic multi-objective MIP.

Malczewski and Ogryczak [133] discussed both utility-function-based and goal programming methods and developed a new approach, based on reference point method and applied it to an interactive decision support system for multi-criteria location problems.

Cho [81] combined Monte Carlo integer programming technique with augmented Lagrangian algorithm in a hierarchical way to obtain an optimum global solution.

Nema and Gupta [105] proposed a normalized composite utility function to consider both risk and cost together.

In Ohsawa [30], to find the set of Pareto-optimal locations in the model, those locations were examined first, based on simple geometrical methods with the help of the farthest-point Voronoi diagram, then, the objective functions are minimized via a solving the scalarized location model with suitable weights. Nickel [31] is another example in which the author has utilized the geometrical and combinatorial arguments of the problem to discretize the problem and find all the Pareto solutions.

Plastria and Carrizosa [54] proposed a low complexity polynomial algorithm based on mathematical and geometric properties of the solution space.

Melachrinoudis [53] used a decomposition strategy to convert this nonconvex bi-criteria problem into bi-criteria linear sub-problems, and solved them by applying the Fourier-Motzkin Elimination Method.

Ogryczak [71] has extended the concept of reference point method into an interactive reference distribution method which controls the aspiration cumulative distribution of outcomes based on the impartiality of the problem.

In Melachrinoudis and Min [91], the proposed multi-objective mixed integer program model claims to generate a set of non-dominated solutions without a prior articulation of preference information due to its usage of a weighting generating method.

Klamroth and Wiecek [33] decomposed their problem to a series of multiple objective convex sub-problems to determine the lower envelope of the non-dominated sets of the sub-problems. Depending on the given distance function, Hershberger algorithm or block sandwich method was used to respectively, give exact solutions for problems with linear measures of distance, or an approximation to the problems with other measures.

In the new algorithm which Zhang and Melachrinoudis [55] have developed, for their maximin–maxisum location problem, they identified the inefficient part of solution space first, then found the non-dominated solutions.

Hamacher et al. [56] have proposed an efficient polynomial time algorithm for general network location decisions based on comparison of bottleneck point sub-edges. As for bi-criteria networks, they used direct mapping of the network via calculating Hershberger algorithm.

Blanquero and Carrizosa [46] proposed an algorithm which decomposed the problem and built the Voronoi cells, and constructed a finite ε-dominating set of Pareto-optimal solution for the bi-objective problem.

Harewood [37], after introducing and solving a maximum availability location problem, used Monte Carlo simulation to model the system as a queuing system with poison call arrival rate, and exponentially distributed service time to evaluate the solutions of its optimization algorithm.

In Melachrinoudis and Xanthopulos [58], the solution methodology was based on the Karush–Kuhn–Tucker (KKT) conditions for nonlinear programming and on Voronoi diagrams. Ohsawa et al. [35] also used Voronoi diagrams and an arrangement of curves and lines to find Pareto optimal solutions.

The bi-criteria semi-obnoxious location problem in Skriver and Andersen [57] was solved using a variant of the Interactive Generalized Big Square Small Square (IGBSSS) method, both in planar and network cases. In the planar case, they used an approximation of weighted distances, while in the network case they proposed an Edge Dividing (ED) algorithm to obtain efficient solutions.

Rakas et al. [59] utilized the concept of fuzzy set theory combined with weighting method to solve their bi-objective problem.

In Skriver et al. [34], they devised a two-phase solution method. In the first phase of their method, all (or a representative subset of) the supported solutions are found by using a weighting method, then in the phase two, a search between the supported solutions is conducted to find unsupported efficient solutions.

Nickel et al. [69] characterized the set of Pareto solutions of all these multi-criteria problems for any polyhedral gauge by reduction to solving a series of bi-criteria problems. Some efficient algorithms were developed, based on finding lexicographic locations and generalized intersection points and scanning two-dimensional ordered elementary convex sets.

Johnson [39] has utilized the method of non-inferior set estimation and converting the bi-objective problem, into a single one with weights.

