**Invited Review**

# OR Models in Urban Service Facility Location: A Critical Review of Applications and Future Developments

**Reza Zanjirani Farahani[1], Samira Fallah[2], Rubén Ruiz[3*], Sara Hosseini[1], Nasrin Asgari[4]**

[1]Department of Management, Kingston Business School, Kingston University, United Kingdom
[2] Rucks Department of Management, Louisiana State University, 2700 Business Education Complex, Baton Rouge, LA 70803, United States
[3]Grupo de Sistemas de Optimización Aplicada, Instituto Tecnológico de Informática, Ciudad Politécnica de la Innovación, Edifico 8G, Acc. B. Universitat Politècnica de València, Camino de Vera s/n, 46021, València, Spain
[4]Roehampton Business School, University of Roehampton, United Kingdom

## ABSTRACT

Facility location models are well established in various application areas with more than a century of history in academia. Since the 1970s the trend has been shifting from manufacturing to service industries. Due to their nature, service industries are frequently located in or near urban areas which results in additional assumptions, objectives and constraints other than those in more traditional manufacturing location models. This survey focuses on the location of service facilities in urban areas. We studied 110 research papers across different journals and disciplines. We have analyzed these papers on two levels. On the first, we take an Operations Research perspective to investigate the papers in terms of types of decisions, location space, main assumptions, input parameters, objective functions and constraints. On the second level, we compare and contrast the papers in each of these applications categories: a) Waste management systems (WMS), b) Large-scale disaster (LSD), c) Small-scale emergency (SSE), d) General service and infrastructure (GSI), e) Non-emergency healthcare systems (NEH) and f) Transportation systems and their infrastructure (TSI). Each of these categories is critically analyzed in terms of application, assumptions, decision variables, input parameters, constraints, objective functions and solution techniques. Gaps, research opportunities and trends are identified within each category. Finally, some general lessons learned based on the practicality of the models is synthesized to suggest avenues of future research.

***Keywords*:** Location; Service Facility; Urban Areas; Operational Research; Modeling.

## 1. INTRODUCTION

Facility location, location analysis, location theory, locational decisions and siting are terms used interchangeably for the same purpose. They address a well-known classic problem referring to the placement of at least one facility (e.g., a resource or server) among several existing facilities (e.g., demand points) to serve them (Farahani & Hekmatfar 2009). Facility location is one of the very first and prominent strategic decisions that has a profound effect on tactical and operational decisions in any organization. It has applications in various areas such as industry, services, politics, business and economics, to name just a few. Facilities can be anything which needs to be located such as hospitals, fire stations, bus stops, train stations, truck terminals, fuel stations, blood banking centers, retail outlets, urban districts, libraries, parks, post offices, airports and waste disposal sites (Daskin 2008).

Facility Location Problems (FLPs) are mainly solved by using various quantitative and qualitative techniques

* ***Corresponding author.*** Email: rruiz@eio.upv.es; Tel: +34 96 387 70 07. Fax: +34 96 387 74 99.

from operations research (OR), management science and operations management. Depending on the nature of the facility to be located, various objective functions may be considered. Among them minimizing travel distance, maximizing service level, minimizing waiting time, maximizing coverage, minimizing transportation costs or avoiding placement next to hazardous facilities are the most popular.

Some scholars believe facility location can be traced back to Pierre de Fermat, Evangelista Torricelli (1608-1647) and Bonaventura Francesco Cavalieri (1598-1647) who independently proposed (and some say solved) the basic Euclidean spatial median problem early in seventeenth century (Drezner & Hamacher 2002, Farahani & Hekmatfar 2009). Research studies on facility location formally date back to 1909 when Alfred Weber considered the location of a warehouse with the objective of minimizing the total travel distance between the warehouse and its customers (Weber 1909). An important turning point for FLPs was in 1964 when Hakimi (1964) attempted to locate (a) switching centers in a communication network and (b) police stations on highways. Hakimi (1964) promoted location theory by proving several important basic theorems, especially in network space and for Median and Centre problems.

Facilities in location problems are characterized over a wide spectrum from manufacturing facilities at one end to service facilities at the other end. It is difficult to find a pure service or manufacturing facility. In other words, most of the products offered by organizations are a mix of services (intangible products) and goods (tangible products). However, if the share of service in the delivered product is significantly higher than the good itself, we can call it a service facility. Restaurants and retailers are examples of service organizations that deliver something tangible while banks, insurance companies and schools are examples of service organizations.

The majority of the research studies published before the 1970s focused on either manufacturing facilities or the movement of tangible goods. However, readers interested in facility location problems may refer to the following references to learn that this area has a rich OR-oriented literature: Handler & Mirchandani (1979), Love et al. (1988), Mirchandani & Francis (1989), Francis et al. (2015), Daskin (1995), Drezner (1995), Owen & Daskin (1998), Plastria (2001), Drezner & Hamacher (2002), Hale & Moberg (2003), Nickel & Puerto (2005), Klose & Drexl (2005), Snyder (2006), Boffey et al. (2007), Şahin & Süral (2007), Alumur & Kara (2008), Melo et al. (2009), Church & Murray (2009), Farahani & Hekmatfar (2009), Farahani et al. (2010), Arabani & Farahani (2012), Campbell and O'Kelly (2012), Farahani et al. (2013a), Farahani et al. (2014) and Farahani et al. (2015). Some of the earliest turning points in this trend were the publication of Toregas et al. (1971) and Church & Revelle (1974) that introduced real-life applications of facility location in emergency departments. In fact, at least two aspects of their work distinguished them from previous publications: (1) the application to a fire department which is a service facility and (2) the application in urban areas which was different from the common industrial areas at that time.

This paper follows this trend with a particular focus on service facilities that are operating in "urban" areas. We are interested in the "service" or tertiary sector since in relation to enterprise turn-over and gross domestic product (GDP) of nations, service industries are playing an increasingly more important role than their manufacturing counterparts, especially in developed countries. For example, in 2012 service industries contributed to producing 79.7% of the GDP of the United States while the rest came from the agriculture and manufacturing industries. Services' share of the GDP of the UK, France, the US, Japan and Germany were 79.6%, 79%, 77.6%, 72.2% and 69.1% respectively (CIA World Fact-book, 2015). We highlight urban areas since according to our survey, unlike manufacturing facilities, the majority of service facilities are located within urban areas.

Urbanization, considered to be the process of people migrating from rural to urban areas, is a common phenomenon in developed and developing countries. Interested readers may refer to Knox & McCarthy (2012) to learn about the basics of this field. There are positive and negative effects in urbanization. Some of the positive effects can be employment opportunities, quality of educational systems and access to health services. There are also negative effects associated with urbanization such as air, water and noise pollution, waste-disposal, high energy consumption (Jones 1991, Sadorsky 2013), traffic congestion, high population density, lack of infrastructure, housing provision, slum development (Vij 2012) and crime. The service facilities located in urban areas play an important role in all the above-mentioned causes. From the literature we identify some unexplored gaps in the urban service facility location (USFL) area compared with manufacturing facilities. Cities have become a significant contributor to the quality of life of individuals as well as to the overall economy. Currently, more than half of the world's population live in urban areas and about 1.3 million people are added to cities every week; this rate is 3 million people per week in developing countries (World Urbanization Prospects, 2014). With this trend, it is estimated that by the year 2050, about 66 percent of world's population will be living in an urban environment (World Urbanization Prospects, 2014). This rapid growth rate in urbanization has resulted in a growing demand for different services in cities. Cities generate 80 percent of the global GDP (Dobbs et al. 2011). As the engine of economies, cities must have an efficient transportation system to facilitate ease of mobility and avoid time, productivity, fuel and pollution costs. According to the American Society of Civil Engineers in 2013, the estimated annual costs of wasted time and fuel due to traffic congestion in the US is about $101 billion (ASCE Report Card for America's Infrastructure 2013). Cities must have sufficient capacity for an increase in residence and the necessary infrastructures to provide required services such as education, healthcare, entertainment and emergency facilities. These facilities must provide acceptable levels of quality and appropriate costs by considering major concerns such as maximizing service and coverage and minimizing traffic congestion and waiting times.

This paper is motivated by the significance of the USFL. In particular, we intend to elaborate on the types of decisions, location models, objective functions and constraints when focusing on the location of service facilities in the current literature with the aim of providing a general framework of problems for both practitioners and scholars, as well as identifying gaps, current trends and providing future research directions.

The rest of this paper is organized as follows: in section 2 the research method and scope used in this survey is explained. Sections 3 to 8 analyze the papers that fall within the scope of this research in terms of type of decisions, location space, main assumptions, input parameters, objective functions and constraints. Section 9 introduces real-life applications in each of applications in USFL models. Section 10 concludes the paper by introducing areas for further research on the USFL.

## 2. RESEARCH METHOD AND SCOPE

In this section, we describe our research method, the scope of our search and various applications of USFL models observed in the literature.

### 2.1. Research method

In order to describe the research method, we follow the procedure of Saunders et al. (2012) as depicted in Figure 1. We analyzed the previous research and then put forward a clear picture of classifications, assumptions, decisions and under-investigated areas for future research directions. Therefore, we took a realistic perspective combined with a pragmatic viewpoint. The research procedure is inductive as we took a bottom-up approach and focused on studying peer-reviewed research publications to identify the gaps and future trends in the field.

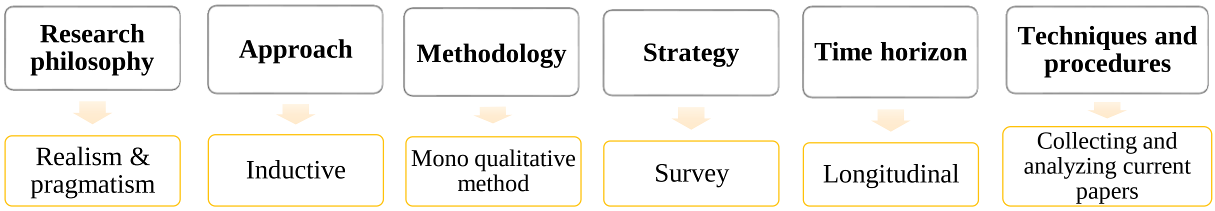


**Figure 1:** Research method based on research onion terminology introduced by Saunders et al. (2012).

Our methodology is mono qualitative and surveying to find the desired research works in SCOPUS (the largest abstract and citation database of peer-reviewed literature) as well as GoogleScholar with the following search strategies:

- ***SCOPUS:*** Title, abstract and keywords of journal papers published until 31 December 2017 are searched for with a combination of the following keywords: “Facility location” along with “Urban”, “City”, “Region”, “Regional”, “Municipal”, “Municipality” and “Area”.
- ***GoogleScholar:*** We searched Google Scholar to double check not only the papers published in recent years but also those published in other journals not listed in SCOPUS as well as recent papers published in established journals but not yet listed in SCOPUS.

**2.2. Scope**

- The survey includes papers that focus on facility location. There will be some papers focusing on other joint decisions such as vehicle routing problem (VRP), allocation and transportation, however facility location decisions comprise the core of this survey.
- We have only considered those papers that have used operations research techniques as either the modeling tool or the solution technique.
- The survey specifically considers real-life applications of facility location problems in urban areas. Therefore, we only considered the papers that explicitly highlight specific applications rather than just solving a general problem theoretically. Note that, there are some papers, such as Albareda-Sambola et al. (2009) that do not explicitly discuss an urban perspective, however, they can be implemented for urban service facility location. We have not included such papers so that we make sure only explicitly application-oriented OR research is included. Moreover, this strategy will limit the number of papers in the scope of the research so that the authors will be able to analyze all the papers on a micro level.
- We did not limit the search to a specific period. However, the results show that the area has drawn significant attention since the early 1970s and reached maturity from 2003 onward.

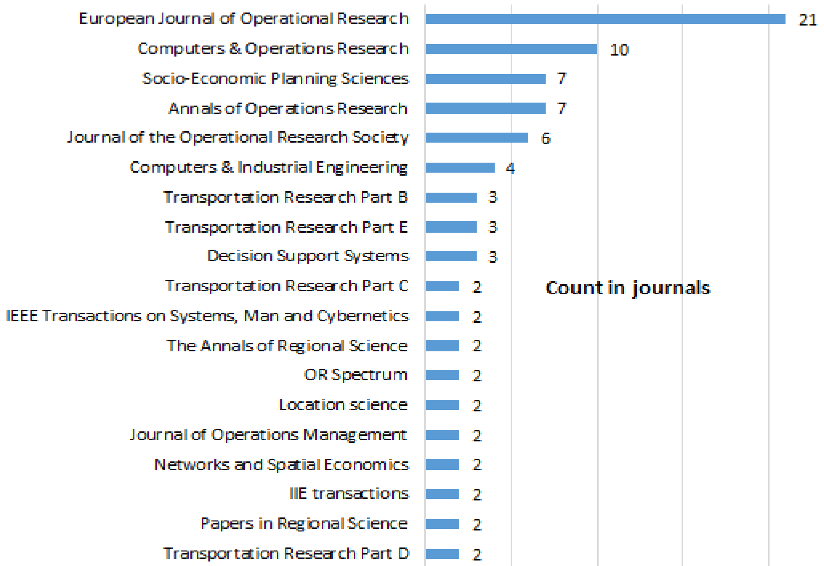


**Figure 2:** Top 20 journals in terms of frequency of the papers relevant to the USFL.

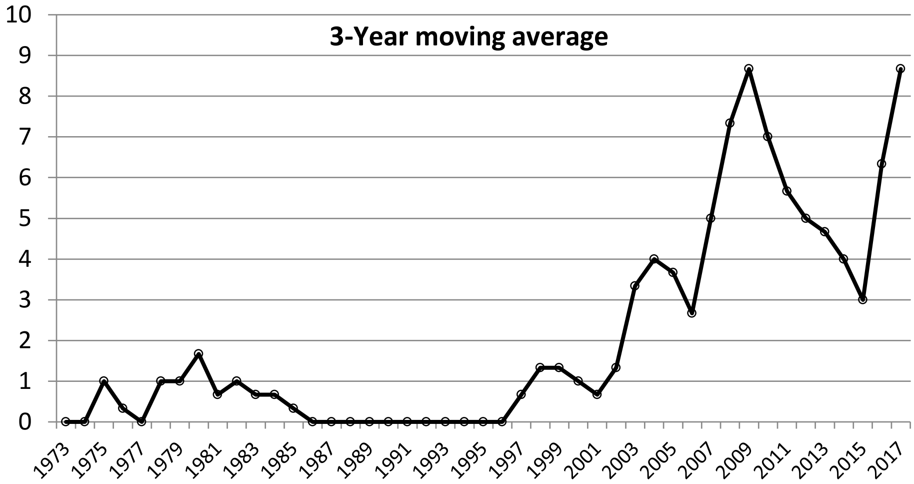


**Figure 3:** Three-Year Moving Average of the Count of the Papers.

- The research focuses on peer-reviewed journal papers rather than books, book chapters or conference papers. Initally, we did not limit our search to any specific journals. In the following step, in order to ensure the quality of the investigated papers, we only admitted the papers that are either in the Academic Journal Guide (AJG) 2018 Chartered Association of Business Schools or the Australian Business Deans Council (ABDC) 2018 journal quality list. Interestingly, the relevant shortlisted papers are mostly from OR journals, where the European Journal of Operational Research (EJOR) heads the list. Figure 2 shows the top 20 journals in terms of frequency of the papers we have found relevant to the USFL.
- Given the abovementioned criteria, we identified a total of 110 papers. Table 1 shows these papers and are organized into six categories; each of these categories will be briefly explained in the subsection below. The categories in Table 1 are sorted in terms of the frequency of the papers from highest to lowest. To make subsequent report generation easier, we have assigned a code to each paper.

**Table 1.** Coded references for the main applications.

| Code | Waste management system *(17 papers)* | Code | Small-scale emergency *(18 papers)* | Code | Transportation *(19 papers)* |
|---|---|---|---|---|---|
| [WMS1] | Khan (1987) | [SSE1] | Berlin & Liebman (1974) | [TSI1] | Jarvis et al. (1978) |
| [WMS2] | Giannikos (1998) | [SSE2] | Aly & White (1978) | [TSI2] | Hamacher et al. (2002) |
| [WMS3] | Killmer et al. (2001) | [SSE3] | Fitzsimmons & Srikar (1982) | [TSI3] | Murray (2003) |
| [WMS4] | Rakas et al. (2004) | [SSE4] | Marianov & ReVelle (1996) | [TSI4] | Skriver & Andersen (2003) |
| [WMS5] | Alumur & Kara (2007) | [SSE5] | Gendreau et al. (1997) | [TSI5] | Farhan & Murray (2006) |
| [WMS6] | Caballero et al. (2007) | [SSE6] | Badri et al. (1998) | [TSI6] | Horner & Groves (2007) |
| [WMS7] | Eiselt (2007) | [SSE7] | Gendreau et al. (2006) | [TSI7] | Farhan & Murray (2008) |
| [WMS8] | Boffey et al. (2008) | [SSE8] | Araz et al. (2007) | [TSI8] | Geroliminis et al. (2009) |
| [WMS9] | Erkut et al. (2008a) | [SSE9] | Yang et al. (2007) | [TSI9] | Wang & Wang (2010) |
| [WMS10] | Cruz-Rivera & Ertel (2009) | [SSE10] | Cheu et al. (2008) | [TSI10] | Geroliminis et al. (2011) |
| [WMS11] | Mitropoulos et al. (2009) | [SSE11] | Erkut et al.(2008b) | [TSI11] | Tu et al. (2016) |
| [WMS12] | Mar-Ortiz et al. (2011) | [SSE12] | Ingolfsson et al. (2008) | [TSI12] | Ghamami et al., (2016) |
| [WMS13] | Coutinho-Rodrigues et al. (2012) | [SSE13] | Rajagopalan et al. (2008) | [TSI13] | He et al. (2016) |
| [WMS14] | Toso & Alem (2014) | [SSE14] | Geroliminis et al. (2009) | [TSI14] | Hong & Kuby (2016) |
| [WMS15] | Asefi et al. (2015) | [SSE15] | Hsia et al. (2009) | [TSI15] | Huang et al. (2016) |
| [WMS16] | Hu et al. (2017) | [SSE16] | Curtin et al. (2010) | [TSI16] | Gupta & Basak (2017) |
| [WMS17] | Olapiriyakul (2017) | [SSE17] | Geroliminis et al. (2011) | [TSI17] | He et al. (2017) |
| **Large-scale disaster** *(22 papers)* | | [SSE18] | Berman et al. (2013) | [TSI18] | Mohammed & Wang (2017) |
| [LSD1] | Current & O'Kelly (1992) | **General service and infrastructure** *(22 papers)* | | [TSI19] | Teye et al. (2017) |
| [LSD2] | O'Kelly & Murray (2004) | [GSI1] | Cohon et al. (1980) | **Non-emergency healthcare** *(12 papers)* | |
| [LSD3] | Chang et al. (2007) | [GSI2] | Greenhut & Mai (1980) | [NEH1] | Calvo & Marks (1973) |
| [LSD4] | Jia et al. (2007a) | [GSI3] | Murray & Gerrard (1997) | [NEH2] | Love & Trebbi (1973) |
| [LSD5] | Jia et al. (2007b) | [GSI4] | Bruns et al. (2000) | [NEH3] | Tien et al. (1983) |
| [LSD6] | Lee et al. (2009) | [GSI5] | Johnson (2003) | [NEH4] | Galvao et al. (2002) |
| [LSD7] | Huang et al. (2010) | [GSI6] | Melachrinoudis & Xanthopulos (2003) | [NEH5] | Johnson et al. (2005) |
| [LSD8] | Görmez et al. (2011) | [GSI7] | Suzuki & Hodgson (2003) | [NEH6] | Galvão et al. (2006) |
| [LSD9] | Lin et al. (2012) | [GSI8] | Wang et al. (2003) | [NEH7] | Doerner et al. (2007) |
| [LSD10] | Murali et al. (2012) | [GSI9] | Wu & Lin (2003) | [NEH8] | Syam & Côté (2010) |
| [LSD11] | Yushimito et al. (2012) | [GSI10] | Pizzolato et al. (2004) | [NEH9] | Mestre et al. (2012) |
| [LSD12] | An et al. (2013) | [GSI11] | Johnson (2006) | [NEH10] | Beliën et al. (2013) |
| [LSD13] | Lu & Sheu (2013) | [GSI12] | Teixeira & Antunes (2008) | [NEH11] | Guerriero et al. (2016) |
| [LSD14] | Salman & Gul (2014) | [GSI13] | Aldajani & Alfares (2009) | [NEH12] | Ratick et al. (2016) |
| [LSD15] | Hu et al. (2015) | [GSI14] | Lee & Xiao (2009) | | |
| [LSD16] | Wei & Murray (2015) | [GSI15] | Koçak (2010) | | |
| [LSD17] | Charles et al. (2016) | [GSI16] | Tuzun Aksu & Ocak (2012) | | |
| [LSD18] | Moreno et al. (2016) | [GSI17] | Kose & Karabay (2016) | | |
| [LSD19] | Oğuz et al. (2016) | [GSI18] | Pelegrín et al. (2016) | | |
| [LSD20] | Paul & MacDonald (2016) | [GSI19] | Tian et al. (2016) | | |
| [LSD21] | Baskaya et al. (2017) | [GSI20] | Zhang et al. (2016) | | |
| [LSD22] | Chowdhury et al. (2017) | [GSI21] | North & Miller (2017) | | |
| | | [GSI22] | Yan et al. (2017) | | |

## 2.3. Observing USFL Applications in the Literature

When it comes to the application of USFL models, our observation shows that the existing papers in the scope of this survery fall within six categories. Therefore, before analyzing the literature in the field from an OR perspective, we provide a brief explanation for each applied category as follows:

**Waste management systems (WMS):** WMS relates to any activity related to collection, transportation, treatment, recycling, incineration and disposal of waste in alignment with rules and regulations. Looking at the trend in the papers in this category, we learn that since the late 1980s this area has always been important in the literature and we predict that this trend will continue in future as well.

