# Optimization of Municipal Solid Waste Management

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**Abstract -** *Continuous increase in population, municipal solid waste (MSW) generation rates, population densities, industrialisation and urbanisation has made MSW an alarming concern of modern life. A small congested area now is producing a lot of solid waste which has to be managed otherwise may lead to nuisances. Therefore, MSW management (MSWM) is required for proper management and treatment of MSW.*

*MSW management includes collection, transfer, treatment and disposal of MSW. Relating resources associated with all these processes is a very difficult and complex task to do. Therefore, mathematical models are used to answer real life questions i.e. through modelling and then optimizing the model using a solver such as C#. It was found out that if optimisation models were applied and integrated with municipal solid waste management, significant amount of money can be saved. This review report shows how optimisation models are applied on MSWM and the models which have been used on previous studies to attain optimal solutions.*

***Key Words***: MSWM; optimisation models; industrialisation; urbanisation; municipal solid waste management.

## 1. INTRODUCTION

The management of municipal solid waste in India has surfaced or continued to be a severe problem because of environmental and aesthetic concerns. Even though only 31% of Indian population resides in urban areas, this population of 377 million (Census of India, 2011) generates a gigantic 1,43,449 metric tonnes per day of municipal solid waste, as per the Central Pollution Control Board (CPCB), 2014-15 and these figures increase every day with an increase in population. To further add to the problem, the total number of towns (statutory and census) in the country has also increased from 5,161 in 2001 to 7,936 In 2011, thus increasing the number of municipal waste generation by 2,775 within a decade (CPHEEO, 2016). This chapter conveys some basic definitions associated with MSWM, optimization models, use of optimization models in MSMW, objectives of this study and organization of report in subsequent sections.

### 1.1 MSW Management (MSMW)

MSW is used to describe the non-hazardous waste from a city, town or village. India has a population of 127 crores and rapidly increasing. According to literature, India has an average MSW generation rate of 0.5 kg/day which seems quite low but multiply 0.5 with 127 crore people and it becomes $0.635x10^9$ kg/day, this figure shows how colossal this problem can be. Increasing population, urbanization, industrialization and densely populated cities and towns have made the situation worse. Therefore, for every municipality, dealing with MSW is becoming a challenge. MSW if not handled properly it can lead to:

- Environmental pollution (leachate, barren land etc)
- Covers space which can be utilized for other activities
- Impact on human health

However, if treated properly MSW can become a source of energy after some treatment, example: biogas, co-fuel etc.

### 1.2 Optimization in MSW Management

The amount of money spent by any medium-sized city is in crores, even a small improvement can result in a significant savings in the overall cost. Around 80% of the total budget is spent on collection and transportation but to account for the social, environmental & economical aspect of MSW efforts should be made on planning, designing and optimization.

MSWM involves a number of strategic, tactical and operational decisions, such as the selection of MSW treatment technologies, the location of treatment sites and landfills, the future capacity expansion strategies of the sites, waste flow allocation to processing facilities and landfills, service territory partitioning into districts, collection days' selection for each district and each waste type, fleet composition determination, and routing and scheduling of collection vehicles. After reviewing a number of research papers it was found that optimization models are used in the following cases under given circumstances:

1) Vehicle Routing - example: finding out the route through which cost is minimum.

2) Facility Location- example: finding out the facility location out of available locations such that cost is minimum for all the operations.

3) Size or Capacity- example: finding out the appropriate capacity so as to incorporate needs of future generation.

Several successful applications of OR (operational research) methods have been described in the last 40 years. However, because MSWM involves institutional, social, financial, economic, technical, and environmental factors, no model described in the literature is able to capture all different aspects to be considered.

