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Using applied operations research and geographical information systems to evaluate effective factors in storage service of municipal solid waste management systems

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ABSTRACT

One of the important elements of municipal solid waste management (MSWM) system is waste storage service. Residents deal with the system in this stage and the efficiency of waste collection element, the most expensive element of waste management system, relies on the performance of storage service. In this study, the performance of two different models including minimize facilities (MF) and maximize capacitated coverage (MCC) was investigated to find optimal locations for storage stations in Alandasht district located in Mashhad- Iran. Four effective factors including total service coverage, residential engagement, surplus container capacity devoted to each station and the ratio of the standard deviation to the arithmetic mean of solid waste allocated to each station were considered to compare these models. The MF model provided the highest service coverage by proposing 26 stations covering 98.56 percent of total residences. According to 26 stations proposed with MF model, MCC was run with 26, 27, 25 and 24 stations. MCC-27 provided the maximum attendance of residents with 54.47 percent. However, the most economical container distribution to the stations proposed with MCC-24 by presenting the minimum ratio of surplus devoted capacity to total demand, 33.74 percent. Finally, MCC-25 provided better distribution of residents to the storage stations, i.e., the minimum ratio of the standard deviation to the average solid waste devoted to stations, 22.13 percent. service area (SA) analysis applied to MF, MCC-25 and MCC-24 showed more than 60 percent of residences are located between 0 and 100 m walking distance for these analyses.

1. Introduction

In MSWM systems, there is a significant relation between spatial locations and related features that can be realistically and reliably modeled in a geographical information system (GIS) environment (Tavares et al., 2009), for example (1) the locations of collection bins and their features (capacity of each bin, type of facility, being suitable for commingled or separated waste and, organic or inorganic waste etc.) (Carlos et al., 2016; Chalkias and Lasaridi, 2009; Valeo et al., 1998), (2) collection routes and their attributes (kind of routes according to their function, one-way or two-way street, number of lanes, travel time and distance etc.) (Chang et al., 1997; Ghose et al., 2006; Kanchanabhan et al., 2011; Zsigraiova et al., 2013), and (3) landfills and their specifications (area of facility, distance from municipal elements and, distance from terrain etc.) (Şener et al., 2010; Sumathi et al., 2008). On the other hand, there are some NP-hard problems such as vehicle routing problem (VRP) (Hannan et al., 2018; Karadimas et al., 2007; Laporte, 1992; Toth and Vigo, 2002), hub location problem (HLP) (Bautista and Pereira, 2006; Ghiani et al., 2012; Hekmatfar and Pishvaee, 2009; Nikouei Mehr and McGarvey, 2017) and supply chain management (SCM) (Elia et al., 2018; Garcia and Hora, 2017; Maria Claudia Lima et al., 2017) all of which have an extreme analogy with real-world problem of MSWM systems. OR consists of a wide range of problem-solving techniques, such as simulation, mathematical optimization so it proposes optimal solutions to complex decision-making problems (Ghiani et al., 2014). Consequently, these two useful tools, GIS and OR, have played part in supporting optimization of MSWM systems over the past decades (Vitorino de Souza Melaré et al., 2017).

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According to studies having been accomplished, GIS has played an important role in planning, scheduling and optimizing different functional elements of MSWM systems. In spite of a wide range of researches that have been studied around route finding and waste landfilling, the number of studies having focused on finding optimal locations for collection bins has not been significant, so far (Purkayastha et al., 2015). The major costs of MSWM systems are devoted to collection (Tchobanoglous and Kreith, 2002) and its optimization leads to considerable reduction in marginal costs, financial and environmental (Nafiz et al., 2017), in management and urban planning. However, waste storage service, as another element of MSWM system, also plays an important role in both efficiency of collection model and increasing residential engagement. Participation of residents is of high importance since people play a key role to achieve goals of optimizations (Andersson and Stage, 2018; Ibáñez-Forés et al., 2018).

