IJE TRANSACTIONS A: Basics Vol. 33, No. 7, (July 2020) 1304-1310

International Journal of Engineering

Journal Homepage: www.ije.ir

A Bi-level Meta-heuristic Approach for a Hazardous Waste Management Problem

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P A P E R I N F O

Paper history:
Received 02 January 2020
Received in revised form 07 February 2020
Accepted 06 March 2020

Keywords:
Hazardous Waste Management
Location-routing Problem
Bi-level Programming
Meta-heuristic Algorithm

A B S T R A C T

This study concentrates on designing a medical waste management system with a hierarchical structure, including a local government and a waste management planner. The upper-level seeks to design and control the waste management facilities by minimizing the environmental risks related to the disposal of medical waste. While, the lower-level model is to determine the waste collection plans by only minimizing its total operational costs. Therefore, this study develops a bi-level mathematical model, in which the benefits of the both stakeholders are taken into account. As this problem poses difficulty in searching for the optimal solution, a bi-level meta-heuristic approach based on the Genetic Algorithm (GA) is employed for solving the problem. Finally, a case study is conducted to show that the proposed model and solution approach are practical and efficient.

***doi**: 10.5829/ije.2020.33.07a.17*

NOMENCLATURE

Index Set:

G	Waste generation nodes	F	Locations of available facilities
F'	Candidate locations for establishing new facilities	O	Vehicle depots
W	Waste types	K	Vehicles for waste collection

Parameters

$fc_{f'}$	Cost of establishing a new facility in location $f' \in F'$ ($)	d_{ij}	Element $i-j$ of distance matrix ($i, j \in (O \cup G \cup F \cup F')$)
tc	The cost of transferring waste ($ per km per kg)	$vc_{wf'}$	Per unit cost of implementing capacity for processing waste type *w* in new established facility $f' \in F'$ ($ per kg)
n_i	Number of people living around the location $i \in (F \cup F')$	n'_{ij}	Number of people living along with transportation link $i-j$ ($i, j \in (O \cup G \cup F \cup F')$)
r_w	Comparative risk of waste type *w* before treating	r'_w	Comparative risk of waste type *w* after treating ($r'_w \ll r_w$)
q_{wg}	Amount of waste type *w* generated in generation node *g* (kg)	c_w	Vehicle capacity compatible with waste type *w* (kg)
$e_{wf'}$	1 denotes the compatibility of waste type *w* with a facility at location $f' \in F'$; 0 denotes their incompatibility	e'_{wk}	1 denotes the compatibility of waste type *w* with vehicle *k*; 0 denotes their incompatibility
τ	Toll coefficient of hazardous waste transportation ($)	Γ	Available budget ($)
M	A sufficiently large number		

Decision Variables

$X_{f'}$	1 denotes the establishment of a facility at location $f' \in F'$; 0, otherwise	Y_{ijk}	1 denotes the order of visiting node *j* by vehicle *k* just after node *i*; 0, otherwise ($i, j \in (O \cup G \cup F \cup F')$)
$U_{wf'}$	Capacity of facility $f' \in F'$ for processing waste type *w* (kg)	V_{wf}	Capacity of available facility $f \in F$ reserved for disposing of waste type *w* (kg)
L_{ik}	Load of vehicle *k* after visiting node $i \in (O \cup G)$		

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Please cite this article as: Z. Saeidi-Mobarakeh, R. Tavakkoli-Moghaddam, M. Navabakhsh, H. Amoozad-Khalili, A Bi-Level Meta-heuristic Approach for a Hazardous Waste Management Problem, International Journal of Engineering (IJE), IJE TRANSACTIONS A: Basics Vol. 33, No. 7, (July 2020) 1304-1310

1. INTRODUCTION

Finding a suitable framework for a hazardous waste management system is among the most important urban management decisions. Both the level of risk faced by the populations and the cost of the waste collection operations are severely affected by the system configuration. The majority of the formulations found in the literature contain variables for locating facilities and routing waste collection trucks in a single level, in which they are needed to be determined by the government authorities at the same time. But in practice, these decentralized decisions are taken by two different Decision-Makers (DMs) with conflicting interests and different amounts of power. Keeping in mind these differences, the government policymakers must be aware of the behavior of the users of the waste management network, the carriers, and consider their behaviors in strategic and tactical decision-making. This leads to bi-level programming, where each DM independently maximizes its interest, while is affected by the actions from the other DM under a hierarchy [1].