**Large-scale disasters (LSD):** Some facilities are located in urban areas to serve in case of disasters. Disasters can be natural or caused by humans. Man-made disasters are caused by either inadvertent human error or terrorist attacks. Disasters are managed through a disaster management cycle (DMC) that consists of four phases: Mitigation, Preparation, Response and Recovery (Van Wassenhove 2006; Altay & Green III 2006; Gupta et al. 2016). Of course the FEMA (Federal Emergency Management Agency) and the US DHS (Department of Homeland Security) replaced Preparation with Prevention and Protection (National Preparedness Goal 2015).

**Small-scale emergency (SSE):** SSEs are similar to LSDs in terms of facing emergency situations. Their main differences are their magnitude and frequency. In other words, SSEs are more frequent but with a smaller magnitude than LSDs. Their higher frequency makes them difficult to manage while providing ample historical data to analyze. Although the magnitude of SSEs is lower than that of LSDs, we cannot ensure their incurred cost is lower because of their frequency; therefore, both categories are highly important in practice.

**General services and infrastructure (GSI):** Public or private service facilities in areas such as banking, education (school, pre-school and primary school), postal services, shopping centers, computer services (e.g. DSL and authentic network), utilities (e.g. power plants) and housing (e.g. real estate) fall within this category. These facilities can take the form of small, medium or large-sized individual or network organizations.

**Non-emergency healthcare systems (NEH):** We have dedicated a category to non-emergency health systems because of their popularity and the existence of a significant number of papers in the area. In fact, the number of papers related to health is more than what we see in the NEH category. In this category, we only investigate non-emergency facilities and other related emergency facilities (e.g. accident and emergency) are covered under SSE. Another reason for paying special attention to this category is its increasing trend over time. While most of the papers in this area are related to general and professional hospitals, some other facilities within this category, such as senior citizen centers or retirement homes are becoming important due to an aging population.

**Transportation systems' infrastructure (TSI):** Transportation modes include land (roads and train), water (ships and boats), air (airplanes) and pipes (such as oil and gas). In urban areas, the land transportation mode is more prevalent than the others. When it comes to the air transportation mode, their fixed entities such as airports sometimes fall within urban areas. Canals are also a part of water transportation modes that are used in some urban areas. Transportation systems consist of three main components: (1) fixed entities (e.g. roads, airports, pipelines and bus stops), (2) moving entities (e.g. airplanes, trains, oil, gas and buses), and (3) control systems installed in either fixed or moving entities. In terms of facility location in urban areas, it seems that locating fixed entities such as bus stops and airports have more applications than the others.

## 3. TYPE OF DECISIONS, LOCATION SPACE AND MAIN ASSUMPTIONS

In this section, according to Table 2, we first discuss the commonalities observed in various applications of USFL models related to the types of decisions, location space and main assumptions. Then, we highlight the factors that differentiate these applications.

### 3.1. Type of decisions

According to the scope of the research, we only focus on the location decisions in USFL models. However, there are some applied research studies in which other joint decisions, namely, allocation and routing, are also made. The trend in making joint decisions has increased over time. This is quite sensible both practically and from an OR point of view since joint decisions result in higher cost savings than hierarchically made decisions. Interestingly, the majority of OR-based USFL applications focus on location-allocation – which is a joint decision – rather than pure locational decisions. Subsequently, pure location and location-routing decisions have been considered in the literature. The superiority in the number of papers in location-allocation over pure locational decisions is more significant in WMS, LSD, SSE and NEH than GSI and TSI.

**Application-specific decisions**

Generally, in all of the application areas, the most popular decision is location-allocation. Except in WMS, in all other areas, after location-allocation decision, location and location-routing decisions are prevalent, respectively. Only in WMS, location decision appears as the least popular decision.

***WMS:*** We observe that the number of papers considering single and multiple facility types are almost the same. Moreover, there is no paper considering continuous space. Practically, after making some strategic decisions on WMS facilities, other tactical and operational decisions need to be made. Critically, we believe that while routing and allocation decisions have already been explored, other tactical and operational decisions such as inventory, transportation, fleet-sizing and relocation can also be made concurrently which could be an area of focus in future research.

***LSD:*** The trend in studies reveals the continuous popularity of location-allocation formulations. In the early 2000s, a greater number of studies tended to focus on location problems and since 2010 the number of location-allocation formulations has increased while location problems have lost momentum. The majority of the LSD papers investigate location-allocation and only a few focus on location-routing. This pattern is sensible because location-routing is more required in the response phase of a disaster when there is not much time for modeling and optimization. On the other hand, location-allocation is also required in all other phases and particularly in preparation and mitigation (the recovery phase is not urgent in terms of time limit). We believe future research should (1) link the location decisions with the phases in DMC; (2) be more disaster specific than generic; and (3) ideally, should integrate pre-disaster phases (mitigation and preparedness) and post-disaster phases (response and recovery).

***SSE:*** We observe that there is no paper on location-routing decision. Moreover, over time, the trend shows most research papers have shifted from location-allocation decision to location only. Considering the nature of SSE facilities (e.g. ambulances and fire stations), it is reasonable that for frequent emergencies, response time is very important. On the other hand, there should be a balance among workloads of serving facilities so that they are not occupied when needed. However, it seems there are other possible joint decisions that have been neglected in the literature. For example, models such as location-routing, location-inventory and location-relocation (for mobile facilities) can also be considered in further research.

***GSI:*** Since GSI covers a wide range of service facilities and, unlike the previous categories, there is no significant difference between the share of papers on location and location-allocation. Chronologically, in the late 1990s and early 2000s most of the papers focused on locating general services and infrastructures but recently location-allocation models have become more popular. It is surprising that with this wide range of applications there is only one joint decision other than location-allocation (i.e. on location routing). For example, there is no paper focusing on location-routing problems. Location-routing is applied to systems in which several facilities are involved in distribution or collection. For example, if we consider the application of retail chains then location-routing could result in huge savings in the system when opening a new branch. As another example, bus services collect students and drop them off at schools every day. This problem has already been studied in the context of VRP but locational decisions can also be added to achieve additional cost savings in finding the location of garages and bus stops. Note that allocation is a strategic decision but routing is a tactical or operational decision. We can make routing decisions if we have information about the day-to-day operations. This shows there are some gaps in the application that can provide us with some future research directions. The majority of GSI facilities are public or governmental with concerns about not only economic aspects (e.g. cost and profit) but also social factors such as accessibility, coverage, fairness and equity. GSI facilities are either individual entities (not chain facilities) or managed individually; e.g. schools in a council are public facilities which are not linked to each other.

***NEH:*** Since NEH facilities provide health services to the public, their accessibility from residential areas is very important. The most popular strategy is "allocating" to ensure the accessibility of each district to at least one NEH facility. That is why we observe that most NEH papers address location-allocation problems rather than only the locational decision. But facility location is also popular in this area. Location-routing is used in one application where a series of users are supposed to be served by mobile facilities which then have to return to a central base (called depot in the classic literature of VRP). We expect to see more papers on location-routing in the future.

***TSI:*** Location and location-allocation problems are almost of equal importance in TSI models. When locating a private facility, e.g. to minimize total cost, location models are more appropriate. But when we intend to locate public facilities to serve people in an urban area then location-allocation is a better option for TSI facilities. We found that few location-routing papers have been investigated. Some location-routing applications can still be investigated in this category. For example, bus stops are good examples of location-routing when (i) we locate bus stops and (ii) determine their sequence to be visited by buses that depart from the main terminal and collect or drop off passengers. Some other similar applications can be developed for TSI in urban areas. Considering the nature of transportation systems, it is expected that more studies will focus on location-routing issues in future research.

### 3.2. Assumptions on location space and nature of facilities

From Table 2, we observe that for all USFL applications, the number of papers that consider multiple facility location models are much higher than single facility models. This seems rational because in all these applications we usually deal with more than one facility. This trend will also continue in the future. But surprisingly, in majority of the applications, all facilities are of the same type (single-type facilities) and this does not reflect the reality. Perhaps the reason is that – unlike what is demanded in practice– considering multiple type facilities makes the problem much more difficult in terms of complexity, solution techniques and run times. Differences between facilities in type is a technological reality and they can also be different in their capacities. However, we expect to see more multiple-type facility location models in the USFL in the future to bridge this gap between theory and practice. The only exception is NEH in which multiple type facilities have been widely studied.

Another observation in terms of location space is that majority of the papers consider a discrete location space. This seems reasonable because, in reality, we normally deal with discrete locations as we are not allowed to locate a facility anywhere in the urban area and discrete models ensure that barriers are avoided. Another reason for this observation is that discrete problems seem to be easier to formulate. Some papers consider location on a network. Network problems are also important and need to receive more attention since in urban areas the majority of facilities are located on connecting roads and are actually network problems. Rarely do papers consider location in a continuous space. Even in some applications such as NEH, WMS and SSE, there is no paper on a continuous plane. In, LSD, TSI and GSI there are some papers on continuous location space. Since we study the problem in urban areas we should expect the continuous plane to be investigated less unless it is used as an approximation tool or it is of the type of facility location with barriers. However, we believe that in large cities, considering continuous space may provide a useful approximation which is neglected in the literature. Moreover, while discrete space is easy to formulate it is not necessarily easy to solve in terms of computational efforts. Note that discrete and continuous spaces are both approximation approaches because (i) in discrete spaces we cannot make a list of many potential points; even if we do so, such a problem cannot be solved computationally; (ii) in continuous spaces barrier regions should be avoided. Therefore, considering continuous space as a possible approach can be tested.

Overall, it seems in those facilities mainly controlled by local authorities and governments (e.g. WMS), covering a fairly wide region with a single facility is impossible; multiple facilities are more appropriate in these areas. For large private organizations such as supermarket chains, multiple facilities should be considered; otherwise, single facility location is more appropriate. Note that, sometimes, organizations prefer to solve a districting problem first to partition an urban area into several regions and then solve a single facility location problem in each region. In this case, they are somehow converting a multiple facilities location problem into several single facility location ones.

We observe that USFL models in the areas related to health and emergency are more mature than the others. For example, facility location area in LSD problems include studies in all three categories of discrete, network and continuous space. As another example, in SSE, instead of having a facility with a large capacity, planners tend to locate multiple facilities with smaller capacities to ensure response times in emergency situations. However, the NEH area is more mature than previously studied areas in terms of location space because (1) the majority of the papers in the area consider multi-type facilities rather than single type, (2) most of the papers consider multi-facility models rather than a single facility, and (3) discrete and network facility location models have been more or less investigated. Perhaps the reason is that NEH facilities have a bigger impact both economically and socially when compared with most of the other areas. We believe this trend will continue in the future.

**Table 2.** Type of decisions, location space and main assumptions for various applications of USFL models.

| Year | Code | Type of decisions | | | Type of facilities | | No. of facilities | | Type of space | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Location | Location-allocation | Location-routing | Single | Multiple | Single | Multiple | Discrete | Continuous | Network |
| 1987 | [WMS1] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| 1998 | [WMS2] | | | ✓ | ✓ | | | ✓ | | | ✓ |
| 2001 | [WMS3] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| 2004 | [WMS4] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| 2007 | [WMS5] | | | ✓ | | ✓ | | ✓ | ✓ | | |
| | [WMS6] | | | ✓ | ✓ | | | ✓ | ✓ | | |
| | [WMS7] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| 2008 | [WMS8] | | | ✓ | ✓ | | ✓ | | ✓ | | |
| | [WMS9] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| 2009 | [WMS10] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| | [WMS11] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| 2011 | [WMS12] | | | ✓ | | ✓ | | ✓ | ✓ | | ✓ |
| 2012 | [WMS13] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| 2014 | [WMS14] | ✓ | | | | ✓ | | ✓ | ✓ | | |
| 2015 | [WMS15] | | | ✓ | | ✓ | | ✓ | ✓ | | ✓ |
| 2017 | [WMS16] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| | [WMS17] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| **% WMS papers** | | 24 | 41 | 35 | 47 | 53 | 6 | 94 | 94 | 0 | 18 |
| 1992 | [LSD1] | | ✓ | | | ✓ | | ✓ | | | ✓ |
| 2004 | [LSD2] | ✓ | | | ✓ | | | ✓ | ✓ | | ✓ |
| 2007 | [LSD3] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| | [LSD4] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| | [LSD5] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| 2009 | [LSD6] | | ✓ | | | ✓ | | ✓ | ✓ | | ✓ |
| 2010 | [LSD7] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| 2011 | [LSD8] | ✓ | | | | ✓ | | ✓ | ✓ | | |
| 2012 | [LSD9] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| | [LSD10] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| | [LSD11] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| 2013 | [LSD12] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| | [LSD13] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| 2014 | [LSD14] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| 2015 | [LSD15] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| | [LSD16] | | ✓ | | | ✓ | | ✓ | | ✓ | |
| 2016 | [LSD17] | | ✓ | | | ✓ | ✓ | | ✓ | | |
| | [LSD18] | | | ✓ | | ✓ | | ✓ | ✓ | | |
| | [LSD19] | ✓ | | | ✓ | ✓ | | ✓ | ✓ | | |
| | [LSD20] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| 2017 | [LSD21] | | ✓ | | ✓ | ✓ | | ✓ | ✓ | | |
| | [LSD22] | | ✓ | | | ✓ | | ✓ | | ✓ | |
| **% LSD papers** | | 23 | 73 | 5 | 55 | 55 | 5 | 91 | 86 | 9 | 14 |
| 1974 | [SSE1] | | ✓ | | ✓ | | | ✓ | ✓ | | ✓ |
| 1978 | [SSE2] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| 1982 | [SSE3] | | ✓ | | ✓ | | | ✓ | | | ✓ |
| 1996 | [SSE4] | | ✓ | | ✓ | | | ✓ | ✓ | | ✓ |
| 1997 | [SSE5] | | ✓ | | ✓ | | | ✓ | | | ✓ |
| 1998 | [SSE6] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| 2006 | [SSE7] | ✓ | | | ✓ | | | ✓ | ✓ | | ✓ |
| 2007 | [SSE8] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| | [SSE9] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| 2008 | [SSE10] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| | [SSE11] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| | [SSE12] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| | [SSE13] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| 2009 | [SSE14] | | ✓ | | ✓ | | | ✓ | | | ✓ |
| | [SSE15] | ✓ | | | ✓ | | ✓ | | ✓ | | |
| 2010 | [SSE16] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| 2011 | [SSE17] | | ✓ | | ✓ | | | ✓ | | | ✓ |
| 2013 | [SSE18] | ✓ | | | | ✓ | | ✓ | | | ✓ |
| **% SSE papers** | | 50 | 50 | 0 | 89 | 11 | 6 | 94 | 72 | 0 | 44 |
| 1980 | [GSI1] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| | [GSI2] | ✓ | | | ✓ | | ✓ | | ✓ | | |
| 1997 | [GSI3] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| 2000 | [GSI4] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| 2003 | [GSI5] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| | [GSI6] | ✓ | | | ✓ | | ✓ | | | ✓ | |
| | [GSI7] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| | [GSI8] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| | [GSI9] | | ✓ | | ✓ | | | ✓ | | | ✓ |
| 2004 | [GSI10] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| 2006 | [GSI11] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| 2008 | [GSI12] | ✓ | | | | ✓ | | ✓ | ✓ | | |
| 2009 | [GSI13] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| | [GSI14] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| 2010 | [GSI15] | ✓ | | | ✓ | | ✓ | | ✓ | | |
| 2012 | [GSI16] | ✓ | | | ✓ | | | ✓ | ✓ | ✓ | |
| 2016 | [GSI17] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| | [GSI18] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| | [GSI19] | | ✓ | | ✓ | | | ✓ | | ✓ | |
| | [GSI20] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| 2017 | [GSI21] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| | [GSI22] | | ✓ | ✓ | ✓ | | | ✓ | | | ✓ |
| **% GSI papers** | | 41 | 59 | 5 | 73 | 27 | 14 | 86 | 82 | 14 | 9 |
| 1973 | [NEH1] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| | [NEH2] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| 1983 | [NEH3] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| 2002 | [NEH4] | ✓ | | | | ✓ | | ✓ | ✓ | | |
| 2005 | [NEH5] | | ✓ | | | ✓ | | ✓ | ✓ | | |
| 2006 | [NEH6] | ✓ | | | | ✓ | | ✓ | ✓ | | |
| 2007 | [NEH7] | | | ✓ | ✓ | | ✓ | | ✓ | | ✓ |
| 2010 | [NEH8] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| 2012 | [NEH9] | ✓ | | | | ✓ | | ✓ | ✓ | | |
| 2013 | [NEH10] | ✓ | | | | ✓ | | ✓ | ✓ | | |
| 2016 | [NEH11] | | ✓ | | | ✓ | | ✓ | ✓ | | ✓ |
| | [NEH12] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| **% NEH papers** | | 42 | 50 | 8 | 25 | 75 | 8 | 92 | 100 | 0 | 17 |
| 1978 | [TSI1] | | | ✓ | ✓ | | | ✓ | ✓ | | |
| 2002 | [TSI2] | ✓ | | | ✓ | | ✓ | | | | ✓ |
| 2003 | [TSI3] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| | [TSI4] | ✓ | | | ✓ | | ✓ | | | ✓ | ✓ |
| 2006 | [TSI5] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| 2007 | [TSI6] | ✓ | | | ✓ | | | ✓ | ✓ | | ✓ |
| 2008 | [TSI7] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| 2009 | [TSI8] | | ✓ | | ✓ | | | ✓ | | | ✓ |
| 2010 | [TSI9] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| 2011 | [TSI10] | | ✓ | | ✓ | | | ✓ | | | ✓ |
| 2016 | [TSI11] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| | [TSI12] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| | [TSI13] | ✓ | ✓ | | ✓ | | | ✓ | ✓ | | |
| | [TSI14] | | | ✓ | ✓ | | | ✓ | | | ✓ |
| | [TSI15] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| 2017 | [TSI16] | | | ✓ | | ✓ | | ✓ | ✓ | | |
| | [TSI17] | ✓ | | | ✓ | | | ✓ | ✓ | | |
| | [TSI18] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| | [TSI19] | | ✓ | | ✓ | | | ✓ | ✓ | | |
| **% TSI papers** | | 42 | 47 | 16 | 95 | 5 | 11 | 89 | 74 | 5 | 32 |
| **% TOTAL** | | **36** | **55** | **11** | **66** | **35** | **8** | **92** | **84** | **5** | **22** |

## 4. MAIN INPUT PARAMETERS AND THEIR NATURE

In this section, according to Table 3, first we provide a description of the commonalities we observed in various applications of USFL models related to the main input parameters. Then, we highlight the observations that differentiate these applications.