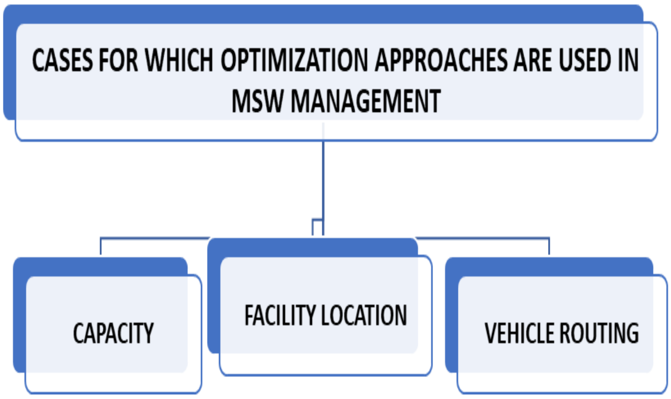


**Figure** Error! No text of specified style in document.**.1** Schematics of various cases in MSW for which optimization approaches are being used

### 1.3 Objective

The specific objectives include:
1) To understand MSMW.
2) To study and report existing optimization models for solving MSWM problems through literature survey.
3) To demonstrate the various optimization models on case studies done in the literature.
4) To understand potential future scope.

## 2 LITERATURE REVIEW
### 2.1 Optimization Models

Optimization means making the best or most effective use out of a situation or resource. Therefore, real-life problem is converted into mathematical model which is than optimized using mathematical models. Objective functions are defined in the optimization models and they are maximized or minimized within the constraints considered.

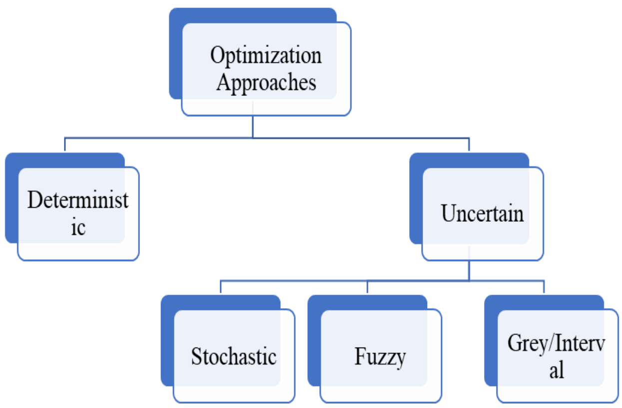


**Figure 2.1** Schematics of various optimization approaches

### 2.1.1 DETERMINISTIC OPTIMIZATION MODELS

Deterministic models are the ones in which sequence of parameters is known and it is assumed that the same sequence will repeat year after year [URL 1].

#### 2.1.1.1 Uncertain/ Inexact Optimization Models (Singh, 2012)

In real world application during the collection of related data, there are inevitable uncertainties in many system parameters such as decision variables, objective functions, and their relationships which could make the waste management systems more complicated (Abichou *et al.*, 2006). Thus, uncertain model methods would be an ideal system analysis tool for decisions that are more feasible for various waste management problems. During the past several decades, various inexact model methods were applied to waste management so as to get more realistic solutions which consider the uncertainty into the picture of decision making. They are mainly categorized as

- Stochastic optimization models (SOM
- Fuzzy optimization models (FOM)
- Interval-parameter optimization models (IOM)
- Combinations of these methods

#### 2.1.2.1Stochastic Optimization Models (SOM):

The SOM focuses on mathematical model problems where there is uncertainty or randomness present in constraints or the objective function. The randomness of parameters is generally taken into account by probabilistic distribution if sufficient data/information is available to estimate it. Two main types of SOM are two-stage stochastic models (TSOM) and chance-constrained models (CCOM).

#### 2.1.2.1.1Two-Stage Stochastic Optimization Models:

TSOM solves the optimization problem in two stages, first waits and sees the changes in variable due to uncertainty or randomness once the random events have occurred go on to 2nd stage where variables obtained in the first stage are used to take corrective measures. The objective is to choose first stage variables such that the sum of first stage cost and second stage cost is minimum. Hence, it can be said that if the effects of random events on the decision-making process are a concern, the decision variables, costs and processes can be divided into two sets, called as TSOMs. The main disadvantage of TSOM is that it cannot be applied when uncertain information is not of satisfactorily enough quality to be presented as random variables.