In Ohsawa et al. [38], they utilized a low complexity polynomial algorithms to find all the efficient solutions by replacing the standard and the farthest-point, Voronoi diagrams with higher-order Voronoi diagrams and investigating other geometrical properties.

Alumur and Kara [89] solved a multi-objective mixed integer program model in which risk played an important part besides the cost.

In Kozanidis [36], an optimal two-phased algorithm was developed in which the first phase ignores the equity objective and enhanced an existing method in order to obtain an initial solution for the problem, then in the second, the equity objective is incorporated to obtain its entire non-dominated frontier upon termination.

Colebrook and Sicilia [100], introduced a general polynomial approach that works by splitting each edge of the network in intervals, according to the breakpoints of all the objective functions, analyzing the values of these functions over the generated intervals to find non-dominated candidate sets and finally utilizing other algorithms to compare pair wise all the points and segments generated to determine the efficient points.

Fernández et al. [47] have presented a new δ-lexicographic method, which is a modification of the classical lexicographic method. This δ-lexicographic method implements a unified interval branch-and-bound method which was similar to the two-phase GBSSS method.

In Araz et al. [73], four approaches, respectively lexicographic multi-objective linear programming, Fuzzy Goal Programming (FGP), Additive FGP (A-FGP-C) and Weighted Additive FGP (WA-FGP-T), were applied to solve the problem. The analysis showed that the proposed FGP model was an effective tool for generating a set of more realistic and flexible optimal solutions.

Karasakal and Nadirler [61], proposed an interactive IGBSSS method, for solving the problem. In the third phase of this approach, two options were suggested for the interactive search: an exact or an approximate procedure. The exact procedure was based on the reference point approach and guaranteed to find an efficient point as the most preferred solution. On the other hand, in the approximate procedure, a hybrid methodology, the best bound search, was used to increase the efficiency of the reference point approach.

In Chan et al. [76], a two-stage multi-objective linear-integer-program to reduce the number of enumerated binary variables and approximate the nonlinear integer problem. In addition to solving this, a weighted-sum approach and to evaluate the solutions, a value function was recommended.

Puerto and Rodríguez-Chía [77] introduced a unification of previous characterizations obtained for the set of weakly efficient solutions of multi-criteria location problems in two-dimensional spaces. In addition, they provided a geometrical description of this kind of solution sets to obtain efficient solutions.

Klimberg and Ratick [44], utilizing the concept of Data Envelope Analysis (DEA) as another objective function, proposed an interactive model named Modified Data Envelope Analysis model (DEA2).

In Pati et al. [99], the solution procedure entailed the partitioning of the objective function according to the priority levels defined and the sequential solution of the resultant mixed integer linear programming models. The solution obtained at each priority levels was used as a constraint at the lower level.

Fernández and Puerto [80] decomposed their location/allocation problem to two nested sub-problems and utilized dynamic programming to solve their problem. In order to do so, they utilized a labeling method to solve exactly the allocation sub-problem as a shortest path problem; and a scalarized approach that finds the supported efficient set.

6.1. Using heuristics techniques

Some of the reviewed papers, particularly, applied heuristics techniques to solve their problem. Examples are:

Karkazis [134], first used Lagrangian relaxation, then designed a hill-climbing-like heuristics along sub-gradient directions to solve the bi-objective competitive location problem.

Maniezzo et al. [104] utilized a heuristics in which first the k-best solutions of single-objective problems are produced, then by combining these reduced solution space, the best solution to the problem was found.

Brimberg and Juel [52] proposed a heuristics based on some mathematical properties of the problem such as block norms, and techniques like branch-and-bound.

Myung et al. [40] considered techniques of constraint method and weighting and developed a heuristics to deal with their uncapacitated bi-objective problem.

Kerbache and Smith [84] proposed a heuristics including an approximate analytical decomposition technique for modeling open finite hierarchical queuing networks (called the generalized expansion method (GEM)) followed by a multi-objective mathematical optimization technique to determine the non-inferior (NI) set of routes for their stochastic network optimization problem.