### 4.1. Input parameters

Referring to the core of the basic facility location models, the usual input data required in these problems are the number and location of existing facilities, potential locations of new facilities, the number of facilities to be located, costs of locating and serving (i.e. fixed costs of opening, operation or transportation), capacity (or maximum capacity) of new facilities to be located, distance (between new facilities and also demand nodes), response time, service level. The potential location of facilities is used as input in around 50% of the papers. However, the popularity of technologies such as GPS (global positioning system) and Maps (particularly Geographic Information Systems) leads us to believe that in real-world applications potential locations tend to be known more often.

**Application-specific parameters**

***WMS:*** There are some inputs that are not commonly used. Quantity of waste disposed in landfills, types of waste materials, treatment technologies and the budget available for opening and operating facilities are examples of these parameters which are application dependent.

***LSD:*** The inputs in LSD models are of practical nature: priorities of demand points and minimum number of facilities at specific demand points to ensure coverage. Critically, we observe the less common inputs are probability of natural disaster, probability of facility disruption, attributes of evacuation vehicles (such as their number, travel speed, capacity and response time for each demand region) and available budget. Unlike in the past, we believe these are important input parameters that need to be considered in future research.

***SSE:*** Some papers in the area have used some specific inputs in their formulations. Among these inputs are maximum and minimum deviations from the goals, maximum number of facilities simultaneously utilized, delay times, average service rates, reliability level, the probability of unavailability of facilities and preference for locations for locating facilities. It seems these parameters are related to some constraints that try to ensure people living in various districts receive a minimum service in emergency situations. Moreover, terms such as reliability and service level reflect the probabilistic nature of some data and the existence of historical data because of the frequent nature of these emergencies. We predict this trend will continue in future research.

***GSI:*** In addition to the abovementioned parameters, some other inputs are used in GSI. They are age of facilities, minimum age of facilities to close them, annual net economic benefits, welfare weight, coverage standards of a facility, weights of demand points and service margins.

***NEH:*** Various parameters used in the area such as the penalty cost of not treating the patients, treatment cost per patient and operation cost are applicable to NEH facilities. A significant number of the papers use the number of hierarchies (if a hierarchical facility location model is implemented), shortest distance between facilities, minimum staff level, staffing per patient, share of demand flow between facilities, length of stay in any facility, working time of personnel, setup time per member of staff, the number of physicians and their capabilities, types of services, utility value of each potential site, weight of demand points, service loads in each period and service rate of any service unit. It seems there is a fairly comprehensive list of input parameters in the literature of NEH that can assist with the models developed by researchers in the future.

***TSI:*** Depending on the application, some special-purpose parameters are also used. Among them we can name traffic flow and time on roads, minimum demand for constructing a facility, weights of location sites, acceptable service standard, confidence levels and the average travel speed on roads.

### 4.2. Nature of the parameters

The input parameters can be static, dynamic, deterministic, probabilistic/stochastic and fuzzy. Note that these classifications are not mutually exclusive. For example, the type of parameter can be static or dynamic; if the value of a static parameter is known then it can also be considered deterministic. Two reasons made us consider one column for probabilistic/ stochastic while these two terms are different: (i) Scarcity of papers in at least one of these areas in each application; (ii) moreover, many authors have used these terms interchangeably.  There is only one model with fuzzy parameters (i.e. SSE9); therefore, we did not consider any column for that in the table.

The majority of papers in all USFL applications study static and deterministic categories with no apparent trend change during the period under study. Obviously, older papers mainly focused on deterministic and static parameters while recently, dynamic and stochastic input parameters are being considered more and more. The differentiation among various USFL applications in terms of the nature of the input parameters follows.

***WMS:*** Only recently have scholars tended to shift from static problems to dynamic versions in WMS which seems reasonable as it is more realistic. Regarding the nature of problems in WMS, more dynamic models as well as probabilistic/ stochastic models need to be formulated. However, there is still a large gap for dynamic and fuzzy problems which are expected to be considered more in future. In particular, dynamics of urban areas and uncertainty (e.g. in waste generated by households) are in line with the nature of WMS problems.

***LSD:*** We believe stochastic and dynamic models are more realistic but they may need historical data. For example, some disasters are low-probability-high-consequence events and there is a lack of sufficient historical data to satisfactorily fit a probability density function.

***SSE:*** The types of models focused on SSE are fairly diverse. Although the majority of the papers are static, a few dynamic models also exist. The number of papers with deterministic and probabilistic/ stochastic models is almost the same. We suggest dynamic and stochastic models be the focus of SSE research studies in the future. However, we do not believe using fuzzy formulations is appropriate for these problems because there is sufficient quantitative historical data about such problems so as to be able to determine and fit the appropriate probabilistic distributions.

***GSI:*** There are some probabilistic/ stochastic papers but there is no research on fuzzy environments. There is no paper with dynamic parameters. It seems GSI location models have been formulated roughly and simply. There are many gaps in this area. Perhaps not knowing enough about the benefits of location analysis and not paying enough attention to the economic benefits of such research have resulted in poor investment in collecting data and conducting such projects.

***NEH:*** There are a few NEH papers considering dynamic and probabilistic/stochastic aspects of the parameters. We do not recommend fuzzy parameters as there is sufficient quantitative historical data within health systems that can be exploited in modeling. However, if dynamic and seasonality aspects of this data are considered, then more precise models will be generated. The same logic applies to the randomness of some data.

***TSI:*** Recent TSI papers consider dynamic and probabilistic/ stochastic input parameters as well. This shows that models are becoming more realistic and are taking advantage of historical data. We believe this trend will be ongoing in the future and we will see fewer studies with solely static and deterministic parameters. However, fuzzy models will not be interesting in such unambiguous environments with sufficient quantitative data.

**Table 3.** Main input parameters for various applications of USFL models.

| Year | Code | Nature of inputs: Static | Dynamic | Deterministic | Stochastic / Probabilistic | Input parameters: Costs | Distance | Number of facilities | Capacity | Potential location of facilities | Amount of demand | Demand points | Min no. of facilities to be served | Service level | Response time | Other inputs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1987 | [WMS1] | ✓ | | ✓ | | ✓ | | | ✓ | ✓ | | ✓ | | | | ✓ |
| 1998 | [WMS2] | ✓ | | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | | | |
| 2001 | [WMS3] | ✓ | | | ✓ | | | | | | | | | | | ✓ |
| 2004 | [WMS4] | ✓ | | ✓ | | | | | ✓ | | ✓ | | | | | |
| 2007 | [WMS5] | | | ✓ | | ✓ | | ✓ | ✓ | | ✓ | | | | | |
| | [WMS6] | | | ✓ | | | | ✓ | ✓ | | | | | | | |
| | [WMS7] | ✓ | | ✓ | | | | ✓ | | | | | | | | |
| 2008 | [WMS8] | ✓ | | ✓ | | | | ✓ | | | | | | | | |
| | [WMS9] | ✓ | | ✓ | | | | | ✓ | | ✓ | | | | | |
| 2009 | [WMS10] | ✓ | | ✓ | | | | | | | ✓ | | | | | |
| | [WMS11] | ✓ | | ✓ | | ✓ | | | ✓ | | ✓ | | | | | ✓ |
| 2011 | [WMS12] | ✓ | | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | | | ✓ |
| 2012 | [WMS13] | ✓ | | ✓ | | | | | | ✓ | ✓ | | | | | ` |
| 2014 | [WMS14] | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | | | | | ✓ |
| 2015 | [WMS15] | ✓ | | ✓ | | ✓ | | | ✓ | ✓ | | ✓ | | | | ✓ |
| 2017 | [WMS16] | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | ✓ |
| | [WMS17] | ✓ | | ✓ | | ✓ | ✓ | | ✓ | ✓ | | ✓ | | | | ✓ |
| **% WMS papers** | | 82 | 6 | 88 | 18 | 53 | 24 | 35 | 71 | 41 | 53 | 29 | 0 | 0 | 0 | 47 |
| 1992 | [LSD1] | ✓ | | ✓ | | ✓ | | | | ✓ | ✓ | ✓ | | | | ✓ |
| 2004 | [LSD2] | ✓ | | ✓ | | | | | | | | | | | | ✓ |
| 2007 | [LSD3] | ✓ | | | ✓ | ✓ | | | ✓ | | | ✓ | | | | ✓ |
| | [LSD4] | ✓ | | ✓ | | | | ✓ | | | ✓ | | ✓ | | | |
| | [LSD5] | ✓ | | | ✓ | | | ✓ | | ✓ | ✓ | ✓ | ✓ | | | ✓ |
| 2009 | [LSD6] | ✓ | | | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | | | | ✓ |
| 2010 | [LSD7] | ✓ | | ✓ | | | | ✓ | | | | | | | | |
| 2011 | [LSD8] | ✓ | | ✓ | | | | ✓ | ✓ | | ✓ | | | | | |
| 2012 | [LSD9] | | ✓ | ✓ | | | | ✓ | ✓ | | ✓ | | | | | ✓ |
| | [LSD10] | ✓ | | | ✓ | | | ✓ | ✓ | | | | | | | ✓ |
| | [LSD11] | ✓ | | ✓ | | | | ✓ | | | | | | | | |
| 2013 | [LSD12] | ✓ | | ✓ | ✓ | | | | | ✓ | | ✓ | | | | ✓ |
| | [LSD13] | ✓ | | | ✓ | | | ✓ | | | | | | | | |
| 2014 | [LSD14] | | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | | | | | | ✓ |
| 2015 | [LSD15] | ✓ | | | ✓ | | ✓ | | | ✓ | ✓ | | | | | ✓ |
| | [LSD16] | ✓ | | | ✓ | | | ✓ | | | ✓ | ✓ | | | | ✓ |
| 2016 | [LSD17] | | ✓ | ✓ | | ✓ | | | ✓ | ✓ | ✓ | ✓ | | | | ✓ |
| | [LSD18] | | ✓ | | ✓ | ✓ | | | ✓ | ✓ | | ✓ | ✓ | | | ✓ |
| | [LSD19] | ✓ | | ✓ | | | ✓ | | | ✓ | | ✓ | | | | |
| | [LSD20] | ✓ | | | | ✓ | | | ✓ | ✓ | | ✓ | | | | ✓ |
| 2017 | [LSD21] | ✓ | | ✓ | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | ✓ |
| | [LSD22] | ✓ | | | ✓ | ✓ | | ✓ | | | ✓ | ✓ | | | | ✓ |
| **% LSD papers** | | 82 | 18 | 55 | 45 | 36 | 18 | 55 | 45 | 45 | 45 | 55 | 14 | 0 | 0 | 73 |
| 1974 | [SSE1] | ✓ | ✓ | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | | | ✓ | ✓ |
| 1978 | [SSE2] | ✓ | | | ✓ | | | | | ✓ | ✓ | | | ✓ | ✓ | |
| 1982 | [SSE3] | | ✓ | | ✓ | | ✓ | | | ✓ | ✓ | ✓ | | | | ✓ |
| 1996 | [SSE4] | ✓ | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ |
| 1997 | [SSE5] | ✓ | | ✓ | | | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | | ✓ |
| 1998 | [SSE6] | ✓ | | ✓ | | ✓ | ✓ | ✓ | | ✓ | | | | | | ✓ |
| 2006 | [SSE7] | | ✓ | | ✓ | | | ✓ | | ✓ | ✓ | ✓ | | | | |
| 2007 | [SSE8] | ✓ | | ✓ | | | ✓ | | ✓ | | | | | | | |
| | [SSE9] | ✓ | | | | | | ✓ | | | | | | | | |
| 2008 | [SSE10] | ✓ | | | ✓ | | | | ✓ | | | | | | | |
| | [SSE11] | ✓ | | ✓ | | | ✓ | ✓ | | | | | | | | ✓ |
| | [SSE12] | ✓ | | | ✓ | | | | | | | | | ✓ | ✓ | ✓ |
| | [SSE13] | | ✓ | | ✓ | | | | | | | | | | | ✓ |
| 2009 | [SSE14] | ✓ | | | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | ✓ |
| | [SSE15] | ✓ | | ✓ | | | | | | | | | | | | ✓ |
| 2010 | [SSE16] | ✓ | | ✓ | | | ✓ | ✓ | | ✓ | | ✓ | | | ✓ | ✓ |
| 2011 | [SSE17] | ✓ | | | ✓ | | ✓ | | | ✓ | ✓ | ✓ | | | | ✓ |
| 2013 | [SSE18] | ✓ | | | ✓ | | ✓ | ✓ | | ✓ | | | | | | ✓ |
| **%SSE papers** | | 83 | 22 | 39 | 61 | 6 | 50 | 50 | 17 | 61 | 44 | 44 | 0 | 22 | 22 | 72 |

| Year | Code | Nature of inputs: Static | Dynamic | Deterministic | Stochastic / Probabilistic | Input parameters: Costs | Distance | Number of facilities | Capacity | Potential location of facilities | Amount of demand | Demand points | Min no. of facilities to be served | Service level | Response time | Other inputs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1980 | [GSI1] | ✓ | | ✓ | | | ✓ | | ✓ | ✓ | ✓ | | | | | ✓ |
| | [GSI2] | ✓ | | ✓ | | ✓ | | | | | ✓ | | | | | ✓ |
| 1997 | [GSI3] | ✓ | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ |
| 2000 | [GSI4] | ✓ | | ✓ | | | | | | | ✓ | | | | | |
| 2003 | [GSI5] | ✓ | | ✓ | | | | ✓ | | | ✓ | ✓ | | | | ✓ |
| | [GSI6] | ✓ | | ✓ | | | | ✓ | | | | | | | | |
| | [GSI7] | ✓ | | ✓ | | | | ✓ | | | ✓ | | | | | |
| | [GSI8] | ✓ | | ✓ | | | | ✓ | | | ✓ | | | | | |
| | [GSI9] | ✓ | | ✓ | | | | ✓ | | ✓ | ✓ | | | | | ✓ |
| 2004 | [GSI10] | ✓ | | ✓ | | | | ✓ | ✓ | | | | | | | |
| 2006 | [GSI11] | ✓ | | ✓ | | ✓ | ✓ | ✓ | | ✓ | | | | | | ✓ |
| 2008 | [GSI12] | ✓ | | ✓ | | | | ✓ | ✓ | | ✓ | | | | | ✓ |
| 2009 | [GSI13] | ✓ | | ✓ | | | | | | | | | | | | ✓ |
| | [GSI14] | ✓ | | ✓ | | | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | ✓ |
| 2010 | [GSI15] | ✓ | | ✓ | | | | | | | ✓ | | | | | ✓ |
| 2012 | [GSI16] | ✓ | | ✓ | | | ✓ | | | ✓ | ✓ | ✓ | | | | ✓ |
| 2016 | [GSI17] | ✓ | | ✓ | | ✓ | ✓ | | ✓ | ✓ | | ✓ | | | | ✓ |
| | [GSI18] | ✓ | | ✓ | | | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | ✓ |
| | [GSI19] | ✓ | | | ✓ | ✓ | | ✓ | | | | ✓ | | | | ✓ |
| | [GSI20] | ✓ | | | | ✓ | | ✓ | ✓ | ✓ | | ✓ | | | | |
| 2017 | [GSI21] | ✓ | | ✓ | | | ✓ | ✓ | | ✓ | | ✓ | | | | ✓ |
| | [GSI22] | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | | | | ✓ |
| **%GSI papers** | | 100 | 0 | 91 | 9 | 27 | 36 | 68 | 32 | 50 | 59 | 45 | 0 | 0 | 0 | 73 |
| 1973 | [NEH1] | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | ✓ |
| | [NEH2] | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ |
| 1983 | [NEH3] | ✓ | | ✓ | | | | ✓ | | | ✓ | | | | | ✓ |
| 2002 | [NEH4] | ✓ | | ✓ | | | ✓ | ✓ | | | ✓ | | | | | ✓ |
| 2005 | [NEH5] | ✓ | | ✓ | | | | | ✓ | | ✓ | | | | | |
| 2006 | [NEH6] | ✓ | | ✓ | | | ✓ | ✓ | | | ✓ | | | | | ✓ |
| 2007 | [NEH7] | ✓ | | ✓ | | | ✓ | | | | | | | | | ✓ |
| 2010 | [NEH8] | ✓ | | ✓ | | ✓ | ✓ | | ✓ | | | | | | | ✓ |
| 2012 | [NEH9] | ✓ | | ✓ | | ✓ | ✓ | | ✓ | | ✓ | | | | | ✓ |
| 2013 | [NEH10] | ✓ | | ✓ | | ✓ | ✓ | | | ✓ | ✓ | | | | | ✓ |
| 2016 | [NEH11] | ✓ | | ✓ | | | | | ✓ | | | | | | | ✓ |
| | [NEH12] | ✓ | | | ✓ | | ✓ | ✓ | | ✓ | | ✓ | | | | ✓ |
| **% NEH papers** | | 92 | 8 | 83 | 17 | 42 | 75 | 50 | 50 | 33 | 67 | 17 | 0 | 0 | 0 | 92 |
| 1978 | [TSI1] | ✓ | | ✓ | | | | ✓ | ✓ | ✓ | ✓ | | | | | |
| 2002 | [TSI2] | ✓ | | ✓ | | | | ✓ | | | | | | | | |
| 2003 | [TSI3] | ✓ | | ✓ | | | | ✓ | | | | | | | | |
| 2003 | [TSI4] | ✓ | | ✓ | | | | | | | ✓ | | | | | |
| 2006 | [TSI5] | ✓ | | ✓ | | | | ✓ | | ✓ | ✓ | ✓ | | | | |
| 2007 | [TSI6] | ✓ | | ✓ | | | | ✓ | | | ✓ | | | | | |
| 2008 | [TSI7] | ✓ | | ✓ | | | | ✓ | | | ✓ | | | | | ✓ |
| 2009 | [TSI8] | ✓ | | | ✓ | | ✓ | | | ✓ | ✓ | | | | | ✓ |
| 2010 | [TSI9] | ✓ | | ✓ | | | ✓ | | | | ✓ | | | | | |
| 2011 | [TSI10] | ✓ | | | ✓ | | ✓ | | | ✓ | ✓ | | | | | ✓ |
| 2016 | [TSI11] | | ✓ | ✓ | | | | ✓ | | ✓ | ✓ | ✓ | | | | ✓ |
| 2016 | [TSI12] | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | |
| 2016 | [TSI13] | ✓ | | ✓ | | | ✓ | ✓ | | ✓ | | ✓ | | | | |
| 2016 | [TSI14] | ✓ | | ✓ | | | | ✓ | | ✓ | | ✓ | | | | ✓ |
| 2016 | [TSI15] | ✓ | | ✓ | | ✓ | ✓ | | | ✓ | | ✓ | | | | ✓ |
| 2017 | [TSI16] | ✓ | | ✓ | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | ✓ |
| | [TSI17] | ✓ | | | ✓ | ✓ | | | | | | ✓ | | | | ✓ |
| | [TSI18] | ✓ | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | | | ✓ |
| | [TSI19] | ✓ | | | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | | | | ✓ |
| **% TSI papers** | | 95 | 5 | 79 | 32 | 26 | 42 | 63 | 26 | 63 | 58 | 53 | 0 | 0 | 0 | 53 |
| **% TOTAL** | | **89** | **10** | **72** | **31** | **31** | **38** | **55** | **39** | **50** | **54** | **43** | **3** | **4** | **4** | **67** |

***Note:*** There is only one paper ([SSE9]) that contains fuzzy parameters. In order to save space, we have not dedicated a column to fuzzy parameters for this paper

## 5. OBJECTIVE FUNCTIONS

In this section, according to Table 4, first we provide a description of the commonalities we observed in various applications of USFL models related to objective functions. Then, we highlight the observations that differentiate these applications.

### 5.1. Common observations

For most of the applications, the objective functions are economic or monetary and of the minimization type. In particular, cost minimization has consistently been considered over a long period of time. Specifically, the vast majority of the objective functions are of the minimization type for WMS, LSD and NEH, respectively. Some objective functions explicitly minimize cost components such as transportation of materials, startup/ opening/ installation operations and maintenance as well as the costs of unmet capacity. Many researchers divide the cost into fixed and variable costs and try to minimize the total annual operation costs or the total cost over a given time horizon. Even some other objective functions such as the minimization of travel distance/ weighted travel distance (as a proxy of accessibility) or the number of located facilities implicitly consider cost. When it comes to maximization-type objectives, maximization of coverage/ demand coverage (as another proxy for accessibility) as well as maximization of distance have been popular in various USFL applications.