#### 2.1.2.1.2Chance-Constrained Optimization Models (CCOM):

If there is a random variable in an optimization problem than any parameter which is a function of that random variable inherently becomes a random parameter. In CCOM random decision variables are written in terms of reliability, for ex, a random decision variable(X) should be greater than a value which is desired(Y) say 80%(value of p) of the time thus converting it into a chance constraint: $P (X \geq Y) \geq p \geq 0.8$ Therefore, it can be said that the focus is on the reliability of the system, i.e., the system's ability to meet feasibility in an uncertain environment.

### 2.1.2.2Fuzzy Optimization Models (FOM):

If the randomness of the parameters cannot be characterized by the probability distribution and is imprecise in nature then the fuzzy logic approach is applied. In case of fuzzy models, some constraint violation is allowed and a membership function is defined which gives an idea about the degree of satisfaction and solved simultaneously. Two types of FOM are:

#### 2.1.2.2.1Fuzzy Flexible Optimization Models:

FFOM is used to deal with imprecise input parameters in optimization problems. Taking an example, a parameter X is defined as: X > 6. But after computation, X = 5.99.

Although it is very close to what is desired still it becomes unacceptable, this may create problems in real-life applications where these things happen all the time. Therefore, instead of rejecting it, it can be said that X= 5.99 is acceptable to a lower degree, hence defining membership function.

#### 2.1.2.2.1Fuzzy Robust Optimization Models:

FROM deals with flexible input parameters as well as objective function constraints. When fuzziness in parameters is involved as fuzzy sets, the uncertain parameters are represented as possibility distribution. Ultimately the parameters are converted into deterministic ones and then solved such that the solution for (almost) all possible values of uncertain parameters and flexibility degrees is close to the value of the optimal solution.

The development of the fuzzy logic-based approaches has provided a platform to model uncertainty. However, Kindler and Tyszewski (1995) found a fundamental problem in fuzzy-based approach in terms of identification of membership function and propagation of uncertainty of membership function into the outputs. To address this issue, Karmakar & Mujumdar (2006) treated membership parameters as interval grey numbers. Further, Huang et al., (1992) identified ineffectiveness of fuzzy models to incorporate imprecise uncertainty of coefficients of objective function and constraints. Also, difficulty to generate membership functions with only extreme values of parameters leads Huang *et al.*, (1992) to introduce the application of grey/interval analysis concepts in environmental system modeling.

### 2.1.2.3Grey/ Interval-Parameter Optimization Models (IOM):

If the data collected is inadequate to define a membership function or a probabilistic distribution, but uncertainties are there, then grey/interval modeling is used. Such uncertainties, with unknown characteristics, cannot be effectively modeled by probabilistic or fuzzy logic approach because of the inadequacy of data to estimate probability distribution and lack of information to precisely define the membership functions. However, knowledge of extreme bounds is required for grey/interval models. The solution algorithms of IOM do not generate more complicated intermediate models but require relatively low computational effort. Compared with previous two models discussed, the interval information for parameters in the IOM is more convenient to obtain than their distributional function or membership information, which is particularly meaningful for real-world applications. (Sun *et al.*, 2014)

**Table 2.1** Difference or features of stochastic theory, fuzzy theory and grey theory (Ju-Long, 1982)

| | STOCHASTIC THEORY | FUZZY THEORY | GREY THEORY |
|---|---|---|---|
| Intention | Large sample uncertainty | Cognitive uncertainty | Small sample uncertainty |
| Foundation | Probability distribution | Function of affiliation | Information coverage |
| Characteristics | More data points | Experience | Few data points |
| Requirement | Probability distribution | Membership function | Any-distribution |
| Objective | Laws of statistics | Cognitive expressions | Laws of reality |