Capacitated bi-criterion model by Galvão et al. [42] was solved using the constraint method and a Lagrangian heuristic. Leung et al. [85] solved their goal programming by an efficient heuristic solution procedure too.

Fonseca et al. [50] has developed a heuristics for their stochastic logistics problem based on finding lexicographic minimum of their two objectives in the iterations.

6.2. Using meta-heuristics techniques

Meta-heuristics techniques, which are more efficient search approaches for larger and more complicated problems than heuristics methods. Many of the recent papers, as seen in this sub-section, have implemented these techniques in order to deal with their large and complicated problems.

One of the meta-heuristics approaches, used to solve multi-criteria location problems, is the Scatter Search (SS). In Du and Evans [49], along with the constraint method (to yield a set of non-dominated solutions) and the dual simplex method (to find optimal solutions with respect to the continuous variables), a scatter search algorithm was used to deal with the binary decision variables.

Lin and Kwok [86] applied two other classes of meta-heuristics: Tabu Search (TS) and Simulated Annealing (SA), and compared their performances through a new statistical procedure. Drezner et al. [106] is another example in which they have use two heuristics including tabu search and a decent algorithm for their minimax regret multi-objective problem.

Stummer et al. [93] extended the original tabu search algorithm and implemented a multi-objective version with a population set, in the first phase of their algorithm, following by a *k*-means clustering in the second phase to allow the decision makers to interactively explore the solution space to determine the "best" configuration.

Caballero et al. [87] used the multi-objective meta-heuristic using an adaptive memory procedure (MOAMP) method, which is based on tabu search.

Uno and Katagiri [98] proposed to apply the interactive fuzzy satisfying method with a tabu search algorithm in order to find several M-Pareto optimal solutions in their location problem, which they regarded as a multi-objective two person zero-sum Stackelberg equilibrium game.

Raisanen and Whitaker [94] implemented a greedy algorithm whose performance was dependent on the order in which the candidate sites are considered. In order to find an optimal ordering of potential base stations, four multiple objective genetic algorithms, Simple Evolutionary Algorithm for Multi-Objective Optimization (SEAMO), Strength Pareto Evolutionary Algorithm version 2 (SPEA2), Pareto Envelop based Selection Algorithm (PESA) and Non-dominated Sorting Genetic Algorithm II (NSGA-II), were compared from many different terms, such as simplicity, quality of solution, time, etc.

According to Cantarella and Vitetta [96], to deal with large scale versions of their problem, they proposed a multi-level heuristic algorithm. At its outer level, new network configurations were analyzed by a genetic algorithm and at its inner level, the traffic signal setting and flow assignment were performed within an asymmetric user equilibrium assignment. Finally, the solutions were tested through some approaches including a clustering procedure, and calculating the values of criteria.

Doerner et al. [88] proposed three algorithms: Pareto-ant colony optimization (P-ACO) technique and performed a selection of tour stops and tour constructions simultaneously, Vector Evaluated Genetic Algorithm (VEGA) and the Multi-Objective Genetic Algorithm (MOGA) and performed the selection of tour stops on an upper procedure level and tour construction in a 2-opt sub-local search. In the end, they suggested a combination of Pareto-ACO and MOGA as a promising technique to find an adequate set of good solution candidates. Zhang and Armstrong [90] is another example in which MOGA was applied to their problem.

Leung [97] proposed a genetic algorithm for its combinatorial goal programming model. The author finds this method more flexible and effective than common models such as the standard gravity model or entropy-maximization model.

In Carrano et al. [63], for the bi-objective joint facility location and network design problems (MJFLND), a two-modularized algorithm was used in which a multi-objective quasi-Newton algorithm was responsible for finding the location of the facilities; and a multi-objective genetic algorithm, was used to find the efficient network design. Moreover, a heuristics was applied to switch between these modules in order to find an efficient solution.

In Dias et al. [92], an interactive memetic algorithm integrating genetic procedures and local search was proposed. The interaction with the decision maker is to define interesting search areas by establishing upper bounds to the objective function values, or through the indication of reference points. It seems that reference point approach built more and better solutions in less iteration.