This paper formulates a bi-level programming problem for deciding about the hazardous waste management system. The upper level of the model reflects the network design problem faced by the government authorities for minimizing the total risk. The lower-level problem seeks to optimize the waste collection activities in terms of the total costs. To tackle this problem, a non-linear mathematical formulation is developed and then owing to its complexity, a bi-level meta-heuristic algorithm is employed.

This paper is structured as follows. A brief literature review is presented in Section 2. The details of our problem and its formulation are given in Section 3. A detailed description of the bi-level meta-heuristic algorithm is provided in Section 4. Next, we describe a real-word example of our problem in Section 5. Section 6 gives the computational results. Finally, Section 7 presents concluding remarks and future research directions.

2. LITERATURE REVIEW

Shih and Lin [2] formulated the problem of planning and scheduling the medical waste collection from multiple hospitals. They proposed a two-phased approach for solving the problem in which the first phase partitions a set of hospitals into waste collection vehicles and the second phase determines the visiting period of each vehicle. Shih and Chang [3] extended the previous work by developing a computer program for the dynamic programming of a large-scale waste collection problem. Shih and Lin [4] proposed a multi-objective optimization problem, in which, in addition to minimization of the cost, two objectives on minimization of transportation risk and balancing of workload for collection system workers were considered. They applied a compromise programming approach for the integration of these objectives. Chaerul et al. [5] employed a goal programming approach for solving a planning model in healthcare waste management with multiple objectives under different relative importance. Alagöz and Kocasoy [6] used a commercial vehicle routing package to identify the most feasible routes in terms of efficiency and economy for the collection of healthcare wastes from the temporary storage rooms and transporting them to the final disposal areas. Shi et al. [7] developed an optimization model with the goal of cost minimization for a medical waste reverse logistics network and used a genetic algorithm to solve this problem. Nolz et al. [8] formulated a collector-managed inventory-routing problem for developing a sustainable logistics system to organize the collection of medical waste. Social objectives in terms of minimizing the public health risks and satisfying pharmacists and local authorities were included in the formulation. Hachicha et al. [9] examined the off-site treatment problem of infectious waste from several medical facilities in a planned stream sterilization disposal center. Alshraideh and Qdais [10] considered a route scheduling model with time windows and stochastic demands in a case study of medical waste collection. The authors considered a chance constraint regarding a pre-defined service level and applied a genetic algorithm to solve the problem. The proposed model by Mantzaras and Voudrias [11] aimed to calculate the optimal location and size of the treatment facilities and transfer stations, the number and capacity of all waste collection and transfer vehicles and their optimal path at minimum cost. Wichapa and Khokhajaikiat [12] proposed a two-stage location-routing problem for infectious medical waste including, (1) a multi-objective facility location with the aim of cost minimization and global priority weights maximization and (2) a vehicle routing problem to minimize transportation costs that was solved using a hybrid genetic algorithm.

As can be understood from the literature review, this is the first study that formulated medical waste management system using a bi-level mathematical formulation. The capabilities of bi-level programming can significantly help to formulate the conflicts between decision-makers in this field.

3. MODEL DEVELOPMENT

3. 1. Problem Definition Our study seeks to design a medical waste management system based on the interests of two groups of non-cooperative DMs. The upper-level DM is to establish new facilities to minimize the environmental side effects of unprocessed medical waste on the people living near treatment facilities and separating the collection of medical waste from general waste and meeting demands of the system for treatment processes. The Environmental Organization with environmental concerns is the upper-level DM and its measures must be funded by the Health and Medical Education Minister as responsible for the production of these wastes. The lower-level problem represents the routing decisions optimization in the designed medical waste management system along with optimization of decisions regarding the amount of waste that must be treated and processed in facilities. Municipality authority as a contractor with the ministry performs the decision making in the stated level for waste collection and aims at the cost-efficiency. To illustrate the details of medical waste management processes, the following explanations are presented:

- Collection: It is important to note that various types of infectious medical wastes are produced by several waste generation nodes in different regions of the considered area. To collect these wastes, a set of vehicles are available in a central depot and are planned in several routes of the waste generation units. It is necessary to note that the vehicle fleet is heterogeneous and includes vehicles with differences in their compatibility with diverse characteristics of hazardous wastes. Furthermore, the partial collection is not allowed by the vehicles or in better words, for collecting each type of waste, the generation nodes must be visited only once. During the planned routes, if the capacity of facilities run out or the available capacity becomes lower than the remaining amount in other generation nodes, the vehicles decide to dump their loads at appropriate facilities. After unloading the collected wastes, the vehicles must move back to the depot.
- Treatment: It is assumed that the current structure of the waste management network does not involve any treatment center. Accordingly, a considerable part of generated wastes is dumped while no treatment processes are exerted, and the requirements of waste treatment are not satisfied by the present system. It is expected that installing a new integrated facility, which comprises both modern treatment and disposal technologies at an available place results in a more centralized waste management processes with lower consequences.

