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A facility location model for municipal solid waste management system under uncertain environment

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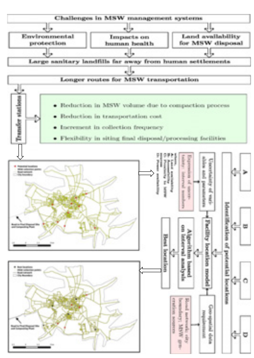
HIGHLIGHTS

- An interval optimization approach is proposed to solve facility location model.
- Multi-parameter uncertainty is modeled for MSW management systems.
- Economically best locations of transfer station are identified under uncertainty.
- The proposed methodology is demonstrated over a complex urban center.

GRAPHICAL ABSTRACT



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ABSTRACT

In municipal solid waste management system, decision makers have to develop an insight into the processes namely, waste generation, collection, transportation, processing, and disposal methods. Many parameters (*e.g.*, waste generation rate, functioning costs of facilities, transportation cost, and revenues) in this system are associated with uncertainties. Often, these uncertainties of parameters need to be modeled under a situation of data scarcity for generating probability distribution function or membership function for stochastic mathematical programming or fuzzy mathematical programming respectively, with only information of extreme variations. Moreover, if uncertainties are ignored, then the problems like insufficient capacities of waste management facilities or improper utilization of available funds may be raised. To tackle uncertainties of these parameters in a more efficient manner an algorithm, based on interval analysis, has been developed. This algorithm is applied to find optimal solutions for a facility location model, which is formulated to select economically best locations of transfer stations in a hypothetical urban center. Transfer stations are an integral part of contemporary municipal solid waste management systems, and economic siting of transfer stations ensures financial sustainability of this system. The model is written in a mathematical programming language AMPL with KNITRO as a solver. The developed model selects five economically best locations out of ten potential locations with an optimum overall cost of [394,836, 757,440] Rs.[1] /day ([5906, 11,331] USD/day) approximately. Further, the requirement of uncertainty modeling is explained based on the results of sensitivity analysis.

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[1] Rs. is Indian currency and 1 Rs. = 0.015 USD as of 18th October 2016.

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1. Introduction

Municipal solid waste (MSW) management is an important environmental concern due to (*i*) rapid population growth; (*ii*) increment in MSW generation rate; (*iii*) environmental protection; (*iv*) human health risk; and (*v*) shrinking of disposal site options because of urbanization (Huang and Chang, 2003; Xu et al., 2009a; Eiselt and Marianov, 2015). Impacts on human health, ensuring environmental protection and shrinking of disposal site options or land availability for disposal sites have ruled out all the possibilities of having small landfills and dumping grounds in the vicinity of human settlements. Consequently, large sanitary landfilling has been found to be the only viable option for disposal of MSW, for instance, the number of landfills in USA reduced from 8000 (in 1988) to 1908 (in 2010) (Stevens, 2002; Eiselt and Marianov, 2015). The reduced number of disposal sites results longer MSW transportation routes. Larger collection vehicles are found to be cost effective for longer transportation of MSW as compared to smaller collection vehicles (Eiselt, 2007). Transfer stations (TSs) are junctions of smaller and larger collection vehicles known as primary collection vehicles (PCVs) and secondary collection vehicles (SCVs) respectively. Being a junction of PCVs and SCVs, locations of TSs are very crucial as far as economical aspect is concerned. Therefore, locations of TSs should be chosen such that the overall cost of MSW management system is minimized similar to any other facility location problems (*e.g.*, fire stations, and warehouses) (Owen and Daskin, 1998). TSs play an important role in collection system such as (*i*) volume reduction due to compaction process; (*ii*) transportation cost reduction; (*iii*) increment in collection frequency; and (*iv*) flexibility in siting final disposal/processing facilities (Cui et al., 2011; USEPA, 2002; Yadav et al., 2016b). This problem statement is graphically depicted in Fig. 1. Additionally, modern TSs are fully closed to prevent the entries of animals and flies, hence maintain a hygienic condition in the vicinity. Therefore, facility location model for TSs siting will help to improve the efficiency of collection system, while decreasing the costs and health hazards. Yadav et al. (2016a) proposed a facility location model for choosing economically best locations for TSs among the given potential locations with deterministic parameters. This study is an extension of Yadav et al.'s (2016a) model by including the inherent uncertainty of MSW management system's parameters with a demonstration on a hypothetical case study. Also, an algorithm is developed to account the uncertainties of variables and parameters of a facility location problem using interval analysis approach. The next subsection reviews past efforts made to implement facility location models in MSW management systems.