Villegas et al. [41] designed three algorithms: non-dominated sorting genetic algorithm (NSGA II), Pareto Archive Evolution Strategy (PAES), and a mathematical programming approach that solved a sequence of integer programs in which one of the objectives was treated as a constraint. The results showed that NSGA algorithm performed better in terms of quality, but in terms of time, was worse than PAES. However, both evolutionary algorithms were less effective than the mathematical programming approach.

Doerner et al. [74] utilized a non-dominated sorting genetic algorithm II (NSGA-II) approach and compared it with a decomposition technique where decomposed problems were solved either exactly or heuristically. Results showed that when it comes to the size of a problem, this algorithm is efficient in time and quality.

Medaglia et al. [62] is another example of application of NSGA-II in multi-objective facility location problems. They combined their algorithm a fast greedy fitness assignment heuristic (GA-GAH), and with a fitness assignment approach based on mixed integer programming (GA-MIP) for its fitness function. Experiments showed that the hybrid GA-MIP obtained better solutions, based on the size of space covered (SSC) metric. Moreover, GA-MIP was compared to the non-inferior Set estimation (NISE) method, and from different points of view, GA-MIP showed a better performance than NISE.

Xu et al. [102], proposed an approach of spanning tree-based genetic algorithm (st-GA) by the Prüfer number representation to solve the problem. They also utilized the expected value and chance-constrained operators, to deal with the random fuzzy objection functions and the random fuzzy constraints and turning them into a deterministic model.

Hong et al. [95] also applied a genetic algorithm with a vertex Prüfer number encoding/decoding to their problem. To deal with their fuzzy multi-objective location model with physical limitations, Yang et al. [78] converted the model into a single unified 'min–max' goal and combined the goal with their genetic algorithm.

In the reviewed literature, meta-heuristic of class genetic algorithms have been vastly applied to multi-criteria location problems and they seem to be more appropriate tools for multi-criteria location problems.

Another meta-heuristic approach in the literature is the Particle Swarm Optimization (PSO) family. Yapicioglu et al. [60], devised three versions of a bi-particle swarm optimization (bi-objective PSO) to solve their problem, but they suggested that a hybrid version was more efficient.

7. Criteria

Most surveys, on multi-criteria location problems, see them from a theoretical point of view, but we dare to say almost none have reviewed the "criteria" in these problems. Therefore we decided to investigate the literature and the criteria used from their applicability point of view.

In single criterion location problems, the criterion has usually been cost or coverage, but in multi-criteria problems, there is at least one other criterion to consider which for the nature of these problems, is in conflict with the first one.

In this section, based on the philosophy behind our categorization, we provide a review on the criteria used in bi-/multi-objective location problems, and then multi-attribute location problems.

7.1. Multi-objective decision criteria

There is a summary of the objectives used in the problems in Table 3, which provides a fine landscape of their classification. We describe each one of these classes of objectives in the following sub-sections.

7.1.1. Cost

There are different types of cost. These types can be divided into fixed and variable categories. Fixed cost includes installation and start-up cost, along with investment. Variable cost can be transportation, operations, production, services, distribution, logistics, waste disposal, maintenance, and environmental cost. Transportation cost is the highest and installation cost the second highest. Several problems have used a 'total cost' criterion which contains all cost under one objective.

7.1.2. Environmental risks

These criteria include transportation risk, natural risk, waste disposal or treatment risk, or the general 'undesirable effects' which is the highest place. However, taking a look at Table 3, one can see that the proportion of environmental risk in location problems is much less than the cost.

7.1.3. Coverage

Almost the entire collection of location problems, are about coverage by distance, time, amount or even coverage deviation. Although many problems use distance and population coverage as their criteria, time is just as important in some problems.

We placed the concept of equity in this category, because these kinds of problems are also about covering, but in an equitable way. Studying the literature, equity has not been considered enough in location problems, as much as coverage.

We also considered the dispersion types of objectives in this category because most of the time the difference between coverage and dispersion is only changing "minimizing" the coverage function to "maximizing" or vice versa.