3. 2. Model Formulation This study presents a bi-level mathematical model that can consider the conflict of stakeholders as shown below:

$$\begin{aligned}\text{Min } f_1 = &\sum_{w\in W}\sum_{f\in F} r_w\, n_f\, V_{wf} \\ &+\sum_{w\in W}\sum_{f'\in F'} r'_w\, n_{f'}\, U_{wf'} \\ &+\sum_{w\in W}\sum_{k\in K}\sum_{i\in G}\sum_{j\in(G\cup F\cup F')} r_w\, e'_{wk}\, L_{ik}\, n'_{ij}\, Y_{ijk}\end{aligned} \tag{1}$$

$$\sum_{f'\in F'}\left(fc_{f'}\, X_{f'} + \sum_{w\in W} vc_{wf'}\, U_{wf'}\right) \le \Gamma \tag{2}$$

$$U_{wf'} \le M\, X_{f'} \quad ;\forall w\in W, f'\in F' \tag{3}$$

$$X_{f'}\in\{0,1\} \text{ and } U_{wf'}, V_{wf} \ge 0 \tag{4}$$

where for given $\{U_{wf'}, V_{wf}, X_{f'}\}$, $\{Y_{ijk}\}$ solves

$$\begin{aligned}\text{Min } f_2 = &\, tc\sum_{k\in K}\sum_{i\in(O\cup G\cup F\cup F')}\sum_{j\in(O\cup G\cup F\cup F')} d_{ij}\, Y_{ijk} \\ &+\tau\sum_{k\in K}\sum_{i\in(O\cup G\cup F\cup F')}\sum_{j\in(O\cup G\cup F\cup F')} n'_{ij}\, Y_{ijk}\end{aligned} \tag{5}$$

$$\sum_{i\in O}\sum_{j\in G} Y_{ijk} = 1 \quad ;\forall k\in K \tag{6}$$

$$\sum_{i\in(O\cup G)} Y_{ijk} - \sum_{i'\in(G\cup F\cup F')} Y_{ji'k} = 0 \quad ;\forall j\in G, k\in K \tag{7}$$

$$\sum_{i\in G} Y_{ijk} - \sum_{i'\in O} Y_{ji'k} = 0 \quad ;\forall j\in(F\cup F'), k\in K \tag{8}$$

$$\sum_{k\in K}\sum_{i\in(O\cup G)} e'_{wk}\, Y_{ijk} = 1 \quad ;\forall j\in G, w\in W \tag{9}$$

$$\begin{aligned}L_{ik} - L_{jk} + \sum_{w\in W} e'_{wk}\, c_w\, Y_{ijk} \le \sum_{w\in W} e'_{wk}\left(c_w - q_{jw}\right) \\ ;\forall i,j\in G, k\in K\end{aligned} \tag{10}$$

$$\sum_{w\in W} q_{iw}\, e'_{wk} \le L_{ik} \le \sum_{w\in W} e'_{wk}\, c_w \quad ;\forall i\in G, k\in K \tag{11}$$

$$Y_{ijk}\left(\sum_{w\in W} q_{jw}\, e'_{wk}\right) \le L_{ik} \quad ;\forall i\in O, j\in G, k\in K \tag{12}$$

$$\begin{aligned}L_{jk} \le \sum_{w\in W} e'_{wk}\left(c_w + \sum_{i\in D}\left(q_{jw} - c_w\right)Y_{ijk}\right) \\ ;\forall j\in G, k\in K\end{aligned} \tag{13}$$

$$\sum_{k\in K}\sum_{i\in G} Y_{ijk}\, e'_{wk}\, L_{ik} \le e_{wj}\, U_{wj} \quad ;\forall j\in F', w\in W \tag{14}$$

$$\sum_{k \in K}\sum_{i \in G} Y_{ijk}\; e'_{wk}\; L_{ik} \le V_{wj} \qquad ;\forall j \in F, w \in W \tag{15}$$

$$Y_{ijk} \ge 0 \qquad ;\forall i, j \in \left(O \cup G \cup F \cup F'\right), k \in K \tag{16}$$

