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A green vehicle routing problem in the solid waste network design with vehicle and technology compatibility

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ABSTRACT

Waste generation is on the rise in most societies due to population growth. Given this concern, it would be highly important to manage municipal solid waste generated in society. Mismanagement in this area could seriously endanger human health and the environment. This paper proposes a systematic approach to optimize the operations of a waste management network for recycling Municipal Solid Wastes (MSWs). In this regard, in this study, a bi-objective MINLP model to determine the best sustainable vehicle routes, allocation, and sequence scheduling problem in recycling centers with the objectives of minimizing costs and maximizing job opportunities is developed. Another important novelty of this paper is Considering waste-vehicle and waste-technology compatibility. To solve the suggested model firstly LP-metric approach is used in small-sized problems and for large sizes this approach was not efficient so the Lagrangian Relaxation (LR) method is employed. Therefore, a set of test problems in different sizes is provided.

1. Introduction

Waste is a type of solid, liquid, or gas substance that is caused by peoples' activities, and in terms of the consumer's point of view, these products are unusable and redundant. Overall, waste is composed of MSW, Industrial Waste, Medical Waste, Electrical Equipment Waste, Agricultural Waste, Construction Waste, and Waste Water. MSW accounts for a large volume of waste worldwide that is produced every day by various urban sectors, including residential, commercial, organizational, structural, and service centers [1]. Today, due to increasingly populated growth, developing industries in countries, urbanization, economic growth, and change in the standard of living [2] have contributed

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to an increase in the production of MSW worldwide [3]. The increasing amount and variety of this waste have made it difficult to collect and dispose of them. Also, traditional-disposal methods, such as burying them under the ground, open dumping [4], or burning them are not efficient in today's society because they are not able to prevent the entry of environmental pollution, which have caused by chemical, microbial or radioactive waste. As a result, the concept of Municipal Solid Waste Management (MSWM) was gradually created; on the one hand, recently it has become one of the most important concerns of all countries for reducing their impacts on the ecosystem and the amount of them. On the other hand, they consist of valuable materials that can be reused for other products or recovered for energy resources, which has extremely economic and environmental advantages [5], particularly decreasing the cost of collection and environmental pollution caused by waste transportation and dumping them. Therefore, the governments have found that should consider all aspects of sustainable development for MSW, which is investigated three main dimensions of economic, environmental, and social [6] simultaneously, that is the best to answer to primary aspects of this problem. Thus, in recent years, the study of MSWM has rendered a fascinating issue for many researchers. The main stage of the MSWM network is appropriate collection and transportation from the generation node to a recovery center or disposal facilities with decreasing costs and environmental contaminants. Also, one of the efficient methods for collecting and transporting MSW is the Vehicle Routing Problem (VRP) to obtain optimal solutions for reducing the cost of transportation and environmental pollutants [7]. Afterward, one of the methods is recycling to recover MSW is to reuse it or its ingredients, In addition, it could be used as energy resources with recycling techniques such as the thermic method [2]. Therefore, the recycling process is an impressive method to evolve sustainability in that it can lead to decreasing environmental impacts and economical costs as well as increasing the satisfaction of human socialites, so recovery of waste is an important approach in MSWM to lead to recycling valuable materials or treatment for hygienic disposal of residual them.

Many studies have been performed to solve different problems in the MSWM network, including optimization of location facilities, VRPs, selecting the appropriate technologies for the waste recovery process, and investigation of various aspects of the problem of sustainability in reverse logistics, by using mathematical and optimization methods around the world. Much research has been done in recent years that will be reviewed, some of them on MSWM in the fields of Facility Location Problem (FLP), VRP, Inventory Problem (IP), or the integration of these problems simultaneously as follows: Nanda and Berruti [6] introduced a model to obtain the optimum location for station sites in MSW, and their aim from this study was reviewed to diminish the overall costs of MSWM in Nashik, India. Tirkolaee and Aydın [8] formulated a location-allocation-inventory problem on the MSW network, including collection and disposal, with minimizing the overall cost of the network which consisted of established sites, collection, transportation, processing, delay of uncollected waste, and increasing pollution emissions. Asefi et al. [9] presented a location-routing problem for collecting and shipping types of waste in the MSW network (including processes of collecting, transporting, treating, recycling, or landfill) to diminish the overall costs of establishing facilities and waste transportation among centers. Then, they obtained the appropriate number of facilities and truck routes by a meta-heuristic algorithm, and finally assessed the performance of the model through a real-case study in Tehran, Iran. Rabbani et al. [10] designed a location inventory routing problem for sustainable waste management. Their model covered 3 aspects of a sustainable system and aimed to diminish the overall cost, volume of population emission, and overall time spent on waste collection and treatment.