7.1.4. Service level and effectiveness

In this category, we gathered service level criteria, along with the effectiveness and efficiency criteria.

7.1.5. Profit

Some problems are interested in the net profit, difference between benefits and costs, or other outcomes of the capital they invested in their facility location decision making. We assembled these criteria under the profit category.

7.1.6. Other criteria

Some other criteria were used in location problems which could not be included in other categories, like resource accessibility as well as social and political risks.

7.2. Multi-attribute decision criteria

As the number of criteria used in such problems are many, we decided to present them in some general categories which you can see in Table 4.

- Cost include land, transportation, installation, maintenance cost, etc.
- Value and benefits can be revenue, land or asset value, or product value.
- Environmental risks are the matters on health effects, sound and optical pollution, smells, air or water pollution, waste collection, etc.
- Resource accessibility and utilization of the facility to be located does not need to be detailed further.
- Having access to public facilities like airports, motor or railways or recreation, resting, accommodation, etc. is important in some problems.
- Political matters and regulations including community consideration, country measures, and government regulations.
- Competition environment and the presence of competitors are gathered in competition criteria.

Table 3
Summary of criteria in bi-/ multi-objective location problems.

Criterion	Model	
	Bi-objective	k-Objective
Cost	Bhaskaran and Turnquist [45]	Alumur and Kara [89]
	Bhattacharya et al. [32]	Badri et al. [72]
	Blanquero and Carrizosa [46]	Bhattacharya et al. [68]
	Brimberg and Juel [52]	Caballero et al. [87]
	Carrano et al. [63]	Doerner et al. [74]
	Costa et al. [43]	Erkut et al. [83]
	Current et al. [51]	Giannikos [103]
	Du and Evans [49]	Hong et al. [95]
	Fernández et al. [47]	Leung [97]
	Fonseca et al. [50]	Leung et al. [85]
	George and ReVelle [48]	Lin and Kwok [86]
	Harewood [37]	Melachrinoudis and Min [91]
	Karasakal and Nadirler [61]	Melachrinoudis et al. [79]
	Karkazis [134]	Nema and Gupta [105]
	Kerbache and Smith [84]	Ogryczak et al. [131]
	Kozanidis [36]	Ogryczak et al. [132]
	Medaglia et al. [62]	Pati et al. [99]
	Melachrinoudis and Xanthopulos [58]	Raisanen and Whitaker [94]
	Rakas et al. [59]	Selim and Ozkarahan [101]
	Skriver and Andersen [57]	Stummer et al. [93]
	Skriver et al. [34]	Xu et al. [102]
	Villegas et al. [41]	Yang et al. [78]
	Yapicioglu et al. [60]	Zhang and Armstrong [90]
Environmental risks	Fonseca et al. [50]	Alumur and Kara [89]
	Melachrinoudis and Xanthopulos [58]	Badri et al. [72]
	Skriver and Andersen [57]	Caballero et al. [87]
	Yapicioglu et al. [60]	Erkut et al. [83]
		Giannikos [103]
		Melachrinoudis et al. [79]
		Nema and Gupta [105]
		Zhang and Armstrong [90]
Coverage (and equity)	Bhaskaran and Turnquist [45]	Araz et al. [73]
	Bhattacharya et al. [32]	Badri et al. [72]
	Blanquero and Carrizosa [46]	Bhattacharya et al. [68]
	Costa et al. [43]	Caballero et al. [87]
	Current et al. [51]	Chan et al. [76]
	Galvão et al. [42]	Cho [81]
	George and ReVelle [48]	Doerner et al. [88]
	Harewood [37]	Doerner et al. [74]
	Johnson [39]	Erkut et al. [83]
	Karasakal and Nadirler [61]	Farhan and Murray [75]
	Kerbache and Smith [84]	Giannikos [103]
	Kozanidis [36]	Hong et al. [95]
	Medaglia et al. [62]	Klimberg and Bennekom [82]
	Ohsawa et al. [35]	Leung et al. [85]
	Plastria and Carrizosa [54]	Lin and Kwok [86]
	Rakas et al. [59]	Melachrinoudis and Min [91]
	Villegas et al. [41]	Melachrinoudis et al. [79]
	Zhang and Melachrinoudis [55]	Ogryczak et al. [132]
		Pati et al. [99]
		Raisanen and Whitaker [94]
		Selim and Ozkarahan [101]
		Stummer et al. [93]
		Yang et al. [78]
Service level and effectiveness	Carrano et al. [63]	Badri et al. [72]
	Harewood [37]	Cho [81]
	Klimberg and Ratick [44]	Doerner et al. [88]
	Karkazis [134]	Klimberg and Bennekom [82]
	Kozanidis [36]	Leung [97]
		Lin and Kwok [86]
		Ogryczak et al. [131]
		Xu et al. [102]
Profit	Johnson [39]	–
	Myung et al. [40]	