The objective function (1) in the upper-level problem aims at minimizing the risk imposed on the population and includes three terms. The undesirability of the facilities (newly established and available) is focused on the first two terms, while the last term minimizes the risk associated with unprocessed medical wastes. The limitation of the budget allocated to establishing new facilities is controlled in Equation (2). According to Equation (3), waste processing in a newly established facility is subjected to its establishment. The type of upper-level decision variables in terms of non-negativity and integrality is determined by Equation (4). The objective function (5) in the lower-level problem targets the minimization of the cost of waste management activities. The lower-level objective function comprises of two terms defined on the waste collection cost and the transportation toll charges for traffic routes. Equation (6) emphasizes on this assumption that the waste management network includes only a central depot where all collection vehicles depart from there. The continuity of the routes traveled by the waste collection vehicles is ensured by formulating Equations (7) and (8). In this study, split pickups are not permitted and Equation (9) imposes this constraint into our formulation. Equations (10)-(13) incorporate two significant features into our formulation: sub-tour elimination and capacity of vehicles. The input flow to the facilities (available and newly established) must not exceed the capacity of the facilities; Equations (14) and (15) guarantee this issue. Analogous to Equation (4), Equation (16) limits the domain of the lower-level decision variable.

4. SOLUTION METHODOLOGY

This section describes a bi-level meta-heuristic approach, which uses the Genetic Algorithm (GA) as the main and subsidiary algorithm. At the first level of this algorithm, the GA generates solutions with information about the new established facilities and their capacities and then these solutions are moved into the second level to construct the collection routes. Since the fitness value of a solution in the upper-level depends on the decisions at the lower-level, we first describe the lower-level GA structure and then turn into the GA at the upper-level.

4. 1. Second Level GA The chromosome representation is an important part of implementing the GA because it enables the algorithm to cover all aspects of a problem. Concerning the special form of the constraints, this paper applies the permutation representation for encoding the solutions into the chromosome. As can be understood from Figure 1, each chromosome is illustrated with a matrix with a dimension of $W \times G$ genes, in which W and G are the number of waste types and waste generation nodes, respectively. Evaluation of the fitness value for each chromosome is done based on the decoding procedure. To construct the collection routes associated with each waste type, the genes of the associated row are added to the routes respectively, until the vehicle's capacity will be exceeded. This procedure is continued to cover all waste generation nodes.

In the GA, the evolution process of a population over successive generations is done through genetic operators, including crossover and mutation. In one hand, the crossover operator blends genetic information between parents and makes children that inherit their parents' promising characteristics. The one-point crossover is employed in the second level of the proposed algorithm in determining the collection routes. One the other hand, the mutation operator tries to maintain an adequate diversity of the population and prevents falling into a local optimum trap. A simple mutation operator is used in this study that its basis is a random selection of a pair of genes and replacement of them.

4. 2. GA in the First Level In the second level, we have a matrix with a dimension of $W \times \left(F' + F\right)$ genes in which W is the number of waste types and F' and F are the potential and available facilities, respectively (see Figure 2 with only potential facilities). Each gene gets a random number between [0, 1]. In establishing new facility, the priority is with the facility that the corresponding column has a greater value. Concerning the budget constraint, a new facility with a certain capacity is established and excess waste is disposed of in the available facilities. In other words, the collection routes of the second level are terminated at a treatment facility with sufficient capacity for unloading the collected waste. Note that the priority of allocating the waste types to the new established facility is determined based on the value of their respective rows. The first level GA applies the same crossover and mutation operators to create an offspring population.