## 3 MEHODOLOGY AND CASE STUDY
## 3.1 Deterministic Approach

Objective function: Let C be the overall daily cost of the MSW management system. Then, Minimize C

$$D_j=0,1 \text{ and } X_{ij} \geq 0 = \sum_{j=1}^{J} F_j * D_j + \sum_{i=1}^{I} \sum_{j=1}^{J} OC_j * X_{ij} + \sum_{i=1}^{I} \sum_{j=1}^{J} TC_{ij} * X_{ij} \quad \text{Eq. 3-1}$$

**Constraints**

$$\sum_{i=1}^{I} X_{ij} \leq D_j * CS_j, \forall j = 1, 2, \dots, J, \forall i = 1, 2, \dots, I \quad \text{Eq. 3-2}$$

$$\sum_{j=1}^{J} X_{ij} = G, \forall i = 1, 2, \dots, I \quad \text{Eq. 3-3}$$

$$\sum_{j=1}^{J} D_j \leq J \quad \text{Eq. 3-4}$$

w

here,
$F_j$ : Daily fixed cost for MSWM facility of the $j^{th}$ site,
$OC_j$ : Operating cost for MSW management facility of $j^{th}$ site,
$D_j$ : Binary variable which is equal to 1 if the facility is to be set up at potential location j,
$X_{ij}$ : Amount of daily MSW to be transferred from generation source to the facility j,

$G_i$ : Amount of daily MSW generated at source I,
$CS_j$ : Daily capacity of waste management facility j,
$TC_{ij}$ : Transportation cost for 1 unit of MSW from generation source i to the facility j,
J : Number of potential location.

**Case study (Yadav *et al.*, 2016b)**

Nashik is located in the northwest of Maharashtra state in India having a total area of the city is 259 km². Presently Nashik has MSW generation rate as approximately 235 g/c/day. It contains compostable materials (40%); recyclables (25%); ash, fine earth and others (18.80%); and textiles, plastic, rubber (16.20%) approximately.


**Figure 3.1** Nashik on the map of India (Source: Yadav *et al.*, 2016b)

Ghanta Gadis /PCVs are used for collection and transportation in the Nashik city for door to door collection of MSW and transportation to management facility.

**Figure 3.2** Primary collection vehicle (Ghanta Gadis) at the time of MSW collection in Nashik (Source: Yadav *et al.*, 2016b)

The integrated MSW management facility is known as Khat Prakalp site. Facilities available at Khat Prakalp site include a pre-sorting unit, an aerobic composting plant, an inert processing plant, a leachate treatment plant, an RDF plant, animal carcasses incinerator and a sanitary landfill. The time horizon for this study is five years (2015-2020). It is assumed that the centroid of the wards of Nashik city is the waste generation point sources (see Fig 3.2) and the current situation to be persistent by the end of the year 2020.

Each and every centroid has the waste load equal to the waste generated in the respective ward per day. Also, the distances between generation sources to final disposal and processing sites are Euclidean distances. The mathematical model is written in a mathematical programming language (AMPL) for binary integer programming (BIP) and the solutions were obtained using KNITRO solver. As a part of results, the number of TSs and the best locations for different scenarios were obtained. For a time of five years, this model revealed the location which would be most economical and that the daily overall costs for MSW management are Rs.172178.