Distance, risk and response time can be considered as a proxy of social objective functions. While in applications such as SSE and GSI some social objectives and a few environmental ones have been considered, a lack of environmental (e.g. noise and pollution levels) and social (e.g. fairness, accessibility and equity) objective functions in most USFL applications is another common observation. Additionally, considering objectives to reflect the environmental impact can be another area to develop. Obviously, simultaneous optimization of several objective functions (e.g. economic, social and environmental) will require multi-objective decision making. The trend suggests that cost is the main economic factor and will continue to be important in the future. However, two other criteria, social and environmental impact, will be added to the current economic function in future WMS problems. In fact, any other adverse impact on people's lives or nature needs to be somehow considered. For example, minimization of $CO_2$ emissions will be vitally important. There are many gaps in this area. Perhaps an issue in including social and environmental objectives is quantifying them. Lessons learned from GSI papers can help researchers to extend such practices to the other USFL applications. Additionally, analyzing trade-offs among the three sustainability pillars can provide insights for policy makers.

### 5.2. Application-specific objectives

***WMS:*** As expected, the maximization of objectives is not popular in WMS. The few maximization objectives specifically used in WMS are maximizing energy recovery and material recovery. WMS is the only application that explicitly considers social rejection/dissatisfaction as a social objective due to unpleasant nature of the problems in this area. Social opposition and dissatisfaction with facilities, minimizing risks and distance to demand points are also used in a few papers. Additionally, a few of the studies minimized some specific objectives such as greenhouse/global warming effects, final disposal to landfills and the number of people too close or too far from facilities.

***LSD:*** A few LSD papers consider the maximization-type objectives. In locating a facility to serve in case of disaster, we may minimize maximum distance from a vulnerable location. Unlike many other USFL models that consider minisum or maxisum objectives, many LSD models focus on maximin or minimax objectives. The reason is that OR modelers are supposed to treat emergency and non-emergency facilities differently depending on their danger level to avoid people being affected. Other less popular minimization objectives include minimum number of staff needed and uncovered demand. The trend in considering these objectives has been consistent over time.

***SSE:*** Minimization and maximization objectives are considered fairly equally in the SSE studies. In particular, "maximizing demand covered" is the most popular objective function in SSE. The reason is that SSE facilities are usually managed by public/governmental organizations. In emergency situations, it is important to ensure that the majority of the districts (if not all) are fairly covered. The other objectives that are maximized are the reliability of service, preferences for locations and population with back up coverage. Back up coverage is an old strategy but still important. In fact, in back up coverage, more than one facility is assigned to serve an existing facility to make sure when the first one is occupied, the standby server can still serve in an emergency situation. The objectives of the minimization type try to minimize response time and number of facilities as well as distance. Unlike many other USFL applications, current objective functions cover social aspects well which is because of the nature of the SSE facilities; it seems that the future objective functions will be more or less in line with the current trend. Perhaps the only development could be to incorporate environmental aspects which have a lower priority in emergency situations. We suggest, in addition to the cost components common among all other USFL applications, the cost of not responding to a demand is considered in SSE models.

***GSI:*** In addition to the abovementioned common objective functions, minimization of population exposure to facilities, maximization of social welfare, minimum distance between facilities and minimum distance from population centers have also been used in this application. It seems that the objective functions used for GSI facilities are richer than in other areas because they not only have a wider variety but also explicitly consider social and environmental objectives. This is partially because of the wide range of facilities that fall within this category. However, it could be used as a template for other categories to show how to form social and environmental objectives.

***NEH:*** Note that hospital waste management is different from general or recyclable waste management (that we considered in WMS) relative to householders because hospital waste is dangerous due to the possibility of infection and disease outbreak. In particular, environmental pollution at hospitals is an interesting objective in line with sustainability pillars. Considering utility for planning region and user satisfaction is also a possible extension.

***TSI:*** Interestingly, unlike most of the previously analyzed categories, in TSI models maximization objective functions are more common than minimization. Covered demand, service access and distance (from noisy and polluted facilities like airports) are other objectives that are maximized. In addition to the abovementioned objectives, the other prevalent economic objective functions are minimization of response time and deadhead time. The other possibilities for extension could be maximizing the service level provided by the facilities.

**Table 4.** Objective functions for various applications of USFL models.

| Year | Code | Minimization | | | | | | | Maximization | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Number of facilities | Distance | Cost | Social rejection/ Dissatisfaction | Risk | Response time | Other objectives | Coverage | Distance | Other objectives |
| 1987 | [WMS1] | | | ✓ | | | | | | | |
| 1998 | [WMS2]* | | | ✓ | ✓ | ✓ | | | | | |
| 2001 | [WMS3] | | | ✓ | | | | | | | |
| 2004 | [WMS4]* | | | ✓ | ✓ | | | | | | |
| 2007 | [WMS5]* | | | ✓ | | ✓ | | | | | |
| | [WMS6]* | | | ✓ | ✓ | | | | | | |
| | [WMS7] | | | ✓ | | | | | | | |
| 2008 | [WMS8]* | | | ✓ | | ✓ | | ✓ | | | |
| | [WMS9]* | | | ✓ | | | | ✓ | | | ✓ |
| 2009 | [WMS10] | | ✓ | ✓ | | | | | | | |
| | [WMS11] | | | ✓ | | | | | | | |
| 2011 | [WMS12] | | | ✓ | | | | | | | |
| 2012 | [WMS13]* | | | ✓ | ✓ | | | | | | |
| 2014 | [WMS14] | | | ✓ | | | | | | | |
| 2015 | [WMS15] | | | ✓ | | | | | | | |
| 2017 | [WMS16]* | | | ✓ | ✓ | | | | | | |
| | [WMS17]* | | | ✓ | | | | ✓ | | | |
| **% WMS papers** | | 0 | 6 | 100 | 29 | 18 | 0 | 18 | 0 | 0 | 6 |
| 1992 | [LSD1] | | | ✓ | | | | ✓ | | | |
| 2004 | [LSD2] | | | | | | | ✓ | | | |
| 2007 | [LSD3] | | ✓ | ✓ | | | | | | | |
| | [LSD4] | | | | | | | | ✓ | | |
| | [LSD5] | | ✓ | | | | | | | | |
| 2009 | [LSD6]* | | ✓ | | | | | ✓ | | | |
| 2010 | [LSD7] | | | | | | | | | ✓ | |
| 2011 | [LSD8]* | ✓ | ✓ | | | | | | | | |
| 2012 | [LSD9] | | | ✓ | | | | | | | |
| | [LSD10] | | | | | | | | ✓ | | |
| | [LSD11] | | | | | | | ✓ | | | |
| 2013 | [LSD12] | | | ✓ | | | | | | | |
| | [LSD13] | | ✓ | | | | | | | | |
| 2014 | [LSD14]* | | ✓ | ✓ | | | | | | | |
| 2015 | [LSD15] | | | ✓ | | | | | | | |
| | [LSD16] | | | | | | | | ✓ | | |
| 2016 | [LSD17] | | | ✓ | | | | | | | |
| | [LSD18] | | | ✓ | | | | | | | |
| | [LSD19] | | ✓ | | | | | | | | |
| | [LSD20] | | | ✓ | | | | | | | |
| 2017 | [LSD21] | | ✓ | | | | | | | | |
| | [LSD22] | | | ✓ | | | | | | | |
| **% LSD papers** | | 5 | 36 | 45 | 0 | 0 | 0 | 18 | 14 | 5 | 0 |
| 1974 | [SSE1] | | ✓ | | | | | | | | ✓ |
| 1978 | [SSE2] | ✓ | | | | | | | | | |
| 1982 | [SSE3] | | | | | | ✓ | | | | |
| 1996 | [SSE4] | | | | | | | | ✓ | | |
| 1997 | [SSE5] | | | | | | | | ✓ | | |
| 1998 | [SSE6]* | | ✓ | ✓ | | | | ✓ | | | |
| 2006 | [SSE7] | | | | | | | | ✓ | | |
| 2007 | [SSE8]* | | ✓ | | | | | | ✓ | | ✓ |
| | [SSE9]* | | ✓ | ✓ | | | | | | | |
| 2008 | [SSE10] | | | | | | | | ✓ | | |
| | [SSE11] | | | | | | | | ✓ | | |
| | [SSE12] | | | | | | | | ✓ | | |
| | [SSE13] | ✓ | | | | | | | | | |
| 2009 | [SSE14] | | | | | | ✓ | | | | |
| | [SSE15]* | | ✓ | | | | | | | | ✓ |
| 2010 | [SSE16] | | | | | | | | ✓ | | |
| 2011 | [SSE17] | | | | | | ✓ | | | | |
| 2013 | [SSE18] | | | | | | | | ✓ | | |
| **% SSE papers** | | 11 | 28 | 11 | 0 | 0 | 17 | 6 | 50 | 0 | 17 |
| 1980 | [GSI1]* | | | ✓ | | | | ✓ | | | |
| | [GSI2] | | | | | | | | | | ✓ |
| 1997 | [GSI3] | | ✓ | | | | | | | | |
| 2000 | [GSI4] | | | ✓ | | | | | | | |
| 2003 | [GSI5]* | | | | | | | ✓ | | | ✓ |
| | [GSI6]* | | | ✓ | | | | | | | ✓ |
| | [GSI7] | | | ✓ | | | | | | | |
| | [GSI8] | | ✓ | | | | | | | | |
| | [GSI9] | | | | | | | | ✓ | | |
| 2004 | [GSI10] | | | ✓ | | | | | | | |
| 2006 | [GSI11]* | | | ✓ | | | | | | | ✓ |
| 2008 | [GSI12] | | | ✓ | | | | | | | |
| 2009 | [GSI13] | | | ✓ | | | | | | | |
| | [GSI14]* | | | | | | | | ✓ | | ✓ |
| 2010 | [GSI15] | | ✓ | | | | | | | | |
| 2012 | [GSI16] | | ✓ | | | | | | | | |
| 2016 | [GSI17] | | ✓ | ✓ | | | | | | | |
| | [GSI18]* | | | | | | | ✓ | | | ✓ |
| | [GSI19]* | | | ✓ | | | | ✓ | | | |
| | [GSI20] | | | ✓ | | | | | | | |
| 2017 | [GSI21] | | | | | | | | | | ✓ |
| | [GSI22] | | | ✓ | | | | | | | ✓ |
| **% GSI papers** | | 0 | 23 | 55 | 0 | 0 | 0 | 18 | 9 | 0 | 36 |
| 1973 | [NEH1] | | | | | | | | | | ✓ |
| | [NEH2] | | | | | | | ✓ | | | |
| 1983 | [NEH3] | | ✓ | | | | | | | | |
| 2002 | [NEH4] | | ✓ | | | | | | | | |
| 2005 | [NEH5] | | | | | | | | ✓ | | |
| 2006 | [NEH6] | | ✓ | | | | | | | | |
| 2007 | [NEH7]* | | ✓ | | | | | ✓ | | | |
| 2010 | [NEH8] | | | ✓ | | | | | | | |
| 2012 | [NEH9] | | ✓ | | | | | | | | |
| 2013 | [NEH10] | | ✓ | | | | | | | | |
| 2016 | [NEH11] | ✓ | | | | | | | | | |
| | [NEH12] | | | | | | | | | | ✓ |
| **% NEH papers** | | 8 | 50 | 8 | 0 | 0 | 0 | 17 | 8 | 0 | 17 |
| 1978 | [TSI1] | | | | | | | ✓ | | | |
| 2002 | [TSI2]* | | | | | | | ✓ | | ✓ | |
| 2003 | [TSI3] | | | | | | | | ✓ | | |
| | [TSI4]* | | | ✓ | | | | ✓ | | | ✓ |
| 2006 | [TSI5] | | | | | | | | ✓ | | |
| 2007 | [TSI6] | | | | | | | | ✓ | | |
| 2008 | [TSI7]* | | | | | | | | ✓ | ✓ | ✓ |
| 2009 | [TSI8] | | | | | | ✓ | | | | |
| 2010 | [TSI9]* | | | ✓ | | | | | ✓ | | |
| 2011 | [TSI10] | | | | | | ✓ | | | | |
| 2016 | [TSI11] | | | | | | | | | | ✓ |
| | [TSI12] | | | ✓ | | | | | | | |
| | [TSI13] | | | ✓ | | | | | ✓ | | |
| | [TSI14] | | | | | | | | ✓ | | |
| | [TSI15] | | | ✓ | | | | | | | |
| 2017 | [TSI16] | | | | | | | | | | ✓ |
| | [TSI17] | | | | | | | | | | ✓ |
| | [TSI18]* | | | ✓ | | | | | | | ✓ |
| | [TSI19] | | | | | | | | | | ✓ |
| **% TSI papers** | | 0 | 0 | 26 | 0 | 0 | 11 | 21 | 37 | 11 | 37 |
| **% TOTAL** | | **4** | **23** | **43** | **5** | **3** | **5** | **16** | **20** | **3** | **19** |

*The asterisk codes mark papers that consider more than one objective functions at the same time. The corresponding models are referred as either bi-objective or multi-objective. Some of these papers implicitly apply MODM (multi-objective decision-making techniques) concepts by identifying Pareto solutions.

Note that there are few other papers that have more than one objective function in row but their codes are not asterisk because they actually two or more single objective models with different objective functions.

## 6. MAIN CONSTRAINTS

According to Table 5, in USFL applications, budget limit, capacity, coverage and assignment (e.g. locating only one facility on each node) are commonly applied and this is what we expect to observe in the future as well. Interestingly, the share of research studies with a budget limit constraint in public and governmental facilities (mainly in LSD and SSE) is higher than in private facilities. While in most of the categories we expect to see a wide range of constraints with a more or less equal share, in LSD problems budget constraints play a significantly more important role than the other constraints. This is because of the nature of LSD facilities which are (i) costly and (ii) managed by public or governmental organizations with strictly limited budgets. Note that, sometimes, a budget limit is implicitly imposed by replacing another constraint like a limitation on the number of facilities to be located.

For public governmental facilities, full coverage of existing facilities is also a popular constraint. However, this is not the case for privately-owned facilities because private facilities do not have to serve all potential customers and partial coverage is also allowed. If there is any material flow between the existing and new facilities, balance equations (also called flow conservation constraint) are used; this is what we observe in WMS in particular. Otherwise, in the case of information and people flow, such constraints are not used.

The other considered constraints are satisfying a minimum demand assigned to each facility in order to be opened, limitation on the amount of supply to be allocated, governmental regulations affecting response times and resource allocation, availability of resources (e.g. capacity in each period), limitation on average waiting times and queue length, rank of facilities, overlap between areas of service, allowing lost demand in each time period, service allocation, assignment restriction, number of facilities to be closed, travel distance, partial demand satisfaction and restriction on the possible number of self-assignment by type of service.

As expected, some studies considered forbidden regions in their models because rules and regulations in some urban areas forbid locating facilities in specific areas. In particular, this is visible for obnoxious facilities like WMS. The traditional but very important facility location constraint of "barrier regions" is incorporated in only one of the studies (LSD). This is a gap in the research because in urban areas we may face many barriers. Note that forbidden facility locations fall within a category in restricted facility location problems. Other restrictions (in addition to forbidden) are (a) barriers and (b) congestion. This is a gap in the area that will be explained in the future research directions of this survey. In particular, we suggest further research on the continuous space models with barrier or forbidden regions (as the constraint) to be conducted.

Last but not least, there are also some application-specific constraints as follows: (i) *WMS:* compatibility of treatment and technology, processing all the waste in the chain according to their types and required technologies and ensuring disposal of all waste generated at each source, (ii) *SSE:* maximum response time and workloads; (iii) *GSI:* revenue-cost constraint, (iv) *NEH:* avoiding the placement of different types of facilities in the same site, retention rate and mandatory staff level; (v) *TSI:* access to refueling stations and spatial and temporal constraints. It seems that constraints are well developed in TSI models reflecting important aspects of reality. However, they are still economic or technical rather than environmental or social constraints. While some social and environmental aspects were reflected as objectives, they can also be applied in the form of constraints. If the rules and regulations related to social and environmental aspects are strict, they need to be applied as constraints. Otherwise, (e.g. if they are voluntary or protreptic), they can be included in the objective function.