Some studies proposing methods to model waste storage service were discussed as follows. (Vijay et al., 2005) using GIS analysis, triangulated irregular network (TIN) to allocate bin locations and using GIS-based arc macro language (AML) programs for estimation of waste generation and waste allocation to each bin. In this research which considered 4.0 km^2 as the study area, the superposition of coverages such as income groups, population density, and bin locations on triangulated irregular network coverage were used to estimate and allocate solid waste to a particular bin. Combination of optimization container locations and then collection routes have been studied by some researchers too (Erfani et al., 2017; Khan and Samadder, 2016; Zamorano et al., 2009). (Zamorano et al., 2009) proposed a model based on GIS, to determine an optimal model for improving Municipal Solid Waste system in Churriana de la Vega (Granada, Spain). In this study, Service Area (SA) analysis, ArcGIS Network Analysis extension, was used to optimize the container locations of the different municipal waste fractions and VRP analysis was applied to calculate the shortest route for the collection of organic matter and rest-waste fraction. (Erfani et al., 2017) provided a model to optimize both municipal solid waste storage and collection service through GIS and modeling operations research. Despite (Khan and Samadder, 2016; Zamorano et al., 2009) using SA analysis to devote inhabitants to storage stations, the analytic tool which considers just impedance cutoff for distributing population to stations, (Erfani et al., 2017) employed Location-Allocation analysis (Azarmand and Neishabouri, 2009; Cooper, 1963) which devotes each population block to the specific storage location. In this case, the essential capacity of each station is determined exactly.

In fact, there are two main factors in waste storage service which must be considered to make model more realistic:

i) Modelling population distribution in a way that shows the real distance between each population block and container locations. (Erfani et al., 2017) distributed total population of each block to buildings located in that block according to the number of stories of each building. The number of stories of each building was assumed to be in proportion to its population. In this research, the population model that had been proposed by (Erfani et al., 2017) was applied.

ii) Using the appropriate model to devote each population block to the nearest storage stations based on specifications and limitations of each station. Generally, because of constraints existing in mechanized self-loading collection vehicles, including limit capacity of container and technical specification of unloading mechanism, municipalities and related authorities prefer to use a same type of storage bin in the storage stations across authorized area. Apart from this, using one type of collection bin can have significant effects on waste storage and collection from economic, social and aesthetic point of views.

In this article, using two location allocation models in a GIS environment, four optimal combinations of chosen stations were proposed and evaluated for the waste storage service. In the evaluation process of models not only the total service coverage was considered, like previous similar studies, but other important parameters including residential engagement, economically allocation of container and uniqueness of population distribution to stations were introduced and assessed, as well. To reach this aim, first, location-allocation model, minimize facilities (MF), was used to determine a minimum number of locations that need to cover all the service area. In this model neither the number of stations nor the maximum capacity of each station were subject to predetermined quantities. In the next step, maximize capacitated coverage (MCC) was applied to impose both number of stations and maximum capacity of each station. MCC model was solved for 26 (according to MF result), 27, 25 and 24 number of stations. Maximize attendance (MA) was run for each model to determine what percentage of inhabitants allocated to each station based on initial model would diminish with distance. Finally, Service Area (SA) analysis was applied to show proportion of residences located in each maximum walking distance.

1.1. Area of study

The area studied in this research, Alandasht district, is located in Ahmadabad neighborhood. This district has an area of 700,000 square meters and 5846 residents. Ahmadabad belongs to zone one of region one of Mashhad, second largest city of Iran. As a populated city, implementing a MSWM system is crucial and necessary. The location of this district is shown in Fig. 2.

Currently, curb service is used to collect MSW in Alandasht district. During past decades, dominated urban design has changed from low-rise detached dwellings and villa houses to medium-rise apartments, however, the storage system is the same as before (Erfani et al., 2017). For current situation of Alandasht district, mechanized curb system which used one shared storage station for several residential complexes is more compatible (Nemerow, 2009; Tchobanoglous and Kreith, 2002). In such a system, usually large containers (750 or 1100 L) are used, and the collector is responsible for transporting containers from a storage station to the collection vehicle. The contents of containers are emptied mechanically using collection vehicles equipped with unloading mechanisms.

2. Methodology

In this study, first, the candidate locations (having the potential to be storage stations) were determined according to criteria recommended by articles, then in the second step, Minimize Facilities was modeled and solved to determine the number of locations that cover maximum population blocks across the area of study. After that, based on the number of locations provided in MF, Maximized Capacitated Coverage was modeled and solved. To make sure the best result has been achieved, MCC was run three times more with a different number of facilities. Finally, based on four important factors including total service coverage, total attendance derived from Maximize Attendance analysis, Surplus Devoted Capacity (SDC) and ratio of standard deviation to average MSW devoted to chosen stations all models were assessed. SA analysis was also used to show what percentage of residents are located between 0 and 50, 50–100 and 100–150 m walking distance to collection stations. Fig. 1 showed the procedure through which models provided solutions and factors were evaluated.