Table 3 (continued)

Criterion	Model	
	Bi-objective	k-Objective
Other criteria	Fernández et al. [47]	Badri et al. [72]
		Caballero et al. [87]
		Chan et al. [76]
		Doerner et al. [74]
		Farhan and Murray [75]
		Hong et al. [95]
		Leung et al. [85]
		Melachrinoudis and Min [91]
		Ogryczak et al. [131]
		Stummer et al. [93]
		Zhang and Armstrong [90]

- Economical criteria, besides cost and value, include labor availability, job opportunities, currency value, business climate and many others.
- Population is important in some location problems.
- Capacity and size of the facility to be located do not need to be described.
- Like multi-objective problems, distances including closeness to markets or customers, suppliers and resources, closeness to forbidden or natural areas are a matter to some problems.

And last but not least, suitability criteria can be qualitative, cultural and social issues, technical suitability, land use, natural threats, convenience to traffic system, infrastructure and any other factors which represent this category.

As time passes by, location scientists are trying more and more to model and solve real-world problems. We all know that real-world problems are complicated systems including lots of criteria (objectives and attributes). Taking a look at the literature reviewed, recent papers have tried to import more criteria to their problems, which are not only financial matters, but environmental, social and even political issues too.

8. Conclusions and directions for further research

In this paper we reviewed literature of facility location problems as much as it uses MCDM tools as solution techniques. We saw the literature on multi-criteria facility location problems has been growing increasingly. The growing attention and interest into these problems, is due to the recognition of the need to consider more criteria in order to achieve closer solutions to reality. In this paper, we reviewed some of the recent works on multi-criteria location problems in three categories of bi-objective, multi-objective and multi-attribute problems. Some of the problems reviewed in this paper, have been applied to real-world problems, which was the main target of this paper. We surveyed theses models and the solution approaches used to solve them.

In addition, when we thought about location criteria, the first one that comes to mind is cost. Moreover, a wide variety of criteria have been proposed in the literature. This paper has investigated these criteria in recent work. Undoubtedly, there are many other researches on multi-criteria location problems, but we hope that this survey helps to facilitate future research in this area. Based on the review papers we suggest the following areas as future research:

- *Reliability:* Every located facility can face disruptions like natural disasters or man-made disaster. This can lead to people's deaths and huge losses. Therefore, located facilities must somehow rectify using the excess inventory, redundant facilities, etc. (see [135]). These kinds of problems can be called location-reliability problems. Considering objective functions that somehow guarantee reliability are becoming very important after Sept. 11 [136].
- *Stochasticity and robustness:* Most of the models used in multi-criteria location problems are considering deterministic parameters while solving models including uncertainty, random parameters or with distribution function are more realistic. Therefore, using stochastic optimization and robustness concept [137] in this area can be an important direction.
- *Sustainability:* In today's world, thinking of objective functions other than economic functions (like profit, cost, revenue, etc.) is becoming a must. Sustainability imposes any development and design like in location planning must also consider social and environmental objective functions [138]. The most important thought that we took into consideration, is how to measure these attributes. Therefore, we can think of a term like sustainable facility location.
- *Network design:* Logistics network design and also supply chain network design are major strategic issues. In network design several decisions including location decisions are made. This area can use multi-objective facility location models. For instance Pishvaee et al. [139] proposed a bi-objective mixed integer programming formulation model for integrated logistics network design. The first objective is to minimize the total cost and the second one is to maximize the

Table 4
Summary of criteria in multi-attribute location problems.