**Table 5.** Main constraints for various applications of USFL models.

| Year | Code | Flow conservation | Capacity | Budget limit | Restricted areas | Distance | Coverage | Assignment | Regional | Other constraints |
|---|---|---|---|---|---|---|---|---|---|---|
| 1987 | [WMS1] | ✓ | ✓ | | | | | | | ✓ |
| 1998 | [WMS2] | | ✓ | | | | | | | ✓ |
| 2001 | [WMS3] | | ✓ | | | | | | | |
| 2004 | [WMS4] | | ✓ | | ✓ | | | | | |
| 2007 | [WMS5] | ✓ | ✓ | | | | | | | |
| | [WMS6] | | ✓ | ✓ | | | | | | ✓ |
| | [WMS7] | | | ✓ | | | | | | |
| 2008 | [WMS8] | | | | ✓ | | | | | ✓ |
| | [WMS9] | | ✓ | ✓ | | | | | | |
| 2009 | [WMS10] | | | | | | | | | ✓ |
| | [WMS11] | | ✓ | ✓ | | | | | | |
| 2011 | [WMS12] | ✓ | ✓ | | | | | | | |
| 2012 | [WMS13] | | | ✓ | | | | | | |
| 2014 | [WMS14] | | | ✓ | | | | | | ✓ |
| 2015 | [WMS15]* | ✓ | ✓ | | | | | | | ✓ |
| 2017 | [WMS16] | ✓ | ✓ | ✓ | | | | | | ✓ |
| | [WMS17] | ✓ | ✓ | | | | | | | ✓ |
| **% WMS papers** | | 35 | 71 | 41 | 12 | 0 | 0 | 0 | 0 | 53 |
| 1992 | [LSD1] | | | ✓ | | | | | | ✓ |
| 2004 | [LSD2] | | | | | | ✓ | ✓ | | ✓ |
| 2007 | [LSD3] | | ✓ | ✓ | | | | | | ✓ |
| | [LSD4] | | | ✓ | | | ✓ | | | |
| | [LSD5] | | | ✓ | | | ✓ | ✓ | | ✓ |
| 2009 | [LSD6] | | ✓ | | | ✓ | | | | ✓ |
| 2010 | [LSD7] | | | ✓ | | | | | | |
| 2011 | [LSD8] | | ✓ | ✓ | | | | | | |
| 2012 | [LSD9] | | ✓ | ✓ | | | | | | ✓ |
| | [LSD10] | | ✓ | ✓ | | | | | | ✓ |
| | [LSD11] | | | ✓ | | | | | | |
| 2013 | [LSD12] | | | | | | | ✓ | | ✓ |
| | [LSD13] | | | ✓ | | | | | | |
| 2014 | [LSD14] | | | | | | | | | ✓ |
| 2015 | [LSD15] | | ✓ | | | | | | | ✓ |
| | [LSD16] | | | ✓ | | | | | | |
| 2016 | [LSD17] | | ✓ | | | | | ✓ | | ✓ |
| | [LSD18] | | ✓ | | | | | ✓ | | ✓ |
| | [LSD19]** | | | | | | | | | ✓ |
| | [LSD20] | | ✓ | ✓ | | | | ✓ | | ✓ |
| 2017 | [LSD21] | | ✓ | | | ✓ | | ✓ | | ✓ |
| | [LSD22] | | | | | ✓ | ✓ | ✓ | | ✓ |
| **% LSD papers** | | 0 | 45 | 55 | 0 | 14 | 18 | 36 | 0 | 68 |
| 1974 | [SSE1] | | | | | | | | | ✓ |
| 1978 | [SSE2] | | | | | | | | | ✓ |
| 1982 | [SSE3] | | | ✓ | | | | | | ✓ |
| 1996 | [SSE4] | | ✓ | ✓ | | | ✓ | | | ✓ |
| 1997 | [SSE5] | | | ✓ | | | ✓ | | | |
| 1998 | [SSE6] | | | ✓ | | | | | | ✓ |
| 2006 | [SSE7] | | | | | | | | | ✓ |
| 2007 | [SSE8] | | ✓ | ✓ | | | | | | |
| | [SSE9]*** | | | | | | | | | ✓ |
| 2008 | [SSE10] | | | ✓ | | | | | | |
| | [SSE11] | | | ✓ | | | | | | |
| | [SSE12] | | | ✓ | | | | | | |
| | [SSE13] | | | | | | ✓ | | | |
| 2009 | [SSE14] | | | ✓ | | | ✓ | | | ✓ |
| | [SSE15] | | | | | | | | | ✓ |
| 2010 | [SSE16] | | | | | | | | | ✓ |
| 2011 | [SSE17] | | | ✓ | | | ✓ | | | ✓ |
| 2013 | [SSE18] | | | | | | ✓ | | | |
| **% SSE papers** | | 0 | 11 | 61 | 0 | 0 | 33 | 0 | 0 | 56 |
| 1980 | [GSI1] | | | | | | | | | ✓ |
| | [GSI2] | | | | | | | | | ✓ |
| 1997 | [GSI3] | | ✓ | | | | | | ✓ | ✓ |
| 2000 | [GSI4] | | | | | | | | | ✓ |
| 2003 | [GSI5] | | | ✓ | | | | | | |
| | [GSI6] | | | | | | | | | ✓ |
| | [GSI7] | | | ✓ | | | | | | |
| | [GSI8] | | | ✓ | | | | | | |
| | [GSI9] | | | ✓ | | | | | | ✓ |
| 2004 | [GSI10] | | ✓ | | | | | | | |
| 2006 | [GSI11] | | | ✓ | | | | | | ✓ |
| 2008 | [GSI12] | | ✓ | ✓ | | | | | | ✓ |
| 2009 | [GSI13] | | | | | | | | | ✓ |
| | [GSI14] | | | ✓ | | | ✓ | | | ✓ |
| 2010 | [GSI15] | | | | | | | | | ✓ |
| 2012 | [GSI16] | | | | | | | | | ✓ |
| 2016 | [GSI17] | | ✓ | | | | ✓ | | ✓ | ✓ |
| | [GSI18] | | | | | | ✓ | | | ✓ |
| | [GSI19] | | | | | | | | ✓ | ✓ |
| | [GSI20] | | | | | | ✓ | | | ✓ |
| 2017 | [GSI21] | | | | | | ✓ | | | ✓ |
| | [GSI22] | | ✓ | | | | | | | ✓ |
| **% GSI papers** | | 0 | 23 | 32 | 0 | 0 | 23 | 0 | 14 | 77 |
| 1973 | [NEH1] | | ✓ | ✓ | | | | ✓ | | |
| | [NEH2] | | ✓ | ✓ | | | | ✓ | | |
| 1983 | [NEH3] | | | | | | | ✓ | | ✓ |
| 2002 | [NEH4] | | | ✓ | | | | | | ✓ |
| 2005 | [NEH5] | | ✓ | ✓ | | | | | | |
| 2006 | [NEH6] | | | ✓ | | | | | | ✓ |
| 2007 | [NEH7] | | | | | | | | | ✓ |
| 2010 | [NEH8] | | ✓ | ✓ | | | | | | ✓ |
| 2012 | [NEH9] | | ✓ | | | | | | | |
| 2013 | [NEH10] | ✓ | | ✓ | | | ✓ | | | |
| 2016 | [NEH11] | | ✓ | ✓ | | | | | | ✓ |
| | [NEH12] | | | | | ✓ | ✓ | | | ✓ |
| **% NEH papers** | | 8 | 50 | 67 | 0 | 8 | 17 | 25 | 0 | 50 |
| 1978 | [TSI1] | | ✓ | ✓ | | | | ✓ | | |
| 2002 | [TSI2] | | | | | | | | | ✓ |
| 2003 | [TSI3] | | | ✓ | | | | | | |
| | [TSI4] | | | | | | | | | ✓ |
| 2006 | [TSI5] | | | ✓ | | | | ✓ | | |
| 2007 | [TSI6] | | | ✓ | | | | | | |
| 2008 | [TSI7] | | | ✓ | | | | ✓ | | |
| 2009 | [TSI8] | | | ✓ | | | | | | ✓ |
| 2010 | [TSI9] | | | | | | | | | ✓ |
| 2011 | [TSI10] | | | ✓ | | | | | | ✓ |
| 2016 | [TSI11] | | ✓ | | | | | | | ✓ |
| | [TSI12] | | ✓ | | | | | ✓ | | ✓ |
| | [TSI13] | | | | | | | ✓ | | ✓ |
| | [TSI14] | | | | | | | ✓ | | ✓ |
| | [TSI15] | | | | | | | ✓ | | ✓ |
| 2017 | [TSI16] | | | | | | | | | ✓ |
| | [TSI17] | | | | | | | ✓ | | ✓ |
| | [TSI18] | | ✓ | | | | | ✓ | | |
| | [TSI19] | | ✓ | ✓ | | | | | | ✓ |
| **% TSI papers** | | 0 | 26 | 42 | 0 | 0 | 0 | 47 | 0 | 63 |
| **% TOTAL** | | **6** | **36** | **48** | **2** | **4** | **15** | **18** | **3** | **63** |

* ***Note:*** There is only one paper ([WMS15]) that contains the constraint of "Minimum demand to be served". In order to save space, we have not dedicated a column to this constraint.

** ***Note:*** There is only one paper ([LSD19]) that contains the constraint of "Barrier regions". In order to save space, we have not dedicated a column to this constraint.

*** ***Note:*** There is only one paper ([SSE9]) that contains the constraint of "forbidden regions". In order to save space, we have not dedicated a column to this constraint.

Moreover, we have embedded the related marks for the abovementioned papers in the "Other constraints" column.

## 7. MODELING AND SOLUTION APPROACHES

In this section, first, we analyze the logic behind USFL modeling approaches. Then, we present a few sample models in the area. Finally, the solutions applied to solve these models are categorized.

### 7.1. Modeling

There are some basic models in the literature of facility location problems (interested readers may refer to Farahani & Hekmatfar (2009) to see those models). Among them, basic single facility location, basic multi-facility location and location-allocation models are originally defined on the continuous plane. Center, median and covering problems are originally developed in networks. Quadratic and also warehouse location models are defined in a discrete space. Some models are defined in mixed location spaces. For example, hub and hierarchical facility location models are normally defined in networks with discrete locations.

Therefore, our main assumptions in Section 3 (i.e. location space and the number of facilities to be located) comprise some basic categorizations for USFL models. Almost all of the existing mathematical formulations are an extension of the original models or a mixture of them depending on the application. For example, a hub model can be a single hub or multiple-hub model depending on the number of facilities to be located and also the nature of service routes that must go via a hub facility. In the same way, we may define a hub facility location in a discrete space, on a network or both. Our general observations in modeling of USFL problems are as follows:

- The vast majority of USFL models are in a discrete space and there are some models in networks. There are only a few models on a continuous plane.
- The vast majority of the papers consider multiple facilities rather than a single facility. Therefore, the traditional single facility location model on the continuous plane is not very practical in USFL.
- For most of the models, a warehouse facility location model is embedded because fixed costs of locating a facility and variable costs of transportation were basically introduced in this model.
- When the constraints of dedicating an existing facility to exactly one (hard) or at least a newly located facility (soft) are applied (as explained in Section 6), the location-allocation concept is exploited in modeling.
- When we deal with non-emergency facility location problems (e.g. NEH), the objective functions can be in the form of minisum or minimax as we see in Median problems.
- When we would like to highlight the emergency aspect of location problems (e.g. in LSD and SSE), the objective functions are in the form of minimax or maximin as we see in the basic Center problems.
- When governmental facilities are to be located (they are supposed to serve all existing facilities or people in an urban area), the model orientation can be similar to what we observe in a Set Covering model. If these facilities are private (i.e. they do not have to serve all people), the concept of the Maximal Covering model will be exploited.
- Considering the nature of the application is critical in prescribing an appropriate model. For example, in NEH, many scholars use Hierarchical models because various types of hospitals and clinics in different geographical areas, providing a wide range of services, are linked hierarchically.
- Last but not least, people in urban areas would like to be close to some facilities such as schools, shops and bus stops and be far from facilities like dumping sites. Therefore, a facility can be desirable or undesirable. Unlike desirable facilities, obnoxious facility location models (e.g. in WMS) are in a category that should maximize

distance from existing facilities. Of course, some facilities can be desirable and undesirable at the same time (e.g. airports).

In this section, we present a few sample models to familiarize readers with the modeling of USFL problems. We present (1) a model in NEH which is a hierarchical model), (2) a model in LSD which is maximal covering, and (3) a model in GSI which is a P-median.

***A sample model in LSD:*** A maximal covering model formulation for determining the locations of medical supplies in large scale emergencies is proposed by Jia et al. (2007a). The model sets, indices and parameters are the following:

$h_i$ = the population of demand point $i$,

$d_{ij}$ = the distance from site $j$ to demand point $i$,

$p$ = the maximal number of facilities that can be placed.

$r$ = quality levels; $r \in \{1,\ldots, q\}$.

Decision variables of the model are $x_j$ =1 if a facility is located at site $j$; 0 if not and $y_i^r$=1 if demand point $i$ is covered at quality level $r$; 0 if not.

The model parameters are as follows:

$D_i^r$= the distance requirement for demand point $i$ to be serviced at quality level $r$,

$Q_i^r$= the minimum number of facilities that must be allocated to demand point $i$ so that $i$ can be considered as covered at quality level $r$,

$w_r$ = the importance weighting factor of the facilities that have quality level $r$ and $a_{ij}^r$= 1 if facility site $j$ can cover demand point $i$ at quality level $r$ (i.e.,: $d_{ij} \leq D_i^r$ ); 0 if not.

The suggested model is presented as follows:

$$max \;\; \sum_r \sum_i w^r h_i y_i^r \tag{1}$$

*s.t.*

$$\sum_j x_j \leq p \tag{2}$$

$$x_j = 0,1 \qquad \forall\, j \in J; \tag{3}$$

$$\sum_{j\in J} a_{ij}^r \; x_j \; \geq Q_i^r y_i^r; \qquad \forall\, i \in I, \;\; r = 1, \ldots q; \tag{4}$$

$$y_i^r \epsilon \{0,1\}; \qquad \forall\, i \in I, \;\; r = 1, \ldots q. \tag{5}$$

Objective function (1) maximizes demand covered by sufficient quantity of facilities at different quality levels. It also incorporates the priority of facilities at each quality level. Constraints (2) and (3) ensure that, at most $p$ facilities will be located in a set $J$ of possible locations. Constraint (4) is used to represent that demand point $i$ is considered covered in quality level $r$ only in the case that more than a required quantity ($Q_i^r$) of facilities are located within the corresponding distance constraint servicing it. Constraint (5) ensures integrality.

***A sample model in GSI:*** A capacitated P-median formulation with an assignment constraint is proposed by Teixeira & Antunes (2008). The model sets and indices are:

$I$ = set of demand centers $\{1, 2,\ldots, n\}$,

$J$ = set of sites $\{1, 2,..., m\}$,

$h_i$ = demand (number of users) at node $i \in I$,

$P_{ij}$= the subset of centers $k \in I$ that are ‘‘near’’ the shortest path from $i$ to $j$, and $|P_{ij}|$ is the cardinality of this set and $A_{ij}$ =the set of units $k \in I$ that immediately precede unit $i$ on a shortest path from district center $j$ to unit $i$.

Decision variables of the model are $x_j$= 1 if a facility is located at site $j$; 0 if not, and $y_{ij}$ is the fraction of the demand from center $i \in I$ that is served at site $j \in J$.

The model input parameters are as follows:

$c_{ij}$ = travel costs for serving all the demand from center $i$ at site $j$ ($c_{ij}=h_i.d_{ij}$),

$d_{ij}$= unit travel cost between center $i$ and site $j$ (or distance, if the unit cost is constant),

$b_j$= minimum capacity for a facility to be open at site $j$,

$B_j$= maximum capacity for a facility to be open at site $j$,

The suggested model is presented as follows:

$$min\ \sum_{i \in I} \sum_{j \in J} c_{ij}\, y_{ij} \tag{6}$$

*s.t.*

$$\sum_{j=1}^{n} y_{ij} = 1; \qquad \forall\ i \in I; \tag{7}$$

$$y_{ij} \le xj; \qquad \forall\ i \in I, j \in J; \tag{8}$$

$$\sum_{i \in I} h_i\, y_{ij} \ge\ b_j\, x_j; \qquad \forall\ j \in J; \tag{9}$$

$$\sum_{i \in I} h_i\, y_{ij} \le\ B_j\, x_j\ ; \qquad \forall\ j \in J; \tag{10}$$

$$\sum_{k \in J | d_{ik} \le d_{ij}} y_{ik} \ge\ x_j; \qquad \forall\ i \in I, j \in J; \tag{11}$$

$$\sum_{k \in P_{ij}} y_{kj} \ge |P_{ij}|\, y_{ij}; \qquad \forall\ i \in I, j \in J; \tag{12}$$

$$y_{ij} \le \sum_{k \in A_{ij}} y_{kj}\ ; \qquad \forall\ i \in I, j \in J; \tag{13}$$

$$x_j \epsilon \{0,1\}; \qquad \forall\ j \in J \tag{14}$$

$$y_{ij} \epsilon \{0,1\}; \qquad \forall\ i \in I, j \in J. \tag{15}$$

Objective function (6) minimizes the travel costs (a proxy for accessibility maximization). Constraint (7) ensures that all the centers have to be served. Constraint (8) states that centers can only be assigned to an open facility. Constraints (9) and (10) represent minimum and maximum capacity limitations respectively. Constraint (11) represents the closest assignment constraint and constraint (14) ensures single assignment constraint. Path assignment constraint is represented by constraint (12) and contiguity is enforced by constraint (13). Constraints (14) and (15) impose integrality constraints on decision variables.

***A sample model in NEH:*** A hierarchical model for locating senior citizen centers proposed by Johnson et al. (2005). The model sets and indices are as follows:

$I$ = set of demand nodes $\{1,2,\ldots,n\}$,

$J$ = set of potential facility locations $\{1,2, ...,m\}$,

$K$ = set of facility service level categories $\{1, 2, ..., p\}$,

Decision variables of the model are

$x_{jk}$=1 if a facility of type $k$ is located at site $j$; 0 if not and

$y_{ijk}$= number of demands at node $i$ for type $k$ services that are assigned to a facility at candidate site $j$.

The model input parameters are as follows:

$h_{ik}$= total demand, for type $k$ senior citizen center services at demand node $i$,

$e_{ijk}$= upper bound on the number of demands at node $i$ for type $k$ services that may be provided at facility location $j$,

$f_{jk}$ = fixed annual cost of locating a type $k$ facility at candidate location $j$,

$v_{jk}$ = variable per-client annual cost of locating a type $k$ facility at candidate location $j$, $G$ = total budget available for locating all facilities and $b_{jk}$ = capacity of type $k$ facility at candidate location $j$.

The suggested model is presented as follows:

$$max \ \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{p} y_{ijk} \quad (16)$$

*s.t.*

$$y_{ijk} \leq h_{ik} \sum_{h=k}^{p} x_{jh}; \qquad \forall\, i,j,k; \quad (17)$$

$$\sum_{k=1}^{p} x_{jk} \leq 1; \qquad \forall\, j; \quad (18)$$

$$\sum_{j=1}^{m} y_{ijk} \leq h_{ik}\,; \qquad \forall\, i,k; \quad (19)$$

$$\sum_{j=1}^{m}\sum_{k=1}^{p}(f_{jk}.x_{jk} + v_{jk} \sum_{i=1}^{n} y_{ijk}) \ \leq \text{G}; \quad (20)$$

$$\sum_{i=1}^{n} y_{ijk} \leq b_{jk}\,; \qquad \forall\, j,k; \quad (21)$$

$$x_{jk} \in \{0,1\}; \qquad \forall\, j,k; \quad (22)$$

$$0 \leq y_{ijk} \ \leq e_{ijk} \quad \text{and integer}; \qquad \forall\, i,j,k. \quad (23)$$

Objective function (16) maximizes total demand for all types of services that are covered. Constraints (17) represent that demand in node *i* for type *k* cannot be provided by a type *k* facility unless a facility is sited at site *j* that provides type $k$ or higher service. Constraints (18) state that only one facility of any service type can be sited at any potential location $j$. Constraints (19) ensure that the number of demand at node *i* for type *k* services that is covered by all facilities cannot be more than the total number of demand at node *i* for type *k* services. Constraint (20) enforces that the total fixed and variable costs of locating facilities cannot exceed the available budget. Constraints (21) state that the total demand for type *k* services that is assigned to potential location *j* cannot be more than the capacity $b_{ik}$. Constraints (22) and (23) impose integrality and bounds on decision variables.

### 7.2. Solution Approaches

In this subsection, according to Table 6, we compare and contrast various USFL applications in terms of the type of solution techniques used. We have divided the solution approaches intro exact (e.g. dynamic programming, simplex and branch & bound), heuristic and meta-heuristics (e.g. genetic algorithm, tabu search and simulated annealing). Obviously, we cannot introduce a specific list for possible heuristic methods because they are fairly unstructured (while some terms such as 2-opt, 3-opt and greedy algorithms are used for some heuristic techniques, there is no comprehensive categorization for them). Some approaches like multi-objective decision making (MODM) techniques and game theory are considered as exact approaches if no specific solution technique has been provided in the related paper. In fact, we believe MODM techniques such as lexicographic and ε–constraint are not solution techniques as they only convert a multi-objective problem into a single objective equivalent; therefore, they are not considered as solution techniques. The same logic applies to the game theoretic approaches because this is a modeling approach where two or more decision makers are involved in a decision making problem. In the same way, in some papers, the authors model a problem in the form of a LP, MIP, IP and do not develop any solution technique. We also consider these papers as exact because after modeling, they solve a real-life problem using a commercial solver such as LINGO, CPLEX, LINDO and XPRESS. Usually an exact solver is embedded in these software products and that is why we put them in the exact approach category.

#### Common observations

Our observation shows that exact solution approaches have been consistently important in all applications. But the vast majority of the exact solution techniques used are based on either LP or discrete location spaces that result in MIP or IP models. Therefore, traditional exact techniques like branch and bound (B&B) and using software products have been common tools to tackle these problems. The main reasons that may make a modeler use heuristic or meta-heuristic techniques are either difficulty in modeling a complicated problem or the size of the model. It seems that the researchers did not have difficulty in solving large-size LP models. But when it comes to IP or MIP models, they can usually solve the problem in small sizes and possibly in medium sizes while in reality it is very likely we face large-size problems in USFL applications.

**Specific solution techniques**

***WMS:*** Traditional techniques like branch and bound (B&B) and using software products such as MINOS, GAMS and CPLEX, have been common tools. But since these problems, particularly in a discrete space, can be computationally complex to solve, over the last decade heuristic solutions (with a special focus on Lagrangian relaxation (LR)) have been increasingly considered as a solution approach. However, it is surprising that meta-heuristic techniques have not been considered as much as heuristic techniques. This is a gap from an OR perspective that can be further developed.

***LSD:*** Most of the LSD models are solved by using exact methods such as goal programing, dynamic programming and also with the help of software products such as MPSX, LINGO, CPLEX and GAMS. Researchers have used heuristics such as the sample average approximation (SAA) scheme, locate-allocate heuristic and LR. Some meta-heuristic methods such as Genetic Algorithms (GA) are also utilized. In recent years meta-heuristic techniques have become more popular but the growth in their use in LSD problems has been slow. On the other hand, the trend in using heuristic techniques is gradually decreasing. This seems reasonable because meta-heuristic techniques often yield better results than heuristic approaches.

***SSE:*** SSE facility location problems in urban areas are large size problems because the number of potential locations, existing facilities (e.g. residential areas) and new facilities (e.g. servers) to be located can represent large numbers. However, small and medium-sized problems can be solved optimally by using commercial software products. Table 6 shows that exact methods such as Lexicographic Linear Programming, Goal Programming, Simplex, B&B and commercial software products like LINDO and CPLEX have always been used in solving such problems. In contrast, for large-sized problems heuristic and meta-heuristic techniques are often employed. Particularly, the trend in using meta-heuristic techniques is increasing. We believe this trend in using these solution approaches will be continued in the future. LR, Greedy heuristics, Tabu Search (TS) and GA have been more popular than other heuristic and meta-heuristic techniques.

***GSI:*** Most GSI models are solved by exact methods such as B&B, Karush-Kuhn-Tucker (KKT) and Voronoi diagrams with software products such as CPLEX, LINGO, Microsoft Excel Solver, XPRESS Optimizer and NUOPT. These methods perform well in solving small and some medium-sized problems. This trend in GSI models is steady. For large-scale problems heuristic and meta-heuristic methods have been used. LR, Lagrangian/surrogate heuristics, heuristics based on two-dimension convolution and TS have been used in solving large-scale problems.