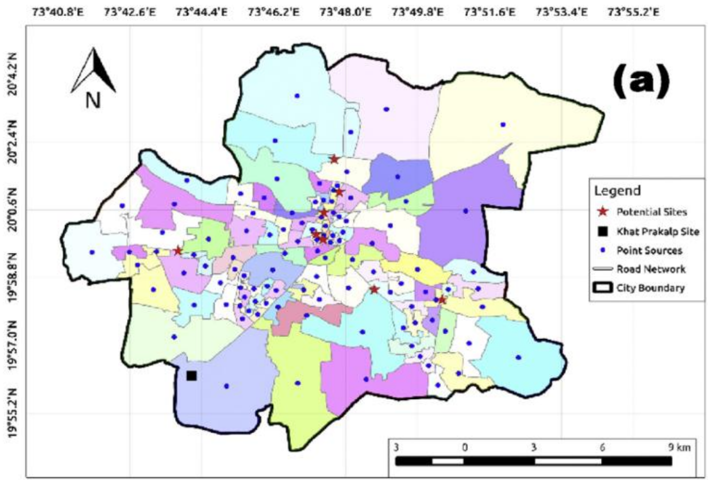


**Figure 3.3** Representing best locations as per case study in Nashik (Source: Yadav *et al.*, 2016b)

## 3.2 UNCERTAIN APPROACH

### 3.2.1 Stochastic Approach

Objective function

$$\text{Max-}\left( \sum_{j=1}^{J} F_j * D_j + \sum_{i=1}^{I}\sum_{j=1}^{J} E\ \beta\ OC_j * X_{ij} + \sum_{i=1}^{I}\sum_{j=1}^{J} TC_{ij} * X_{ij} + E\beta \sum_{i=1}^{I} q_i^+ W_i^+(\omega) \right) \quad \text{Eq. 3-5}$$

**Constraints**

$$\sum_{i=1}^{I} X_{ij} \le D_j \ \forall j \quad \text{Eq. 3-6}$$

$$W_i^+(\omega) = G_i(\omega) - \sum_{j=1}^{J} x_{ij} \ \forall i \quad \text{Eq. 3-7}$$

$$D_j \in \{0,1\} \quad \text{Eq. 3-8}$$

$$0 \le X_{ij} \quad \text{Eq. 3-9}$$

$$W_i^+(\omega) \ge 0, \forall i, j \quad \text{Eq. 3-10}$$

where,
$E_{ij}$ : Binary value which is equal to one if TS(j= 1,2,..J) has been chosen for the source (i= 1,2…I),
β : Fraction of MSW which needs to be sent to the RDF plant,
$W_i^+(\omega)$ : Excess amount of waste at i in state ω,
$q_i^+$ : Penalty paid per unit of waste $G_i$ which is not collected from source I,
$F_j$ : Daily fixed cost for MSWM facility of the jth site,
$OC_j$ : Operating cost for MSWM facility of jth site,

$D_j$ : Binary variable which is equal to 1 if the facility is to be set up at potential location j,
$X_{ij}$ : Amount of daily MSW to be transferred from generation source to the facility j,
$x_{ij}$ : Fraction of waste from source I goes to facility location j,
$G_i$ : Amount of daily MSW generated at source i,
$CS_j$ : Daily capacity of waste management facility j,
$TC_{ij}$ : Transportation cost for 1 unit of MSW from generation source i to the facility j,
P : Number of potential location.

**Case study** (Source: Yadav *et al.*, 2016)
The developed two stage stochastic model for the same site in Nashik was written in a mathematical programming language (AMPL) using KNITRO 5.2 (nonlinear interior-point trust region optimizer) solver. This model chooses 3 best sites among 8 potential sites (Figure 3.4) with Rs.175853 as daily cost of MSWM.

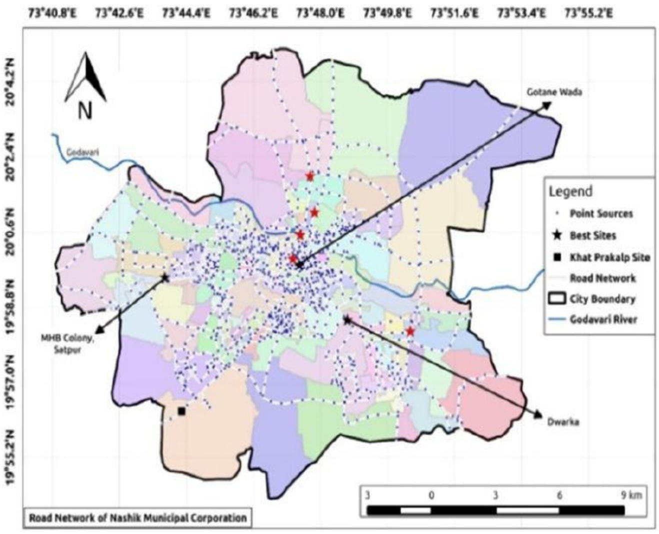


**Figure 3.4** Representing best locations as per case study in Nashik (Source: Yadav *et al.*, 2016a)

## 3.2.2 Fuzzy Approach

Objective function

$$\text{Min } Z = \sum_{j=1}^{J} F_j * D_j + \sum_{i=1}^{I}\sum_{j=1}^{J} OC_j * X_{ij} + \sum_{i=1}^{I}\sum_{j=1}^{J} TC_{ij} * X_{ij}$$