Criteria	References	
Cost	Aras et al. [109] Chan and Chung [115] Chou et al. [116] Fernández and Ruiz [112] Guimarães Pereira et al. [130] Guo and He [114] Lahdelma et al. [127]	Tabari et al. [119] Turetken [129] Tuzkaya et al. [108] Tzeng et al. [110] Wadhwa et al. [125] Yong [124] Farahani and Asgari [123]
Value and benefits	Guimarães Pereira et al. [130] Guo and He [114] Lahdelma et al. [127]	Norese [121] Tuzkaya et al. [108] Farahani and Asgari [123]
Environmental risks	Aras et al. [109] Barda et al. [120] Fernández and Ruiz [112] Guimarães Pereira et al. [130] Lahdelma et al. [127]	Norese [121] Turetken [129] Tuzkaya et al. [108] Wadhwa et al. [125]
Resource accessibility and utilization	Aras et al. [109] Barda et al. [120] Chan and Chung [115] Chou et al. [116]	Fernández and Ruiz [112] Kinra and Kotzab [111] Lahdelma et al. [127] Yong [124]
Public facility accessibility	Aras et al. [109] Barda et al. [120] Chou et al. [116] Fernández and Ruiz [112] Guimarães Pereira et al. [130]	Kinra and Kotzab [111] Lahdelma et al. [127] Norese [121] Shen and Yu [117] Tzeng et al. [110]
Political matters and regulations	Badri [113] Canbolat et al. [122] Chou et al. [116] Kahraman et al. [118] Kinra and Kotzab [111]	Shen and Yu [117] Tabari et al. [119] Turetken [129] Wadhwa et al. [125]
Competition	Badri [113] Chou et al. [116]	Kahraman et al. [118] Tzeng et al. [110]
Economical (besides costs and benefits)	Badri [113] Barda et al. [120] Canbolat et al. [122] Ertuğrul and Karakaşoğlu [126] Fernández and Ruiz [112] Guimarães Pereira et al. [130] Kahraman et al. [118] Kinra and Kotzab [111]	Norese [121] Shen and Yu [117] Tabari et al. [119] Turetken [129] Tuzkaya et al. [108] Wadhwa et al. [125] Yong [124]
Population	Canbolat et al. [122] Guimarães Pereira et al. [130] Lahdelma et al. [127]	Norese [121] Tzeng et al. [110]
Capacity	Norese [121] Tuzkaya et al. [108]	Tzeng et al. [110]
Distance	Ertuğrul and Karakaşoğlu [126] Guimarães Pereira et al. [130]	Norese [121] Tuzkaya et al. [108]
Suitability	Aras et al. [109] Barda et al. [120]	Canbolat et al. [122] Chou et al. [116]

responsiveness of a logistics network. This model is solved using an efficient multi-objective memetic algorithm. In other words, integrating multi-criteria location decision with other network design decisions, like routing, inventory, transportation, etc. can be of important development.

- *Supply chain:* Supply chain nature necessitates more than one stack holders that compromises to stay alive and competitive. Therefore, in a supply chain there is more than one objective function. Melo et al. [140] have published a very comprehensive review paper, related to facility location in supply chain. They show that in addition to economic factors using other objectives like resource utilization and customer responsiveness are becoming popular. Customer responsiveness including fill rate maximization and product lateness minimization. In the context of reverse logistics, specific customer service measures can be defined such as the cycle time (the time required to transport, returned products from collection centers to repair facilities and the time necessary to repair the faulty products).
- *Game theory:* While using game theory as a powerful technique in competitive location problems has a fairly rich history [8], in this context we excluded game objectives (like market shares); however, game theory can be assumed a special kind of MODM that has its own technique. On the other hand, applying multi-criteria location problems in business environment, can lead to using cooperative and non-cooperative games and some special solution techniques like bi-level [141] and multi-level programming.

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