***NEH:*** Most of the models, especially small scale ones, are solved with exact methods such as zero-one compatible algorithms and branch-and-cut methods using commercial software such as LINGO, CPLEX and GAMS. Among the few heuristic and meta-heuristic methods used are 3-P median heuristics, LR, Pareto Ant Colony, vector evaluated GA, multi-objective GA and SA (some papers have used more than one meta-heuristic).

***TSI:*** While using exact methods has been popular in these problems until recently, over the last decade a significant number of studies have considered meta-heuristic techniques to solve these problems. It is surprising why heuristic techniques did not draw much attention. However, the popularity of meta-heuristic techniques shows that while these problems are mainly modeled in discrete space, they are difficult to solve in terms of computational effort. Among the meta-heuristic methods, hybrid hypercube-GA and GA have been used.

**Table 6.** Solution approaches for various applications of USFL models.

| Year | Code | Exact | Heuristic | Meta heuristic |
|---|---|---|---|---|
| 1987 | [WMS1] | ✓ | | |
| 1998 | [WMS2] | ✓ | | |
| 2001 | [WMS3] | ✓ | | |
| 2004 | [WMS4] | ✓ | | |
| 2007 | [WMS5] | ✓ | | |
| | [WMS6] | | | ✓ |
| | [WMS7] | ✓ | | |
| 2008 | [WMS8] | | ✓ | |
| | [WMS9] | ✓ | | |
| 2009 | [WMS10] | | ✓ | |
| | [WMS11] | | ✓ | |
| 2011 | [WMS12] | ✓ | ✓ | |
| 2012 | [WMS13] | ✓ | | |
| 2014 | [WMS14] | ✓ | | |
| 2015 | [WMS15] | ✓ | | |
| 2017 | [WMS16] | ✓ | | |
| | [WMS17] | ✓ | | |
| **% WMS papers** | | 76 | 24 | 6 |
| 1992 | [LSD1] | ✓ | | |
| 2004 | [LSD2] | | ✓ | |
| 2007 | [LSD3] | ✓ | | |
| | [LSD4] | | ✓ | ✓ |
| | [LSD5] | ✓ | | |
| 2009 | [LSD6] | ✓ | ✓ | |
| 2010 | [LSD7] | ✓ | | |
| 2011 | [LSD8] | ✓ | | |
| 2012 | [LSD9] | | ✓ | |
| | [LSD10] | | ✓ | |
| | [LSD11] | | ✓ | |
| 2013 | [LSD12] | ✓ | | |
| | [LSD13] | | ✓ | |
| 2014 | [LSD14] | ✓ | | |
| 2015 | [LSD15] | ✓ | | |
| | [LSD16] | ✓ | | |
| 2016 | [LSD17] | ✓ | | |
| | [LSD18] | | ✓ | |
| | [LSD19] | ✓ | | |
| | [LSD20] | | ✓ | |
| 2017 | [LSD21] | ✓ | | |
| | [LSD22] | | ✓ | |
| **% LSD papers** | | 59 | 45 | 5 |
| 1974 | [SSE1] | ✓ | | |
| 1978 | [SSE2] | ✓ | | |
| 1982 | [SSE3] | | ✓ | |
| 1996 | [SSE4] | ✓ | | |
| 1997 | [SSE5] | | | ✓ |
| 1998 | [SSE6] | ✓ | | |
| 2006 | [SSE7] | ✓ | | |
| 2007 | [SSE8] | ✓ | | |
| | [SSE9] | | | ✓ |
| 2008 | [SSE10] | ✓ | | |
| | [SSE11] | ✓ | | |
| | [SSE12] | | ✓ | |
| | [SSE13] | | | ✓ |
| 2009 | [SSE14] | | ✓ | |
| | [SSE15] | ✓ | | |
| 2010 | [SSE16] | ✓ | | |
| 2011 | [SSE17] | | | ✓ |
| 2013 | [SSE18] | ✓ | ✓ | |
| **% SSE papers** | | 61 | 22 | 22 |
| 1980 | [GSI1] | ✓ | | |
| | [GSI2] | | ✓ | |
| 1997 | [GSI3] | | ✓ | |
| 2000 | [GSI4] | ✓ | | |
| 2003 | [GSI5] | ✓ | | |
| | [GSI6] | ✓ | | |
| | [GSI7] | ✓ | | |
| | [GSI8] | | ✓ | ✓ |
| | [GSI9] | ✓ | ✓ | |
| 2004 | [GSI10] | | ✓ | |
| 2006 | [GSI11] | ✓ | | |
| 2008 | [GSI12] | ✓ | | |
| 2009 | [GSI13] | | ✓ | |
| | [GSI14] | ✓ | | |
| 2010 | [GSI15] | ✓ | | |
| 2012 | [GSI16] | ✓ | | |
| 2016 | [GSI17] | ✓ | | |
| | [GSI18] | ✓ | | |
| | [GSI19] | | ✓ | |
| | [GSI20] | ✓ | | |
| 2017 | [GSI21] | ✓ | | |
| | [GSI22] | ✓ | | |
| **% GSI papers** | | 73 | 32 | 5 |
| 1973 | [NEH1] | ✓ | | |
| | [NEH2] | ✓ | | |
| 1983 | [NEH3] | ✓ | | |
| 2002 | [NEH4] | | ✓ | |
| 2005 | [NEH5] | ✓ | | |
| 2006 | [NEH6] | ✓ | ✓ | |
| 2007 | [NEH7] | | ✓ | ✓ |
| 2010 | [NEH8] | ✓ | | ✓ |
| 2012 | [NEH9] | ✓ | | |
| 2013 | [NEH10] | ✓ | | |
| 2016 | [NEH11] | ✓ | | |
| | [NEH12] | ✓ | | |
| **% NEH papers** | | 83 | 25 | 17 |
| 1978 | [TSI1] | ✓ | | |
| 2002 | [TSI2] | ✓ | | |
| 2003 | [TSI3] | ✓ | | |
| | [TSI4] | | ✓ | |
| 2006 | [TSI5] | ✓ | | |
| 2007 | [TSI6] | ✓ | | |
| 2008 | [TSI7] | ✓ | | |
| 2009 | [TSI8] | | ✓ | |
| 2010 | [TSI9] | ✓ | | |
| 2011 | [TSI10] | | | ✓ |
| 2016 | [TSI11] | | | ✓ |
| | [TSI12] | ✓ | | |
| | [TSI13] | ✓ | | |
| | [TSI14] | ✓ | | |
| | [TSI15] | ✓ | | |
| 2017 | [TSI16] | ✓ | | |
| | [TSI17] | ✓ | | |
| | [TSI18] | ✓ | | |
| | [TSI19] | | ✓ | |
| **% TSI papers** | | 74 | 16 | 11 |
| **% TOTAL** | | **70** | **28** | **10** |

## 8. APPLICATIONS

In this section, we focus on real-life applications of the USFL models in our six basic applied categories. The type of the application and its location in the world are summarized in Table 7. Most of the categories have only been practiced in developed countries and few have been implemented in developing nations. However, in general, we try to be insightful in providing some general future research directions in each category before providing a more specific list of suggestions in the final section of the paper.

***WMS:*** Solid waste is the most popular research area in this category and Waste Electrical and Electronic Equipment (WEEE) is the one least focused on. Nowadays, drivers such as sustainability, pressure of regulations, social responsibility and consumers' willingness make managing WEEE increasingly important. This area has already drawn some attention in terms of pricing and partnership, but obviously it is understudied when considering location aspects. This is a gap that can be further explored in the literature. Another observation is that the countries which have applied OR techniques to the location of WMS facilities in urban areas are mainly developed countries. Obviously, such a research subject can also be applicable to developing countries. This will be easy in the downstream part of the WMS supply chain starting from depots toward recycling, recovery and landfill sites. However, we suggest that the upstream part of this supply chain, which is households and shops, be included in this research as well. The issue is that in developing countries households may be less willing to contribute to the process of separating waste at the supply point. Encouraging them by considering some incentives in the models can result in practical insights and solutions.

***LSD:*** Locating shelters, pre-positioned stockpiles, medical supplies and sirens have already drawn attention. Among disasters it seems that earthquakes, floods and terrorist attacks have been studied while there are many other types of disasters which are neglected. Interested readers may refer to Gupta et al. (2016) to see a comprehensive list of disasters. When it comes to the location of case studies, except for an application in Turkey, it is mostly developed countries that have been studied while many recent deadly disasters have happened in developing countries that have not been studied. This is another important gap.

***SSE:*** The applications of SSEs in urban areas are limited to ambulance emergency medical services (EMS), fire stations and police patrols. When it comes to the type of emergency, it seems only "fire" has been explicitly considered as the most prevalent emergency in urban areas. In fact, these facilities can be divided into two groups: (1) moving vehicles (e.g. fire trucks and ambulances) and (2) fixed facilities (e.g. fire stations and hospitals). We study "hospitals" in another section titled "Non-emergency healthcare systems (NES)". The reason is that in hospitals mainly only one department, named accident & emergency (A&E) is in charge of emergency situations in urban areas and the rest do not deal with them. Moreover, A&E is one of the departments in a hospital; A&Es are not considered independent facilities to be located. All applications have been focused on developed countries. This share is slightly different from what we observed in LSDs. The reason is that in terms of publicity and media coverage, LSDs are valued far above SSEs while in terms of incurred cost and the number of casualties and fatalities this may not be the case.

***GSI:*** GSI facility location research in urban areas is widely investigated not only in developed nations but also in developing countries. These facilities are owned by either private or public organizations. Some of these applications are for-profit facilities and some are not-for-profit facilities. We expect to see wider applications of this category in the future and particularly in the areas of retailing, hospitality (e.g. hotels), social work, media, communications, electricity, gas and water supply, game shops, restaurant chains, fuel stations, museums, zoos and botanical gardens.

***NEH:*** The majority of applications are in hospitals and particularly professional (e.g. organ transplant and breast cancer) and special-purpose hospitals. The applications are either on a single hospital level or over a network of hospitals. Hierarchical facility location problems have been widely used in modeling these problems in the network where the location of facilities in a multi-level network is determined so as to serve people at the lowest level of hierarchy both efficiently (cost objective) and effectively (service availability). In addition to fixed or mobile hospitals, other applications such as residential care and senior citizen centers are becoming popular.

***TSI:*** Surprisingly, only a limited number of nations have considered TSI facility location problems in urban areas. They are either large (e.g. the US, China and Australia) or small (e.g. Taiwan and Greece) countries. We believe this can be extended to other nations. The majority of the applications are related to the fixed entities of a land transportation system. Note that the fixed entities of a transportation system can be divided into (1) links (e.g. connecting roads) and (2) nodes (e.g. bus stops, garages, airports and charging stations etc.). Obviously, the majority of the papers study TSI facility location on nodes of transportation systems, which is realistic in urban areas. We believe this will also be the case for future research.

**Table 7.** Application of OR for various applications of USFL models.

| AREA | CODE | APPLICATION | PLACE |
|---|---|---|---|
| Waste Management System | [WMS1] | Solid waste disposal | - |
| | [WMS2] | Disposal or treatment facilities | - |
| | [WMS3] | Hazardous waste facilities | Albany, New York, US |
| | [WMS4] | Landfill (as undesirable facilities) | Prince George s County, Maryland, US |
| | [WMS5] | Hazardous waste management | Central Anatolia, Turkey |
| | [WMS6] | Plants for the disposal of solid animal waste | Andalusia, Spain |
| | [WMS7] | Landfills and garbage transfer stations | New Brunswick, Canada |
| | [WMS8] | Waste disposal site for low-level (domestic and nontoxic industrial) waste | Algarve, Portugal |
| | [WMS9] | Municipal solid waste management (SWM) | Central Macedonia, Greece |
| | [WMS10] | Collection of End-of-Life Vehicles (ELV) | Mexico |
| | [WMS11] | Solid waste management | Achaia, Greece |
| | [WMS12] | Collection of Waste of Electric and Electronic Equipment (WEEE) (recovery network) | Galicia, Spain |
| | [WMS13] | Sorted waste containers (Waste management) | Coimbra, Portugal |
| | [WMS14] | Recycling of urban solid wastes | Sorocaba + São Paulo, the State of São Paulo, Brazil |
| | [WMS15] | Municipal solid waste | New South Wales, Australia |
| | [WMS16] | Municipal Solid waste | Shanghai, China |
| | [WMS17] | Solid waste | Pathum Thani, Thailand |
| | * Giannikos (1998) and Khan (1987) have explicitly mentioned that their models are applicable to the area but they have not applied the models to any specific case study. | | |
| Large –Scale Disasters | [LSD1] | Emergency warning sirens | Midwestern city, USA |
| | [LSD2] | Siren system | Dublin, Ohio, USA |
| | [LSD3] | Rescue resource storehouses in flood | Taipei City, Northern Taiwan |
| | [LSD4] | Medical supplies | Los Angeles, California, USA |
| | [LSD5] | Medical services | Los Angeles, California, USA |
| | [LSD6] | Point of dispensing (PoD) for public-health emergency | Atlanta, Georgia USA |
| | [LSD7] | General (e.g. for large-scale emergencies in a whole city) | - |
| | [LSD8] | Supply storage for treating earthquake | Istanbul, Turkey |
| | [LSD9] | Temporary depots for relief operations (in case of earthquake) | Los Angeles County, USA |
| | [LSD10] | Medicine delivery point (case of bioterrorist attack) | Los Angeles County, USA |
| | [LSD11] | Distribution centers to provide a quick response time for disaster relief | US |
| | [LSD12] | Pick-up facilities in case of evacuation | Mississippi, USA |
| | [LSD13] | Urgent relief distribution centers (URDCs) in earthquake | Taiwan |
| | [LSD14] | Emergency service facilities after a disaster | Istanbul, Turkey |
| | [LSD15] | Emergency rescue centers | Pudong District of Shanghai, China |
| | [LSD16] | Antennas and emergency warning sirens | Paradise Valley, Arizona Dublin, Ohio, USA |
| | [LSD17] | Optimization of International Federation of Red Cross and Red Crescent Societies existing network | Worldwide |
| | [LSD18] | Facility location, transportation and fleet sizing decisions in emergency logistics | Rio de Janeiro, Brazil |
| | [LSD19] | Relief item depots | Prince islands, Turkey |
| | [LSD20] | Location and capacities of distribution centers in an earthquake prone region | Los Angeles, USA |
| | [LSD21] | Pre-positioning of relief items | Istanbul, Turkey |
| | [LSD22] | Distribution center locations, their corresponding service regions and ordering quantities | Mississippi, USA |
| | * Huang et al. (2010) has explicitly mentioned that their models are applicable to the area but it has not applied the models to any specific case study. | | |
| Small- Scale Emergency | [SSE1] | Ambulance (EMS) | District of Columbia, USA |
| | [SSE2] | Emergency service | USA |
| | [SSE3] | Ambulance (EMS) | Austin, Texas,USA |
| | [SSE4] | Ambulances (i.e. site limited numbers of emergency vehicles) | - |
| | [SSE5] | Ambulance (EMS) | Island of Montreal, Canada |
| | [SSE6] | Fire station | Dubai, the UAE |
| | [SSE7] | Ambulance (EMS) | Montreal, Canada |
| | [SSE8] | Emergency services | - |
| | [SSE9] | Fire stations | Derbyshire, UK |
| | [SSE10] | Emergency vehicles to fire stations | Singapore |
| | [SSE11] | Emergency vehicle locations (ambulances) | Edmonton, Alberta, Canada |
| | [SSE12] | Ambulance (EMS) | Edmonton, Alberta, Canada |
| | [SSE13] | EMS | - |
| | [SSE14] | Emergency vehicles (e.g. ambulances) | California, USA |
| | [SSE15] | Ambulance (EMS) | - |
| | [SSE16] | Police patrol | Dallas, Texas, USA |
| | [SSE17] | Emergency response units + transit mobile repair units (TMRU) | Athens, Greece |
| | [SSE18] | Fire stations | Toronto, Canada |

| AREA | CODE | APPLICATION | PLACE |
|---|---|---|---|
| | * Araz et al. (2007), Hsia et al. (2009), Marianov & ReVelle (1996) and Rajagopalan et al. (2008) have explicitly mentioned that their models are applicable to the area but they have not applied the models to any specific case study. | | |
| General Services and Infrastructure | [GSI1] | Power plant siting | Six-state region in the US |
| | [GSI2] | Public facility (general) | - |
| | [GSI3] | Coffee buying centers | Busoga, Uganda |
| | [GSI4] | Postal service | Switzerland |
| | [GSI5] | Tenant-based subsidized housing | Cook county, Illinois, USA |
| | [GSI6] | Power plants, chemical plants, waste dumps, airports or train stations | - |
| | [GSI7] | Multi-service facility (MSF) concept | Edmonton, Alberta, Canada |
| | [GSI8] | Bank branches | Amherst, New York, USA |
| | [GSI9] | Authentic network | Yuanlin, Changhua, Taiwan |
| | [GSI10] | Primary public schools | Vitoria, Espírito Santo, Brazil |
| | [GSI11] | Subsidized housing | Cook County, Illinois, USA |
| | [GSI12] | School network planning | Coimbra, Portugal |
| | [GSI13] | Banking automatic teller machines (ATMs) | Khubar City, Saudi Arabia |
| | [GSI14] | Digital subscriber line (DSL) services | Fairfield County, Ohio, USA |
| | [GSI15] | Shopping center | Adapazari City, Sakarya, Turkey |
| | [GSI16] | Municipal services (e.g., issuance of licenses and permits, tax collection, and welfare services) | Ataşehir, Istabul, Turkey |
| | [GSI17] | Locating public service facilties | _ |
| | [GSI18] | Expansion of municipalities' chains | Spain |
| | [GSI19] | Locating vehicle inspection stations | Fushun city, China |
| | [GSI20] | Examining the effect of road network structures on facility locatios | USA |
| | [GSI21] | Selecting good show locations for a travelling entertainment troupe | Bavaria, Germany |
| | [GSI22] | Rental byke location, allocation and routing | the New Taipei City, Taiwan |
| | * Greenhut & Mai (1980) and Melachrinoudis & Xanthopulos (2003) have explicitly mentioned that their models are applicable to the area but they have not applied the models to any specific case study. | | |
| Non-Emergency Healthcare | [NEH1] | Healthcare facilities | - |
| | [NEH2] | Healthcare system | - |
| | [NEH3] | Various types of health facilities | - |
| | [NEH4] | Maternal and perinatal healthcare facilities | Rio de Janeiro, Brazil |
| | [NEH5] | Senior centers | Allegheny County, Pennsylvania |
| | [NEH6] | Perinatal facilities | Rio de Janeiro, Brazil |
| | [NEH7] | Mobile healthcare facilities | Thiès region, Senegal |
| | [NEH8] | Healthcare service | USA |
| | [NEH9] | Hospital | South region of Portugal |
| | [NEH10] | Organ transplant centers | Belgium |
| | [NEH11] | Healthcare service network | Calabria, Italy |
| | [NEH12] | Designing a network of medical screening facilities | Dominican Republic |
| | * Calvo & Marks (1973), Love & Trebbi (1973) and Tien et al. (1983) have explicitly mentioned that their models are applicable to an area but they have not applied the models to any specific case study. | | |
| Transportation Systems | [TSI1] | Bus garage | River City, Louisville, Kentucky, USA |
| | [TSI2] | Airport (as an example) | - |
| | [TSI3] | Bus stop | Brisbane, Australia |
| | [TSI4] | Obnoxious (undesirable) facility | - |
| | [TSI5] | Park-and-ride facilities (desirable) and recycling facilities (undesirable) | Columbus, Ohio, USA |
| | [TSI6] | Rail park-ride facilities | - |
| | [TSI7] | Park-and-ride | Columbus, Ohio, USA |
| | [TSI8] | Emergency vehicles | California, USA |
| | [TSI9] | Passenger vehicle refueling stations | Taiwan |
| | [TSI10] | Transit mobile repair units (TMRU) + Emergency response units | Athens, Greece |
| | [TSI11] | Electric taxi (ET) charging stations | Shenzhen, China |
| | [TSI12] | Charging facilities for plug-in electric vehicles | |
| | [TSI13] | Public electric vehicle (EV) charging stations | Beijing, China |
| | [TSI14] | Extending refueling stations for alternative-fuel vehicles (AFVs) | Orlando, Florida, USA |
| | [TSI15] | Electric vehicle charging network | Toronto, Ontario, Canada |
| | [TSI16] | Planning alternative terminal location | Puri, Odisha, India |
| | [TSI17] | Designing a geographical service region for car -sharing service providers | San Diego, USA |
| | [TSI18] | Food (halal meat) supply chain design | London, UK |
| | [TSI19] | Locating intermodal terminal (IMT) locations | The state of NSW, Australia |
| | * The model of Farhan & Murray (2006) has two applications: (1) Park-and-ride facilities (a desirable facility) and recycling facilities (an undesirable facility). Therefore, this paper can be under either WMS or TSI. We put it in just one category in order to avoid duplication and keep balance between the numbers of papers in categories.<br>** The application of the models in Geroliminis et al. (2009) and Geroliminis et al. (2011) is twofold. It can be either TSI category or SSE. We put it under TSI to keep balance between the numbers of papers in categories.<br>*** Hamacher et al. (2002) and Horner & Groves (2007) have explicitly mentioned that their models are applicable to the area but they have not applied the models to any specific case study. | | |

## 9. CONCLUSIONS AND FUTURE RESEARCH

In this survey, USFL problems were investigated. Initially, without limiting the survey to specific journals, we considered those papers published in peer-reviewed journals where (1) specific applications of USFL models are included in real-life problems and (2) OR techniques are used as the main methodology in modeling or solving these problems. Later, we applied a quality testing criterion to shortlist the papers which are published in high-quality journals. Overall, 110 journal papers were shortlisted. We structured the paper from an OR perspective in terms of types of decisions, location space, main assumptions, input parameters, objective functions and constraints. Then, we suggested six clusters to categorize these papers since our investigation showed that the vast majority of the papers in the literature fall into only six categories. These categories are named WMS, LSD, SSE, GSI, NES and TSI. Each of the categories was analyzed critically in terms of applications, assumptions, decisions, input parameters, constraints, objective functions and solution techniques. Some gaps and trends have been observed and accordingly some suggestions for future research directions are explored for each of the six categories.