$$+\sum_{i=1}^{I}\sum_{j=1}^{J} OC_k * Y_{jk} + \sum_{i=1}^{I}\sum_{j=1}^{J} TC_{jk} * Y_{jk} \qquad \text{Eq. 3-11}$$

Positive ideal solution (PIS) and negative ideal solution (NIS) for objective function:

$$Z^{PIS} = \min Z \qquad \text{Eq. 3-1}$$

$$Z^{NIS} = \max Z \qquad \text{Eq. 3-2}$$

Linear relationship function is defined as:

$$\mu_h = \begin{cases} 1 & Z < Z^{NIS} \\ \frac{Z^{NIS} - Z}{Z^{NIS} - Z^{PIS}} & Z^{PIS} \le Z \le Z^{NIS} \\ 0 & Z > Z^{PIS} \end{cases} \qquad \text{Eq. 3-14}$$

$\mu_h$ is the degree of satisfaction for the objective function.

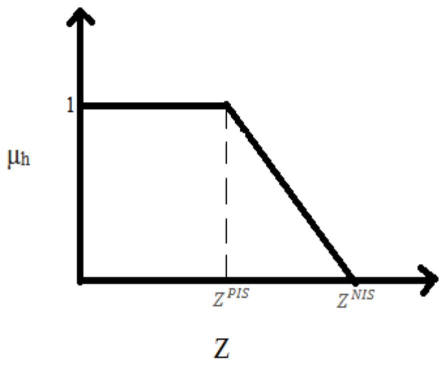


**Figure 3.5** The membership function system (Source: Jabbarzadeh & Jabalameli, 2016)

**Constraints**

$$\sum_{j=1}^{J} D_j \le J \qquad \text{Eq. 3-15}$$

$$\sum_{i=1}^{I} Xij \le D_j * CS_j, \forall\, j = 1, 2, \dots, J, \forall\, i = 1, 2, \dots, I \qquad \text{Eq. 3-16}$$

$$\sum_{j=1}^{J} Xij = G_i, \forall\, i = 1, 2, \dots, I \qquad \text{Eq. 3-17}$$

where,
$OC_k$ : Daily operating cost for MSWM facility of $k^{th}$ landfill site,
$Y_{jk}$ : Amount of daily MSW to be transferred from $j^{th}$ TS site to $k^{th}$ landfill site,
$TC_{jk}$: Transportation cost for 1 unit of MSW from $j^{th}$ TS site to $k^{th}$ landfill site,
$F_j$ : Daily fixed cost for MSWM facility associated with $j^{th}$ site,
$OC_j$ : Daily operating cost for MSWM facility of $j^{th}$ site,
$D_j$ : Binary variable which is equal to 1 if the facility is to be set up at potential location j,
$X_{ij}$ : Amount of daily MSW to be transferred from generation source or consumer to the facility j,
$G_i$ : Amount of daily MSW generated at source i,
$CS_j$ : Daily capacity of waste management facility j,
$TC_{ij}$ : Transportation cost for 1 unit of MSW from generation source i to the facility j,
J : Number of potential location,
K : Total number of landfill sites.