In recent years, there have been different studies considering the sustainability factors for MSW. For instance, Farahbakhsh and Forghani [11] investigated a location-routing problem with sustainable aims to minimize the total cost, pollution emissions, and maximize social service on the MSW system (including collocation and sorting facilities). Sagnak et al. [12] formulated a mixed-integer linear programming Sustainable model for Municipal Waste Management (MWM) due to the COVID-19 pandemic. They considered reducing environmental risks and the total time of transportation; then they examined the performance of the model in Iran.

Furthermore, most researchers have been interested in formulating mathematical models for MSW systems in an environment of uncertainty. Akbarpour et al. [13] investigated MSWM with a stochastic model in an industrial city. They minimized the total transportation cost and maximized the revenue from recycled waste. Afterward, they evaluated different algorithms to find the best solution. Eren and Tuzkaya [14] developed a multi-objective model for MWM in the Covid-19 pandemic under uncertainty. This model found out the safest and the shortest routes for collecting medical waste. Finally, their model was used for medical waste collection in a specific district in Istanbul.

As mentioned earlier, an important phase in the MSWM system is the use of effective technologies for waste processing to recycling, reuse, or treatment and ultimately sanitary disposal. Therefore, some studies emphasized this section from the MSW management system. For example, Qazi et al. [15] assessed waste-to-energy conversion technologies for the different MSW systems in the Sultanate of Oman with the use of economic and environmental aims such as reducing the amount of waste, greenhouse gas emissions, and the improved casts of landfills. Shahnazari et al. [16] evaluated the best recovery energy technologies to obtain energy resources from the MSW by analyzing technical, economical, and environmental criteria using decision-making methods.

As it is determined, some aspects have not been done considering studies previously, and introduce some of them as follows:

- There has not been investigated a simultaneous location-allocation-vehicle-routing with a robotic sequencing schedule mathematical model.
- Considering location and recycling technologies for each facility in MSWM has not been conducted.
- Establishing a specific technology and method to recycle and produce new products for each type of waste has not been done.
- Considering waste-vehicle and waste-technology compatibility.
- Devising LR algorithms to tackle the problem complexity.

Consequently, this study presents a novel mathematic model, which is an integrated bi-objective mixed integer nonlinear programming location-allocation-inventory-VRP with scheduling robot in a recycling center, to obtain the optimum location, recycling technologies, collecting routes, and the amounts of stored waste in each period as well as specify the quantity of the generated products for MSWM networks.

The rest of the paper is structured as follows. Section 2 presents the problem description and formulation. Section 3 addresses methodologies for solving the model. Section 4 investigates numerical tests to assess the performance of the model, and approves model validation. Eventually, Section 5 performs a conclusion and further research.

2. Problem description and formulation

2.1. Problem description

This paper proposes a systematic approach to optimize the operations of a waste management network for recycling solid wastes. In this regard, in this study, a bi-objective MINLP model to determine the best vehicle routes and allocation, and the sequence scheduling problem in the recycling center with the objectives of minimizing costs and maximizing job opportunities is developed. As is shown in ***Figure 1***, each vehicle starts its route from one depot, and then, collects its compatible types of waste from the generation nodes and comes back to the same depot that started its route. Then, it continues to the allocated recycling centers to discharge each kind of waste into a compatible facility. Each facility has a technology that is compatible with a specified type of waste. During the processing of each kind of waste by compatible technology, a specified product will produce. Robots process some activity on wastes in the recycling center to produce a new product. Furthermore, the scheduling robots process at the recycling center is considered. The needs of each product are met by the recycling facility that produces that type of product. The waste can only be processed in the period when it is produced. At the beginning of each period, a quantity of waste enters facilities, then facilities will produce the related products by using wastes, and at the end of each period, demands will be satisfied.