We learned that the NEH area is more mature than the other studied areas in terms of location space because (1) the majority of the papers in the area consider multi-type facilities rather than single type, (2) most of the papers consider multi-facility models rather than a single facility, (3) discrete and network spaces have been widely studied, and (4) there is a fairly comprehensive list of input parameters in the literature of NEH that can assist with the models developed by researchers for other applications in the future. Perhaps the reason is that NEH facilities have a bigger impact both economically and socially when compared with most of the other areas. We believe this trend will continue in the future. In this section, we consolidate and integrate our observations and lessons learned for all of the categories and synthesize future research directions.

***1. Joint decisions integrated with location*:** We observed that in addition to making only locational decisions for USFL problems (which is a strategic decision), scholars make some other strategic, tactical and operational decisions jointly to achieve better results. Location-allocation and location-routing are the most popular joint decisions made for USFL problems. Obviously, this can be extended to other decisions such as fleet sizing, transportation, distribution and inventory.

***2. Realistic distance measures:*** In facility location problems, one of the most important inputs is the distance between new and existing facilities. In most of the current USFL studies, the distance is given with no explanation about how it is calculated. In the literature of facility location, in order to calculate distance, usually rectilinear (or Manhattan), Euclidean and squared Euclidean distances are considered. Each of these distance measures has its own application. There are many other distance measures such as Minkowski distance, Chebyshev distance (or infinity norm), aisle distance, block distance, gauge measures, Hilbert curve, Mahalanobis distance, Hamming distance, Levenshtein distance and Hausdorff distance which have not been tested to see whether they are more realistic in real-life USFL problems (interested readers may refer to Zarinbal (2009) to learn about these measures). Additionally, nowadays, technologies such as Maps (particularly Geographic Information Systems) and GPS navigators, unlike traditional distance measures, are able to readily obtain exact distances between two points. These tools may be exploited in future research studies.

***3. Sustainability:*** In order to have sustainable cities, aside from economic objectives, social and environmental factors must be considered. As a result, some objectives and constraints such as pollution, noise, fossil fuel crisis and costs of energy must be considered while planning for urban areas. We observed that although recently social and environmental functions (e.g. accessibility and noise pollution) have been increasingly considered in formulated models, the majority of models still focus on economic objectives. Drivers such as regulations and consumer pressure make us consider sustainability in our models. Note that quantifying social and environmental aspects is more difficult than economic aspects. Another important point is that we should know when a social/environmental aspect needs to be included as an objective and when as a constraint. If there is a strict limit set by regulations or top managers of an organization, then it is a constraint; otherwise we should consider an objective function for that. When it comes to solving these models, there is a possibility that we have more than one objective function. This makes us exploit multi-objective decision making (MODM) techniques in analyzing and solving the model and see a trade-off among objectives (Farahani et al. 2010).

***4. Uncertainty of parameters:*** We observed that the majority of the studied USFL case studies assume that the input parameters are deterministic and do not change over time. This simplifying assumption makes problem modeling and finding solutions easier. Besides, sometimes we do not have sufficient historical data to monitor changes in the input parameters. However, we believe that in reality, input parameters not only may change but also might be random. In cases where we lack sufficient quantitative data we may use fuzzy theory concepts in our model formulations. On the other hand, if the inputs change over time we may use multi-period (dynamic) modeling. If we observe parameters follow a random distribution, we can consider stochastic modeling.

***5. Continuous space with restriction:*** In most case studies, researchers choose some potential points in urban areas and use discrete space modeling. They decide whether or not to locate a new facility in each of these potential locations. In other words, when using discrete location modeling we ignore many other feasible areas that can be considered as the location of new facilities. One possible approach is to include more feasible space on the continuous plane. Obviously, one may criticize this approach arguing that there are lots of restricted regions in urban areas and there is a possibility that the optimal solution falls in the restricted areas. In order to solve this issue, we may solve a facility location with restricted areas. Note that restricted areas can be divided into three groups that can be considered depending on the nature of the case under study: i) forbidden, ii) congested and iii) barrier. We cannot locate a facility within a forbidden region (e.g. national parks) but might pass through it (Amiri-Aref et al. 2016). A facility may not be located in a congested area (e.g. forests and lakes); while passing through it is permitted but is costly. A barrier region is where a facility cannot be located; additionally we cannot pass through it. These areas are unexplored in the context of USFL.

***6. Decision makers' risk attitude:*** In an uncertain environment, various decision makers (DMs) may make different decisions depending on their risk attitudes. Considering the nature of the facility location problem, the decision maker can be risk averse, risk seeking or risk neutral. Rarely do USFL scholars consider the DM risk attitude. For emergency facilities, the DM is usually risk averse in order not to endanger people's lives. In business oriented facilities (e.g. where the DM tends to maximize profit), he may take a risk seeking approach. Hence, the behavioral aspect of the DM is an important gap in USFL literature that can be further explored in the future.

***7. Dynamic models and relocations:*** A key input parameter in facility location problems (including USFL) is the weight of existing facilities. In USFL problems, the weight can be interpreted as the population of a district, demand of a region and the number of patients etc. Obviously, this weight is subject to change over time. For example, the population of a district may increase or decrease. Note that facility location is a strategic decision. Therefore, the time horizon could be up to decades and over such a long period these changes can be significant. In real-life problems there are two main strategies to take dynamics of weights into consideration: (1) if the located facility is very expensive, we should consider a finite or infinite time horizon that comprises multiple periods. In each period, the weights change and we can determine the appropriate location for the new facility in a way to be optimum during the time horizon; (2) if the facility is not very expensive or it is mobile, we can relocate it; then we need to decide when during the time horizon and where the new facility should be relocated to. This area is fairly unexplored in USFL problems. Interested readers may refer to Boloori Arabani and Farahani (2012) to learn about facility location dynamics.

***8. Demand aggregation:*** In USFL problems we may deal with tens of thousands of "demand points" (DP) usually for individual private residences. A difficulty with modeling location models in urban or regional areas is that the number of DPs may be quite large, because each home, shop and retailer etc. might be a DP. Therefore, it may not be possible or practical (and also unnecessary) to include every DP in the model. For different problems such as location of bank branches, tax offices, network traffic flow and vehicle exhaust emission inspection stations, an aggregation approach is used. To do this, for example, you may suppose that every DP in each zone of the larger urban area is at the centroid of the zone. The result is a smaller model to solve, but with an intrinsic error. If we want to have aggregated models with a small number of aggregated demand points and also a small error, the question is how to aggregate the DPs. The question is how to trade off the benefits and the costs of aggregation. This area is fairly understudied in USFL literature. Interested readers may refer to Francis et al. (2015) to learn about the basics and concept of aggregation error for location models.

***9. Competition:*** When facing a business USFL problem, in which the private sector intends to maximize its profit, the new facility may compete with some similar facilities in the market run by other private owners. Therefore, cannibalization effects might appear, resulting in the loss of profit by the new facility. Therefore, the owner of the new facility may choose another location in order to stay away from the current rivals while still being attractive for customers in terms of accessibility. Competitive facility location models can make USFL problems more realistic (interested readers may refer to. Eiselt et al. (1993) and Drezner (2014) to read more about basics of these models).

***10. Location sharing:*** Sometimes instead of competing or looking for new locations, we may develop collaborations with some existing businesses to share locations. Usually, we choose businesses that have the same customer groups as ours but the product we offer should be different to avoid competition. For example, in order to reduce location costs, in some large cities (e.g. London) many DHL post office branches share a location with retail stores such as Ryman (British stationer and supplier of home and office essentials), STAPLES (American office supply retailing corporation) and WH Smith (British book seller). In fact, this is one of the concepts in supply chain management which is implemented by these companies in a USFL context.

***11. Reliability:*** Every located facility faces disruptions such as natural or man-made disasters. Therefore, located facilities must somehow rectify using excess inventory and redundant facilities. These types of problems can be called location-reliability problems. Snyder et al. (2006) divided these models into two major categories: design versus fortification. "Design" means locating new facilities when nothing exists in advance; i.e., we are facing a design from scratch problem. In "fortification" there is a current network and we want to improve it so that the network can resist disasters. In the current USFL literature, we saw few studies considering the concept or "backup coverage" in which there are some standby facilities to serve in case of disruption. This area needs more research in the future.

***12. Impact of IT:*** In today's world we cannot ignore the impact of information technology (IT) on people's lives.

In USFL problems this will also affect the location of facilities. For example, in the past supermarket chains used to disperse their retail branches across a city to make sure customers had access to at least one branch. This tended to increase their market share or profit. The reason was that customers used to visit shops on foot. Nowadays, there are at least two other shopping options to be added to traditional on-foot shopping: 1) On-line shopping and home delivery and 2) on-line shopping, click and collect. In other words, customers shop through the Internet; then the delivery can be at home or they can drive to the supermarket to collect the ready to pick up order. These options make the need for physical access to shops less than before. Therefore, in modeling location problems we need to consider how IT would affect physical access or travel.

***13. Solution approaches:*** Most of the USFL problems are formulated in discrete location space. These problems are proved to be computationally hard to solve. Therefore, heuristic and meta-heuristic techniques are designed to solve these models. We observed that meta-heuristic techniques are understudied in solving these problems. Some efforts have been made over recent years with a special focus on using GA, TS and SA. There are many other meta-heuristic techniques that may help us reach better, near optimal solutions. USFL decisions are strategic; therefore, the main concern is not computational time but it is the objective function value. In fact, since USFL decisions are costly, even a 1% improvement in the objective function value can amount to significant savings. More refined metaheuristics or combinations of metaheuristics with exact methods (matheuristics) can be tested on USFL problems.

**14. Centralization versus decentralization:** There is a close relationship between the number of facilities to be located and the capacity of each facility. For example, theoretically, locating only one service facility with a large capacity in an urban area (centralization) may be ideal in terms of total cost for the owner but it is not attractive in terms of accessibility for customers. On the other hand, locating many small-size facilities (decentralization) makes them easily accessible to customers but the investment cost is huge. Keeping the balance between the number of facilities and their capacities is an example of considering economic and social impacts. This area is another gap in the literature of USFL problems.

## ACKNOWLEDGEMENT

Rubén Ruiz is partially supported by the Spanish Ministry of Economy and Competitiveness, under the project "SCHEYARD – Optimization of Scheduling Problems in Container Yards (No. DPI2015-65895-R) financed by FEDER funds.

## REFERENCES

Albareda-Sambola, M., Fernández, E., Hinojosa, Y. and Puerto, J., 2009. The multi-period incremental service facility location problem. *Computers & Operations Research* **36**(5) 1356–1375.

Aldajani, M.A. and Alfares, H.K. 2009. Location of banking automatic teller machines based on convolution. *Computers & Industrial Engineering* **57**(4) 1194–1201.

Altay, N., W.G. Green III. 2006. OR/MS research in disaster operations management. *European Journal of Operations Research* **175**(1) 475–493.

Alumur, S. and Kara, B.Y. 2007. A new model for the hazardous waste location-routing problem. *Computers & Operations Research* **34**(5) 1406–1423.

Alumur, S. and Kara, B.Y. 2008. Network hub location problems: The state of the art. *European journal of operational research,* **190**(1) 1–21.

Aly, A.A. White, J.A. 1978. Probabilistic formulation of the emergency service location problem. *Journal of the Operational Research Society* **29**(12)1167-1179.

American Society of Civil Engineers. Report Card for America's Infrastructure. 2013, Online: http://www.asce.org/reportcard.

Amiri-Aref, M. Farahani, R.Z. Javadian, N. and Klibi, W. 2016. A rectilinear distance location–relocation problem with a probabilistic restriction: mathematical modelling and solution approaches. *International Journal of Production Research* **54**(3) 629–646.

An S. Cui N. Li X. Ouyang Y. 2013. Location planning for transit-based evacuation under the risk of service disruptions. *Transportation Research Part B: Methodological* **54** 1–16.

Arabani, A.B. and Farahani, R.Z. 2012. Facility location dynamics: An overview of classifications and applications. *Computers & Industrial Engineering* **62**(1) 408–420.

Araz, C. Selim, H. and Ozkarahan, I. 2007. A fuzzy multi-objective covering-based vehicle location model for emergency services. *Computers & Operations Research* **34**(3) 705–726.

Asefi H. Lim S. Maghrebi, M. 2015. A mathematical model for the municipal solid waste location-routing problem with intermediate transfer stations. *Australasian Journal of Information Systems* **19** 21–35.

Badri, M.A. Mortagy, A.K. and Alsayed, C.A. 1998. A multi-objective model for locating fire stations. *European Journal of Operational Research* **110**(2) 243–260.

Baskaya, S., Ertem, M.A. and Duran, S., 2017. Pre-positioning of relief items in humanitarian logistics considering lateral transhipment opportunities. *Socio-Economic Planning Sciences*, 57, pp.50-60.

Berlin, G.N. and Liebman, J.C. 1974. Mathematical analysis of emergency ambulance location. *Socio-Economic Planning Sciences* **8**(6)323–328.

Beliën, J. De Boeck, L. Colpaert, J. Devesse, S. and Van den Bossche, F. 2013. Optimizing the facility location design of organ transplant centers. *Decision Support Systems* **54**(4)1568–1579.

Berman O. Hajizadeh I. Krass D. 2013. The maximum covering problem with travel time uncertainty. *IIE Transactions* **45**(1)810–96.

Boffey, T.B. Mesa, J.A. Ortega, F.A. and Rodrigues, J.I. 2008. Locating a low-level waste disposal site. *Computers & Operations Research* **35**(3) 701–716.

Boffey, B., R. Galvãob, L. Espejob. 2007. A review of congestion models in the location of facilities with immobile servers. *European Journal of Operational Research* **178**(3) 643–662.

Boloori, A., A. Farahani, R., Z. 2012. Facility location dynamics: an overview of classifications and applications. *Computers & Industrial Engineering* **62**(1) 408-420.

Bruns, A. Klose, A. and Stähly, P. 2000. Restructuring of Swiss parcel delivery services. *OR Spectrum* **22**(2) 285–302.

Caballero, R. González, M. Guerrero, F.M. Molina, J. and Paralera, C. 2007. Solving a multiobjective location routing problem with a metaheuristic based on tabu search. Application to a real case in Andalusia. *European Journal of Operational Research* **177**(3) 1751–1763.

Calvo A.B. Marks D.H. 1973. Location of health care facilities: An analytical approach. *Socio-Economic Planning Sciences* **7**(5) 407–422.

Campbell, J.F. and O'Kelly, M.E., 2012. Twenty-five years of hub location research. Transportation Science, 46(2), pp.153-169.

Chang M.-S. Tseng Y.-L. Chen J.-W. 2007. A scenario planning approach for the flood emergency logistics preparation problem under uncertainty. *Transportation Research Part E: Logistics and Transportation Review* **43**(6) 737–754.

Charles, A., Lauras, M., Van Wassenhove, L.N. and Dupont, L., 2016. Designing an efficient humanitarian supply network. *Journal of Operations Management*, 47, pp.58-70.

Cheu, R.L. Huang, Y. and Huang, B. 2008. Allocating emergency service vehicles to serve critical transportation infrastructures. *Journal of Intelligent Transportation Systems* **12**(1) 38-49.

Chowdhury, S., Emelogu, A., Marufuzzaman, M., Nurre, S.G. and Bian, L., 2017. Drones for disaster response and relief operations: a continuous approximation model. *International Journal of Production Economics*, 188, pp.167-184.

Church, R.L. A.T. Murray. 2009. *Business Site Selection, Location Analysis and GIS*. Wiley, New York.

Church, R. ReVelle, C. 1974. The Maximal Covering Location Problem. *Papers in Regional Science* **32** (1) 101–118.

Central Intelligence Agency (CIA). 2015. "The World Factbook", available at: https://www.cia.gov/library/publications/the-world-factbook/fields/2012.html (retrieved on 7 August 2016).

Cohon J.L. ReVelle C.S. Current J. Eagles T. Eberhart R. Church R. 1980. Application of a multiobjective facility location model to power plant siting in a six-state region of the U.S. *Computers & Operations Research* 9(1–2)107–123.

Coutinho-Rodrigues, J. Tralhão, L. and Alçada-Almeida, L. 2012. A bi-objective modeling approach applied to an urban semi-desirable facility location problem. *European Journal of Operational Research* **223**(1) 203–213.

Cruz-Rivera, R. and Ertel, J. 2009. Reverse logistics network design for the collection of end-of-life vehicles in Mexico. *European Journal of Operational Research* **196**(3) 930–939.

Curtin, K.M. Hayslett-McCall, K. and Qiu, F. 2010. Determining optimal police patrol areas with maximal covering and backup covering location models. *Networks and Spatial Economics* **10**(1) 125-145.

Current, J. and O'Kelly, M. 1992. Locating emergency warning sirens. *Decision Sciences* **23**(1) 221-234.

Daskin, M.S. 1995. *Network and descrete location analysis.* John Wiley and Sons, New york.

Daskin, M.S. 2008. What you should know about location modeling. *Naval Research Logistics* **55**(4), 283–294.

Drezner, T. (2014) A review of competitive facility location in the plane, *Logistics Research* **114**(7) 1-12.

Drezner, Z. 1995. *Facility location: A survey of applications and theory*. Springer, Berlin.

Drezner, H. Hamacher, W. (Eds.), 2002. *Facility Location: Applications and Theory*. Springer, New York.

Dobbs, R. Smit, S. Remes, J. Manyika, J. Roxburgh, C. & Restrepo, A. 2011. *Urban World: Mapping the Economic Power of Cities.* McKinsey Global Institute.

Doerner, K. Focke, A. and Gutjahr, W.J. 2007. Multicriteria tour planning for mobile healthcare facilities in a developing country. *European Journal of Operational Research* **179**(3) 1078-1096.

Eiselt, H.A. 2007. Locating landfills—Optimization vs. reality. *European Journal of Operational Research* **179**(3) 1040–1049.

Eiselt, H. A., G. Laporte and J. F. Thisse (1993). Competitive location models: A framework and bibliography. *Transportation Science* **27**(1) 44-54.

Erkut, E. Ingolfsson, A. and Erdoğan, G. 2008b. Ambulance location for maximum survival. *Naval Research Logistics*, **55**(1) 42–58.