**Case study (Source: Jabbarzadeh & Jabalameli, 2016)**

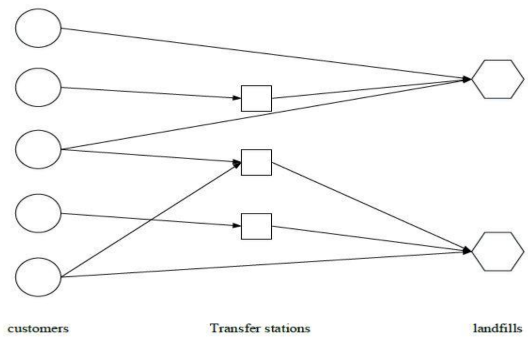


**Figure 3.6** The structure of waste transportation system (Source: Jabbarzadeh & Jabalameli, 2016)

Tehran is one of the most populated regions and is an industrial region of Iran. The main difficulty with solid waste management in Tehran is the large amount of waste per day i.e. 7.641million ton in average. It is expected to increase in near future justifying the need for establishment of infrastructures including transfer stations, landfills, and transportation vehicles as well as utilization of compacting technologies for managing and treating such a large amount of waste. Compacting technologies can considerably reduce the volumes of wastes (up to 40%) and rates of energy at transfer stations without any need for vast spaces. While there were 11 active transfer stations in Tehran, five locations were identified as potential sites for establishing new transfer stations.

Solution of fuzzy multi-objective programming model concluded that optimal total cost is IRR 9867318 per day (1 Iranian Rial = 0.0019 Indian Rupee). Therefore, ₹18747.9 per day.

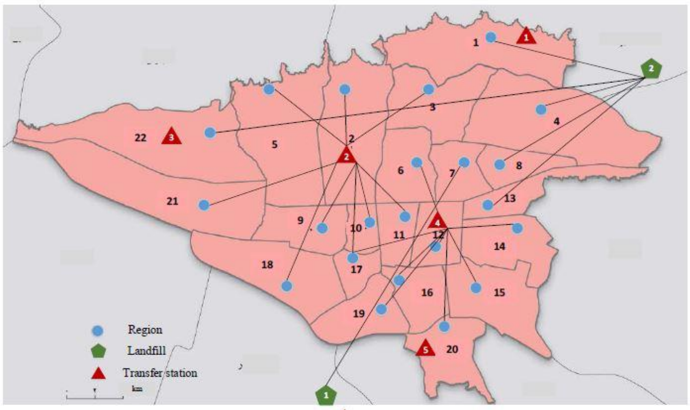


**Figure 3.4** Optimal decisions for locations and allocation of transfer stations in Tehran (Source: Jabbarzadeh & Jabalameli, 2016)

### 3.2.3 Grey Approach

Objective function

$$\text{Min } [Z^L(X_v^n,D),\ Z^U(X_v^n,D)] = \sum_{j=1}^{J} F_j * D_j \oplus \sum_{i=1}^{I}\sum_{j=1}^{J} [OC_{ij}^L, OC_{ij}^U] \odot [X_{ij}^L, X_{ij}^U] \oplus \sum_{i=1}^{I}\sum_{j=1}^{J} [TC_{ij}^L, TC_{ij}^U] \odot [X_{ij}^L, X_{ij}^U] \qquad \text{Eq. 3-18}$$

**Constraints**

$$\sum_{i=1}^{I} [A_{ij}^L, A_{ij}^U] \odot [X_{ij}^L, X_{ij}^U] \preceq [B_j^L, B_j^U], j = 1, 2, \ldots, J' \qquad \text{Eq. 3-19}$$

$$\sum_{i=1}^{I} [A_{ij}^L, A_{ij}^U] \odot [X_{ij}^L, X_{ij}^U] = [B_j^L, B_j^U], j = J' + 1, \ldots, J \qquad \text{Eq. 3-20}$$

$$\sum_{i=1}^{I} D_j \le P \forall i, j \qquad \text{Eq. 3-21}$$

$$G_i * E_{ij} \ge X_{ij}^L \ \forall i, j \qquad \text{Eq. 3-22}$$

$$X_{ij}^L \ge 0, \forall i, j \qquad \text{Eq. 3-23}$$

where,

$[Z^L(X_v^n,D), Z^U(X_v^n,D)]$ - Objective function,

$[A_{ij}^L, A_{ij}^U]$, $[B_j^L, B_j^U]$ - Parameters presented as interval numbers.