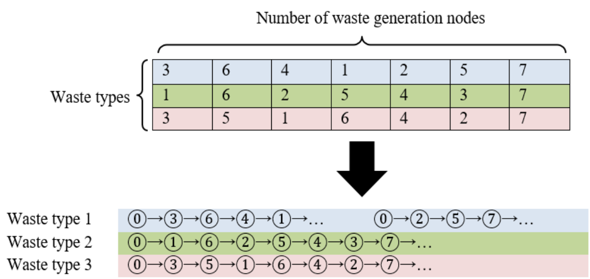

Figure 1. Solution representation in the second level GA

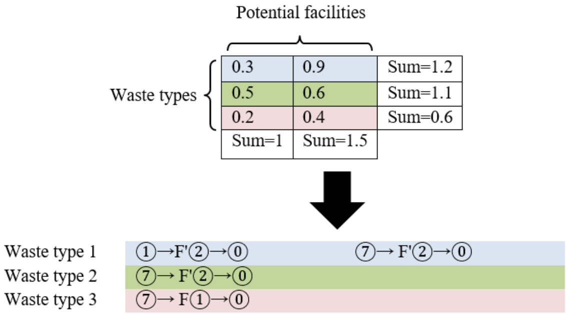

Figure 2. Solution representation in the first level GA

5. CASE STUDY

To demonstrate the application of the proposed model, one of the major cities in Iran, which is dealing with waste management issues in the past decade, is considered as the real-life case study. Isfahan is located in the center of Iran and is one of the highly populated and industrialized cities of the country. Besides the inefficient waste management system, Isfahan is suffering from lack of a proper medical waste management system. According to official guidelines and policies, medical centers should treat their wastes and turn them into general waste before dumping them in landfill sites. This has led to a conflict between the municipality of the city, and the Department of Environment in which both believe that medical centers should be responsible for the waste treatment processes. Therefore, the ministry has allocated a budget for the infrastructure needed to revise the current waste management system. The city requires an exclusive waste management system to cover medical waste all over the city. In the other words, medical waste even after treatment should not be considered as general waste. In this regard, we have included all of the medical centers and hospitals all over the city of Isfahan in the study. The average waste generation rates for medical centers and hospitals are also extracted from the literature and acknowledged using interviews with Department of Environment experts [13].

To design a medical waste management system, all candidate locations for facilities all over the city are determined, and also critical areas for constructions are considered. It is noteworthy that other aspects such as geomorphological criteria are taken into consideration in determining the candidate locations. In Figure 3, the identified locations are shown.

6. COMPUTATIONAL RESULTS

6. 1. Parameter Tuning

Parameter tuning is one of the important steps in implementing meta-heuristic algorithms since the parameters of the algorithm play a

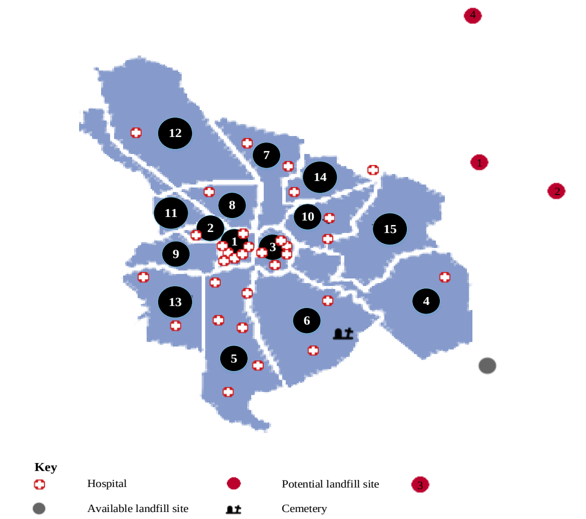

Figure 3. Geographical distribution of hospitals and facilities in Isfahan

significant role in the quality of the obtained results and the running time of the algorithm as well. There are various methods for parameter tuning which are mainly based on the design of experiments. Design of experiments helps tune the algorithm parameters using a limited number of experiments which offers good accuracy in a limited time. This study uses the Taguchi method for parameter tuning. The influencing parameters of GA are namely, population size (N_p), the maximum number of generations ($Max\_iteration$), crossover rate (P_c) as well as mutation rate (P_m). The determined experiments using the Taguchi method based on the defined levels of each parameter are summarized in Table 1. It is noteworthy that the Minitab statistical package is used for implementing the Taguchi method in this study.

6. 2. Performance Evaluation of the Bi-level Meta-heuristic Algorithm

This section is dedicated to the obtained results from the proposed mathematical model. The obtained results indicate the optimal location of facilities along with other decision variables. Figure 4 illustrates how the bi-level algorithm converges to the optimal solution. According to this figure, the designed system's effects on the people living near the waste management facilities as the upper-level objective is equal to 611,120 person × ton. According to the findings,

TABLE 1. Parameters and their optimal values

Algorithm	Parameter			
	N_p	$Max\_iteration$	P_c	P_m
First level GA	100	125	0.8	0.1
Second level GA	75	50		

also the total amount of the objective for the lower-level design is equal to $ 38.526. Furthermore, Figure 4 compares the performance of the GA against the well-known Particle Swarm Optimization (PSO). As can be observed, the GA ahieves a better solution by maintaing fine balances between the crossover and mutation operators in searchig the solution space. The main reason for the superiority of the GA to PSO in this study is that the updating process during the iterations of PSO is continuous and requires solution representation with a continuous structure. Notably, the bi-level meta-heuristic algorithms are implemented using MATLAB software on a Core i7 computer with 8 GB of RAM and 2.1 GHz CPU. Table 2 shows the obtained optimal results from the proposed mathematical formulation which was solved using the tuned GA algorithm.