Erkut, E. Karagiannidis, A. Perkoulidis, G. & Tjandra, S. A. (2008a). A multicriteria facility location model for municipal solid waste management in North Greece. *European Journal of Operational Research* **187**(3), 1402–1421.

Farahani, R. Z. and Hekmatfar, M. 2009. *Facility Location Concepts, Models, Algorithms and Case Studies*. Berlin Heidelberg, Springer.

Farahani, R.Z. Hekmatfar, M. Fahimnia, B. and Kazemzadeh, N. 2014. Hierarchical facility location problem: Models, classifications, techniques, and applications. *Computers & Industrial Engineering* **68** 104–117.

Farahani, R.Z. Hekmatfar, M. Arabani, A.B. and Nikbakhsh, E. 2013a. Hub location problems: A review of models, classification, solution techniques, and applications. *Computers & Industrial Engineering* **64**(4) 1096–1109.

Farahani, R.Z. Rashidi Bajgan, H. Fahimnia, B. and Kaviani, M. 2015. Location-inventory problem in supply chains: a modelling review. *International Journal of Production Research* **53**(12) 3769–3788.

Farahani, R.Z. SteadieSeifi, M. and Asgari, N. 2010. Multiple criteria facility location problems: A survey. *Applied Mathematical Modelling* **34**(7) 1689–1709.

Farhan B. Murray A.T. 2006. Distance decay and coverage in facility location planning. *Annals of Regional Science* **40**(2) 279–295.

Farhan, B. and Murray, A.T. 2008. Siting park-and-ride facilities using a multi-objective spatial optimization model. *Computers & Operations Research* **35**(2) 445–456.

Fitzsimmons J.A. Srikar B.N. 1982. Emergency ambulance location using the contiguous zone search routine. *Journal of Operations Management* **2**(4) 225–237.

Francis, R.L. McGinnis, L.F. and White, J.A. 2015. *Facility layout and location: an analytical approach* (2nd edition), Pearson College Division.

Francis, R. L., T. J. Lowe, M. B. Rayco and A. Tamir.2009. Aggregation error for location models: Survey and analysis, *Annals of Operations Research* **167**(1) 171-208.

Galvao, R.D. Espejo, L.G.A. and Boffey, B. 2002. A hierarchical model for the location of perinatal facilities in the municipality of Rio de Janeiro. *European Journal of Operational Research* **138**(3) 495–517.

Galvão, R.D. Espejo, L.G.A. Boffey, B. and Yates, D. 2006. Load balancing and capacity constraints in a hierarchical location model. *European Journal of Operational Research* **172**(2) 631–646.

Gendreau, M. Laporte, G. and Semet, F. 1997. Solving an ambulance location model by tabu search. *Location science* **5**(2)75–88.

Gendreau, M. Laporte, G. and Semet, F. 2006. The maximal expected coverage relocation problem for emergency vehicles. *Journal of the Operational Research Society* **57**(1) 22–28.

Geroliminis, N. Karlaftis, M.G. and Skabardonis, A. 2009. A spatial queuing model for the emergency vehicle districting and location problem. *Transportation research part B: methodological* **43**(7) 798–811.

Geroliminis, N. Kepaptsoglou, K. and Karlaftis, M.G. 2011. A hybrid hypercube–genetic algorithm approach for deploying many emergency response mobile units in an urban network. *European Journal of Operational Research* **210**(2) 287–300.

Ghamami, M., Nie, Y. and Zockaie, A., 2016. Planning charging infrastructure for plug-in electric vehicles in city centers. *International Journal of Sustainable Transportation*, 10(4), pp.343-353.

Giannikos, I. 1998. A multiobjective programming model for locating treatment sites and routing hazardous wastes. *European Journal of Operational Research* **104**(2) 333–342.

Görmez, N. Köksalan, M. and Salman, F.S. 2011. Locating disaster response facilities in Istanbul. *Journal of the Operational Research Society* **62**(7) 1239–1252.

Greenhut M.L. Mai C.C. 1980. Towards a general theory of public and private facility location. *The Annals of Regional Science* **14**(2)1–11.

Guerriero F. Miglionico G. Olivito F. 2016. Location and reorganization problems: The Calabrian health care system case. *European Journal of Operational Research* **250**(3) 939–954.

Gupta, S. and Basak, B., 2017. Alternate terminal location planning using accessibility analysis for improved pilgrim movement. *Anatolia*, 28(3), pp.351-362.

Gupta, S., M. Starr, R.Z. Farahani, N. Matinrad. 2016. Disaster management from a POM Perspective: Mapping a new domain. *Productions and Operations Management* **25**(10) 1611–1637.

Hakimi, S.L. 1964. Optimum locations of switching centers and the absolute centers and medians of a graph. *Operations research* **12**(3) 450–459.

Hale, T.S. and Moberg, C.R., 2003. Location science research: a review. *Annals of operations research* **123**(1) 21-35.

Hamacher, H.W. Labbe, M. Nickel, S. and Skriver, A.J. 2002. Multicriteria semi-obnoxious network location problems (MSNLP) with sum and center objectives. *Annals of Operations Research* **110**(1–4) 33–53.

Handler, G.Y. Mirchandani, P.B. 1979. *Location on Networks*. M.I.T. Press, Cambridge, MA.

He, L., Mak, H.Y., Rong, Y. and Shen, Z.J.M., 2017. Service region design for urban electric vehicle sharing systems. *Manufacturing & Service Operations Management*, 19(2), pp.309-327.

He, S.Y., Kuo, Y.H. and Wu, D., 2016. Incorporating institutional and spatial factors in the selection of the optimal locations of public electric vehicle charging facilities: A case study of Beijing, China. *Transportation Research Part C: Emerging Technologies,* 67, pp.131-148.

Hong, S. and Kuby, M., 2016. A threshold covering flow-based location model to build a critical mass of alternative-fuel stations. *Journal of Transport Geography,* 56, pp.128-137.

Horner, M.W. and Groves, S. 2007. Network flow-based strategies for identifying rail park-and-ride facility locations. *Socio-Economic Planning Sciences* **41**(3) 255–268.

Huang, K., Kanaroglou, P. and Zhang, X., 2016. The design of electric vehicle charging network. *Transportation Research Part D: Transport and Environment*, 49, pp.1-17.

Hsia, H.C. Ishii, H. and Yeh, K.Y. 2009. Ambulance service facility location problem. *Journal of the Operations Research Society of Japan* **52**(3) 339–354.

Hu S.-L. Han C.-F. Meng L.-P. 2015. A scenario planning approach for propositioning rescue centers for urban waterlog disasters. *Computers & Industrial Engineering* **87** 425–435.

Hu, C., Liu, X. and Lu, J., 2017. A bi-objective two-stage robust location model for waste-to-energy facilities under uncertainty. *Decision Support Systems*, 99, pp.37-50.

Huang, R. Kim, S. and Menezes, M.B. 2010. Facility location for large-scale emergencies. *Annals of Operations Research* **181**(1) 271–286.

Ingolfsson, A. Budge, S. and Erkut, E. 2008. Optimal ambulance location with random delays and travel times. *Health Care Management Science* **11**(3) 262–274.

Jarvis J.J. Unger V.E. Jr. Corradino J.C. Schimpeler C.C. Roark A.L. 1978. Bus support facility location analysis:

An approach based on system optimization. *Transportation Planning and Technology* **4**(3)153–157.

Jia, H. Ordóñez, F. and Dessouky, M.M. 2007a. Solution approaches for facility location of medical supplies for large-scale emergencies. *Computers & Industrial Engineering* **52**(2) 257–276.

Jia, H. Ordóñez, F. and Dessouky, M. 2007b. A modeling framework for facility location of medical services for large-scale emergencies. *IIE transactions* **39**(1) 41–55.

Johnson M.P. 2003. Single-period location models for subsidized housing: Tenant-based subsidies. *Annals of Operations Research* **123**(1) 105–124.

Johnson M.P. 2006. Single-period location models for subsidized housing: Project-based subsidies. *Socio-Economic Planning Sciences* **40**(4) 249–274.

Johnson, M.P. Gorr, W.L. and Roehrig, S. 2005. Location of service facilities for the elderly. *Annals of operations research* **136**(1) 329–349.

Jones, D. W. (1991) How urbanization affects energy-use in developing countries, *Energy Policy*, **19**(7) 621–630.

Khan A.M. 1987. Solid-waste disposal with intermediate transfer stations: An application of the fixed-charge location problem. *Journal of the Operational Research Society* **38**(1) 31–37.

Killmer, K.A. Anandalingam, G. and Malcolm, S.A. 2001. Siting noxious facilities under uncertainty. *European Journal of Operational Research* **133**(3) 596–607.

Klose, A. and Drexl, A. 2005. Facility location models for distribution system design. *European Journal of Operational Research* **162**(1) 4–29.

Knox, P.L., McCarthy, L. M. (2012) Urbanization: An Introduction to Urban Geography (3rd Edition), Pearson Education.Kose, E. and Karabay, S., 2016. Mathematical programming model proposal to solve a real-life public sector facility location problem. *International Journal of Operational Research*, 26(1), pp.1-12.

Koçak H. 2010. Convex programming approach to the shopping mall (AVM) site selection problem and Sakarya. *European Journal of Social Sciences* **13**(2) 219–228.

Lee, Eva K.; Chien-Hung Chen; Pietz, Ferdinand; Benecke, Bernard.2009. Modeling and optimizing the public-health infrastructure for emergency response. *Interfaces 39*(5) 476–490.

Lee G. Xiao N. 2009. Examining the tradeoff between residential broadband service coverage and network connectivity using a bi-objective facility location model. *Papers in Regional Science* **88**(3) 547–562.

Li, J., Liu, Q., Sang, Y. (2012) Several issues about urbanization and urban safety, *In: International Symposium on Safety Science and Engineering in China, Procedia Engineering,* **43**(1) 615–621.

Lin, Y.H. Batta, R. Rogerson, P.A. Blatt, A. and Flanigan, M. 2012. Location of temporary depots to facilitate relief operations after an earthquake. *Socio-Economic Planning Sciences* **46**(2) 112–123.

Love, R.F. Morris, J.G. Wesolowsky, G.O. 1988. *Facilities Location: Models and Methods*. North Holland, New York.

Love C.G. Trebbi G. 1973. Regional health care planning. *IEEE Transactions on Systems, Man and Cybernetics* **1** 10–18.

Lu, C.C. and Sheu, J.B. 2013. Robust vertex p-center model for locating urgent relief distribution centers. *Computers & Operations Research* **40**(8) 2128–2137.

Marianov, V. and ReVelle, C. 1996. The queueing maximal availability location problem: a model for the siting of emergency vehicles. *European Journal of Operational Research* **93**(1) 110–120.

Mar-Ortiz J. Adenso-Diaz B. González-Velarde J.L. 2011. Design of a recovery network for WEEE collection: The case of Galicia, Spain. *Journal of the Operational Research Society* **62**(8) 1471–1484.

Melachrinoudis, E. and Xanthopulos, Z. 2003. Semi-obnoxious single facility location in Euclidean space. *Computers & Operations Research* **30**(14) 2191–2209.

Melo, M.T. Nickel, S. and Saldanha-da-Gama, F. 2009. Facility location and supply chain management–A review. *European Journal of Operational Research* **196**(2) 401–412.

Mestre, A.M. Oliveira, M.D. and Barbosa-Póvoa, A. 2012. Organizing hospitals into networks: a hierarchical and multiservice model to define location, supply and referrals in planned hospital systems. *OR spectrum* **34**(2) 319–348.

Mirchandani, P.B. Francis, R.L.,1989. *Discrete Location Theory*. Wiley Publications, New York.

Mitropoulos, P. Giannikos, I. and Mitropoulos, I. 2009b. Exact and heuristic approaches for the locational planning of an integrated solid waste management system. *Operational Research* **9**(3) 329–347.

Mohammed, A., Wang, Q. and Li, X., 2017. A cost-effective decision-making algorithm for an RFID-enabled HMSC network design: A multi-objective approach. *Industrial Management & Data Systems*, 117(9), pp.1782-1799.

Moreno, A., Alem, D. and Ferreira, D., 2016. Heuristic approaches for the multiperiod location-transportation problem with reuse of vehicles in emergency logistics. *Computers & Operations Research*, 69, pp.79-96.

Murali, P. Ordóñez, F. and Dessouky, M.M. 2012. Facility location under demand uncertainty: Response to a large-scale bio-terror attack. *Socio-Economic Planning Sciences* **46**(1) 78–87.

Murray, A.T. 2003. A coverage model for improving public transit system accessibility and expanding access. *Annals of Operations Research* **123**(1–4) 143–156.

Murray A.T. Gerrard R.A. 1997. Capacitated service and regional constraints in location-allocation modeling. *Location Science* **5**(2) 103–118.

National Preparedness Goal (2015) (2nd ed.) Homeland Security. https://www.fema.gov/media-library-data/1443799615171-2aae90be55041740f97e8532fc680d40/National_Preparedness_Goal_2nd_Edition.pdf (last visit on 26 October 2017).

Nickel, S. and Puerto, J. 2005. *Facility Location - A Unified Approach*. Springer Verlag, Berlin Heidelberg.

North, J. and Miller, F.L., 2017. Facility location using GIS enriched demographic and lifestyle data for a traveling entertainment troupe in Bavaria, Germany. *Decision Support Systems*, 99, pp.30-36.

O'Kelly M.E. Murray A.T. 2004. A lattice covering model for evaluating existing service facilities. *Papers in Regional Science* **83**(3) 565–580.

Olapiriyakul, S., 2017. Designing a sustainable municipal solid waste management system in Pathum Thani, Thailand. *International Journal of Environmental Technology and Management*, 20(1-2), pp.37-59.

Owen, S.H. and Daskin, M.S. 1998. Strategic facility location: A review. *European Journal of Operational Research* **111**(3) 423–447.

Oğuz, M., Bektaş, T., Bennell, J.A. and Fliege, J., 2016. A modelling framework for solving restricted planar location problems using phi-objects. *Journal of the Operational Research Society*, 67(8), pp.1080-1096.

Paul, J.A. and MacDonald, L., 2016. Location and capacity allocations decisions to mitigate the impacts of unexpected disasters. *European Journal of Operational Research*, 251(1), pp.252-263.

Pelegrín, B., Fernández, P. and Pérez, M.D.G., 2016. Profit maximization and reduction of the cannibalization effect in chain expansion. *Annals of Operations Research*, 246(1-2), pp.57-75.

Pizzolato, N.D. Barcelos, F.B. Lorena, N. and Antonio, L. 2004. School location methodology in urban areas of developing countries. *International Transactions in Operational Research* **11**(6) 667–681.

Plastria, F. 2001. Static competitive facility location: an overview of optimisation approaches. *European Journal of Operational Research* **129**(3) 461–470.

Rajagopalan, H.K. Saydam, C. and Xiao, J. 2008. A multiperiod set covering location model for dynamic redeployment of ambulances. *Computers & Operations Research* **35**(3) 814–826.

Ratick, S., Osleeb, J. and Si, K., 2016. The maximal cover location model with hedging: siting facilities under uncertainty, a lead poisoning screening network for the Dominican Republic. *International Regional Science Review*, 39(1), pp.77-107.

Rakas, J. Teodorović, D. and Kim, T. 2004. Multi-objective modeling for determining location of undesirable facilities. *Transportation Research Part D: Transport and Environment* **9**(2) 125–138.

Sadorsky, P. (2013) Do urbanization and industrialization affect energy intensity in developing countries? *Energy Economics*, **37**(1) 52–59.

Salman F.S. Gül S. 2014. Deployment of field hospitals in mass casualty incidents. *Computers & Industrial Engineering* **74**(1) 37–51.

Saunders, M. Lewis, P. & Thornhill, A. 2012. *Research Methods for Business Students*. 6th ed. Pearson.

Şahin, G. and Süral, H. 2007. A review of hierarchical facility location models. *Computers & Operations Research* **34**(8) 2310–2331.

Skriver, A.J. and Andersen, K.A. 2003. The bicriterion semi-obnoxious location (BSL) problem solved by an $\epsilon$-approximation. *European Journal of Operational Research* **146**(3) 517–528.

Snyder, L.V. 2006. Facility location under uncertainty: a review. IIE Transactions **38**(7) 547–564.

Suzuki, T. and Hodgson, M.J. 2003. Multi-service facility location models. *Annals of Operations Research* **123**(1–4) 223–240.

Syam, S.S. and Côté, M.J. 2010. A location–allocation model for service providers with application to not-for-profit health care organizations. *Omega* **38**(3) 157–166.

Teye, C., Bell, M.G. and Bliemer, M.C., 2017. Entropy maximising facility location model for port city intermodal terminals. *Transportation Research Part E: Logistics and Transportation Review*, 100, pp.1-16.

Teixeira, J.C. and Antunes, A.P. 2008. A hierarchical location model for public facility planning. *European Journal of Operational Research* **185**(1) 92–104.

Tian, G., Zhou, M., Li, P., Zhang, C. and Jia, H., 2016. Multiobjective optimization models for locating vehicle inspection stations subject to stochastic demand, varying velocity and regional constraints. *IEEE Transactions on Intelligent Transportation Systems*, 17(7), pp.1978-1987.

Tien, J.M. El-Tell, K. and Simons, G.R. 1983. Improved formulations to the hierarchical health facility location-allocation problem. *IEEE transactions on systems, man, and cybernetics* **6**(1) 1128–1132.

Toregas, C., Swain, R., ReVelle, C. and Bergman, L., 1971. The location of emergency service facilities. Operations research, 19(6), pp.1363-1373.

Toso E.A.V. Alem D. 2014. Effective location models for sorting recyclables in public management. *European Journal of Operational Research* **234**(3) 839–860.

Tu W. Li Q. Fang Z. Shaw S.-L. Zhou B. Chang X. 2016. Optimizing the locations of electric taxi charging stations: A spatial-temporal demand coverage approach. *Transportation Research Part C: Emerging Technologies* **65**(1) 172–189.

Tüzün Aksu, D. and Ocak, Z. 2012. Location of municipal centers for new counties within the Istanbul metropolitan municipality. *Journal of Urban Planning and Development* **138**(2)143–152.

Van Wassenhove, L.N. 2006. Blackett memorial lecture humanitarian aid logistics: supply chain management in high gear. *Journal of Operational Research Society* **57**(5) 475–489.

Vij, D. (2012) Urbanization and solid waste management in India: Present practices and future challenges, *Procedia - Social and Behavioral Sciences*, **37**(1) 437–447.

Wang, Q. Batta, R. Bhadury, J. and Rump, C.M. 2003. Budget constrained location problem with opening and closing of facilities. *Computers & Operations Research* **30**(13) 2047–2069.

Wang, Y.W. and Wang, C.R. 2010. Locating passenger vehicle refueling stations. *Transportation Research Part E: Logistics and Transportation Review* **46**(5) 791–801.

Weber, A. 1909. Uber den Standort der Industrien. 1. Teil: Reine Theorie des Standorts. Verlag J.C. B. Mohr, Tubingen.

Wei R. Murray A.T. 2015. Continuous space maximal coverage: Insights, advances and challenges. *Computers & Operations Research* **62**(c) 325–336.

Wu, T.H. and Lin, J.N. 2003. Solving the competitive discretionary service facility location problem. *European Journal of Operational Research* **144**(2) 366–378.

Yan, S., Lin, J.R., Chen, Y.C. and Xie, F.R., 2017. Rental bike location and allocation under stochastic demands. *Computers & Industrial Engineering*, 107, pp.1-11.

Yang, L. Jones, B.F. and Yang, S.H. 2007. A fuzzy multi-objective programming for optimization of fire station locations through genetic algorithms. *European Journal of Operational Research* **181**(2) 903–915.

Yushimito, W.F. Jaller, M. and Ukkusuri, S. 2012. A Voronoi-based heuristic algorithm for locating distribution centers in disasters. *Networks and Spatial Economics* **12**(1) 21–39.

World Urbanization Prospects: The 2014 Revision (United Nations). Department of Economic and Social Affairs, Population Division, New York, 2015.

Zarinbal, M. 2009. Distance functions in location problem. In: R. Z. Farahani and M. Hekmatfar, ed., *Facility Location: Concepts, Models, Algorithms and Case Studies*, Physica-Verlag, Heidelberg1-17.

Zhang, T., Zeng, Z., Jia, T. and Li, J., 2016. Examining the amenability of urban street networks for locating facilities. *Physica A: Statistical Mechanics and its Applications*, 457, pp.469-479.