NOTE: The binary operation $\circledast$ (where, $* \in \{+,-,\cdot,/\}$) between two interval numbers $[A^L, A^U]$ and $[B^L, B^U] \in$ I can be defined as follows:

$$[A^L, A^U] \circledast [B^L, B^U] = \{a_{t_1} * b_{t_2} | t_1, t_2 \in [0,1]\} \equiv [\min_{t_1,t_2}(a_{t_1} * b_{t_2}), \max_{t_1,t_2}(a_{t_1} * b_{t_2})].$$

**Case study** (Source: Yadav *et al.*, 2018)

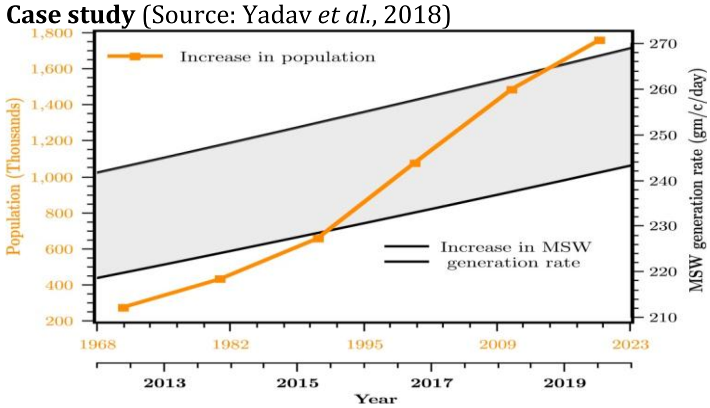


**Figure 3.5** Projected population and MSW waste generation rate of Nashik by arithmetical increase method (Source: Yadav et al., 2018)

The developed grey model for Nashik city was written in a mathematical programming language (AMPL) using KNITRO 5.2 solver to find the best facility location. For old and large cities arithmetical increase method is found to be appropriate for population projection. MSW generation in Nashik is estimated to be [429, 475] TPD i.e. [243, 269] gm/c/day (approximately) by the end of the year 2020 (Fig 3.8). The overall cost for MSWM under this situation was found out to be approximately ₹203,337/day.

## 5. SUMMARY AND CONCLUSIONS

In this report we tried to review the relevant literature on optimization of MSWM. it was found out that there can be three broad categories in which optimization models can be used in MSWM which are facility location, facility capacity/size and vehicle routing in a particular area.

It was noted that there was a lot of scope in facility location for optimization of MSWM. To find facility location, deterministic optimization model was used, which computed the best location for waste management facility in Nashik. Then, a case study of Tehran was discussed, where stochastic OM was applied and best facility locations were found out. Fuzzy and Grey OMs were again applied on Nashik to find best facility location in case of data scarcity.

The reviewed literature also highlights that modelling with multiple objectives is preferable because in real-life there are multiple objectives that need to be addressed. The decision-maker can even give different weightage according to his conscience and then find the optimal solution.

Through study of various case studies, it was found out that optimization models can significantly reduce cost. and can be used as a reliable tool for long term planning. However, there were a smaller number of literatures solving for uncertainty. Thus. more focus can be on using uncertain and hybrid models by integration of different kinds of uncertain models. More focus should be given to recycling of MSW, but if more focus is given to recycling of MSW than we can never reach minimization of cost, therefore it can be said that economically it is not optimised but it is environmentally.

More tools must be compiled with the optimisation models so that complexities and variations in reality can be accounted, such as using GPS in collection vehicles so that traffic congestions can be avoided and maximization of operational timing can be done.

Life cycle assessment LCA which is a tool to evaluate the environmental effects of a process throughout its entire life cycle must be included in optimisation process because there are chances that a process which is now economical can have bad effect on environment on a longer run. Thus, it is important to include environmental impacts while planning for MSWM.

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