Following are the main findings of this research:

- The obtained results indicate that the designed medical management system for the city of Isfahan requires two trucks for the collection of infectious waste. The model has balanced the utilization of these truck to obtain the most efficient workload.
- Considering the conflict between objectives of the model which is the optimization of both environmental and economic aspects, the model has decided to impose more costs to minimize the environmental issues. That's why the optimum routing decisions for the designed medical waste management system in some districts are longer than what is expected.

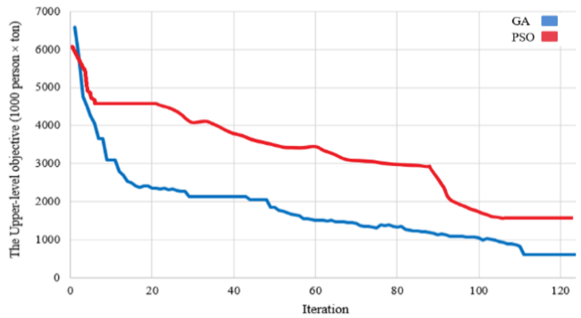

Figure 4. Convergence to the optimal solution

TABLE 2. Optimal waste collection routes

	Waste type			
	Infectious		**Sharp**	**Pathological**
Optimal routes	D14	D5	D14	D14
	↓	↓	↓	↓
	D7	D3	D7	D7
	↓	↓	↓	↓
	D12	D6	D12	D8
	↓	↓	↓	↓
	D2	D4	D8	D12
	↓	↓	↓	↓
	D8	P2	D2	D2
	↓		↓	↓
	D13		D13	D13
	↓		↓	↓
	D1		D6	D5
	↓		↓	↓
	D5		D5	D1
	↓		↓	↓
	D3		D1	D3
	↓		↓	↓
	D10		D3	D10
	↓		↓	↓
	D14		D10	D14
	↓		↓	↓
	F'2		D14	D4
			↓	↓
			D4	D6
			↓	↓
			F'2	C

7. CONCLUSIONS

Considering the benefits of different stakeholders, this paper proposed a mathematical formulation framework for optimization of the medical waste management system. The upper-level model seeks to design and control the facilities in the medical waste management system by minimizing the environmental risks, while the lower-level model is to determine the waste collection plans by minimizing the total operational costs. As the developed problem is proven to be NP-hard, bi-level meta-heuristic algorithms based on the GA and PSO were employed for solving the problem. Finally, the performance of the developed mathematical formulation and solution approaches were tested in a real medical waste management system. Although the GA offers a high-quality solution, the exact solution methodologies can be approached in the future study.

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Persian Abstract

چکیده

این تحقیق روی یک مسئله‌ی مدیریت پسماند خطرناک با ساختار سلسه مراتبی، شامل دولت محلی و برنامه‌ریز مدیریت پسماند تمرکز دارد. سطح بالای این فرآیند سلسه مراتبی در تلاش برای طراحی و کنترل زیرساخت‌های مدیریت پسماند با هدف کمینه‌سازی ریسک‌های زیست‌محیطی مرتبط با دفع پسماند است. از سوی دیگر، مدل ارائه شده برای سطح پایین، به دنبال تعیین طرح‌های جمع‌آوری پسماند صرفا با هدف کمینه‌سازی هزینه‌های عملیاتی است. بنابراین این تحقیق، یک فرمول ریاضی دو سطحی برای توصیف مسئله پیشنهاد می‌کند که منافع هر دو ذینفع در نظر گرفته شود. به دلیل پیچیدگی ساختار مسئله در دستیابی به جواب بهینه، یک الگوریتم فراابتکاری دو سطحی بر پایه‌ی الگوریتم ژنتیک برای حل مسئله مورد استفاده قرار گرفت. در پایان، یک مطالعه‌ی موردی به منظور نمایش کاربردی و کارا بودن مدل و رویکرد حل پیشنهادی صورت پذیرفت.