1.1. Facility location models for MSW management

Different approaches have been followed by the researchers to establish a financially sustainable MSW management system for any city. Fig. 2 describes these different approaches along with their specific objectives and representative literatures. These approaches include routing of vehicles under given circumstances (Beltrami and Bodin, 1974; Chang et al., 1997; Karadimas et al., 2007; Benjamin and Beasley, 2010); selection of appropriate locations from a number of given potential locations (facility location problems) and expansion of size or capacity of certain facility over a defined period of time (Huang et al., 1994b; Nie et al., 2004; Li et al., 2008; Xu et al., 2009b). Evidently, facility location problems are one of the most prevalent approaches to make MSW management system financially sustainable (Marks and Liebman, 1970; Gottinger, 1988; Kirca and Erkip, 1988; Or and Curi, 1993; Costi et al., 2004; Badran and El-Haggar, 2006; Yeomans, 2007; Yadav et al., 2016a). Facility location problems are the broad classes of optimization problems that have been widely studied in operations research fraternity (Hamacher and Drezner, 2002; Melo et al., 2009; Laporte et al., 2015). Often, parameters of MSW management systems are inherently uncertain in nature (Huang et al., 1995; Wang et al., 2012) and ignorance of uncertainty may lead to problems like the insufficient capacity of facilities or incomplete collection of MSW generated. The next subsection continues the discussion on uncertainties in MSW management systems through a comprehensive literature review.

1.2. Accounting for uncertainty

As already discussed, many system parameters in MSW management system *e.g.*, waste-generation rate, functioning cost of facilities, transportation cost, and revenues are associated with uncertainties; therefore, it is necessary to account for this system with uncertainties of variables and parameters. In system analysis, there are several approaches to deal with uncertainty such as stochastic programming, fuzzy programming, and interval programming (Shmoys and Swamy, 2006; Chang et al., 2008; Fan et al., 2012).

In stochastic programming, uncertainty is usually characterized by a probability distribution of the parameters. In several MSW management studies, stochastic programming models have been developed by Gorelick (1990), Huang et al. (2001), Li and Huang (2006) and Wang et al. (2012). However, the problem in this methodology lying in difficulty to generate probability distributions with inadequate data *e.g.*, daily MSW generation. It may be difficult to state a reliable probability distribution for MSW generation as it fluctuates within a certain interval (Marti, 1990). It has been further observed that it is extremely hard to solve a large stochastic programming with all uncertain data with given probability distributions (Birge and Louveaux, 2011).

Fuzziness is another type of uncertainty characteristics and can not be described by probability distributions (Möller et al., 2003). In fuzzy mathematics, parameters are considered as fuzzy sets and are described by possibility distributions. Fuzzy sets allow its members to have different grades of membership (membership function) within the interval $[0, 1]$. These membership functions of fuzzy objective and constraints are determined subjectively by the decision makers. In past, several studies have proposed MSW management system with the inclusion of fuzzy programming *e.g.*, Fan et al. (2014), Karadimas et al. (2006), Ojo and Anyata (2009) and Srivastava and Nema (2011). However, fuzzy models can not effectively incorporate inherent uncertainties with imprecise coefficients of the objective function and constraints (Huang et al., 1993). Also, it is difficult to create membership functions with very limited information such as the extremes of waste generation rate (Almeida et al., 2011). This issue leads to difficulties in generating sound decision schemes.

Huang et al. (1992) introduced the applications of algorithms based on grey/interval programming in the field of MSW management. In grey or interval programs, the values of parameters vary within two known extreme values. These algorithms have the advantage in type of input data requirement over fuzzy and stochastic programming such as insufficiency of data for generating probability distribution or fuzzy membership function (Sun et al., 2014). Also, an effective communication of uncertain information can be achieved using these algorithms (Huang et al., 1997). In last two decades, a number of algorithms based on grey programming have been developed and proposed for MSW management systems, for example, grey linear programming (Huang et al., 1993), grey dynamic programming (Huang et al., 1994a), and grey mixed integer linear programming (Huang et al., 1995). Further, Karmakar and Mujumdar (2006, 2007) used interval grey numbers to address the uncertainty of fuzzy membership functions and expressed upper and lower bounds of fuzzy membership functions as interval grey numbers.

To solve grey/interval programming problems, the two-step method is used. In this method, the parent problem is transformed into two submodels, one for the most favorable case and another for the least favorable case. It is expected that interval solutions of these submodels include all possible optimal solutions of each and every