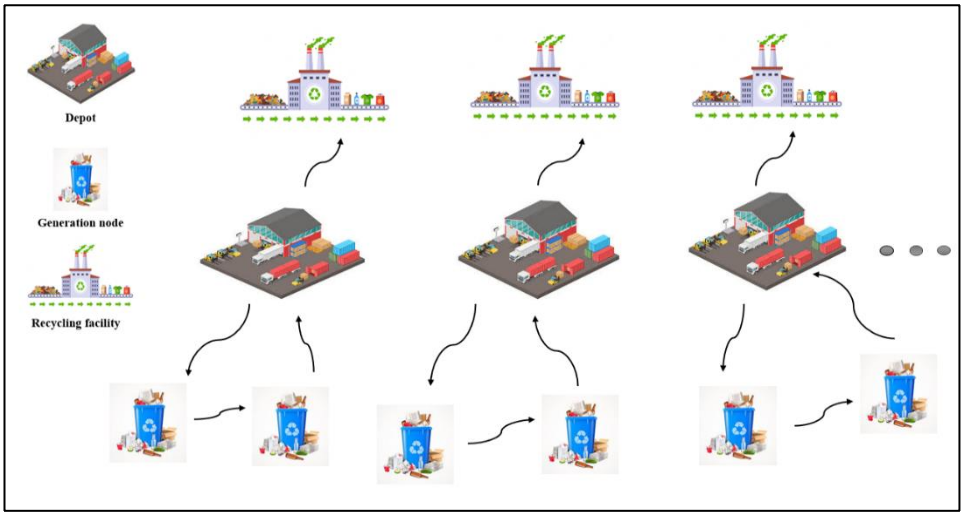

Figure. 1. An exemplary solution to the problem

2.2. Problem assumptions

This research has several assumptions, which are investigated as follows:

- Each customer can produce all kinds of recycling waste.
- Generation node's locations are known.
- The model is multi-depot.
- Amount of each type of recycling waste produced by a customer in each period is a random number.
- Demands of each product are known and will be fulfilled at the end of the time horizon.
- Wastes are separated at generation nodes, and partial waste collection is not allowed.
- Recycling centers are capacitated.
- The amount of *waste* that enters each facility should not exceed *its* capacity.
- One technology can be applied to each facility.
- Vehicles are heterogeneous.

- Each vehicle could visit each generation node only once in each period.
- Robots are different and have a variety of skills.
- All parameters are deterministic.

2.3. Mathematical formulation

This problem is formulated as a MINLP model, consists of an integrated problem, including VRP and the sequence scheduling problem. In contrast to NLP models, MINLP models are able to select and evaluate multiple facilities by using binary variables.

2.4. Equations

The first Objective Function (OF) is to minimize the costs, which is shown in ***Eq. (1)***. ***Eq.(1a) – (1d)*** explain how each part of the mentioned cost is calculated.

$$Min\ z_1 = Ccost + Tcost + Pcost - Revenue \tag{1}$$

$$Revenue = \sum_{r\in R}\sum_{q\in Q}\sum_{w\in W} so_{wqr}\, d_{wqt}\, rr_{rq} \tag{1a}$$

$$Ccost = \sum_{r\in R}\sum_{q\in Q} fr_{rq}\ rr_{rq} \tag{1b}$$

$$Tcost = \sum_{d=1}^{D}\sum_{o=1}^{O}\sum_{r=1}^{R} c_o dis_{dr} y_{dr} \tag{1c}$$

$$Pcost = \sum_{r\in R}\sum_{w\in W}\sum_{q\in Q}\sum_{t\in T} pr_{wqr}\, \alpha_{wq}\, pd_{rwqt}\, com_{wq} \tag{1d}$$

The revenue shown in ***Eq.(1a)*** is the total revenue earned by selling different kinds of recyclable wastes, where so_{wqr} is the sale value of each unit of product produced from processing waste type w with technology q at recycling centers r, d_{wqr} is Total demand for the product generated from processing waste type w with technology q in period t at recycling center r and rr_{rq} is 1 if a recycling facility with technology q is opened in potential location r. $Ccost$ shown in ***Eq.(1b)*** is the capital cost described as the total cost of establishing recycling facilities where fr_{iq} is the establishment cost of a recycling facility at node $i \in r$ with technology q. $Tcost$ shown in ***Eq.(1c)***, is the transportation cost where c_o is transportation cost per unit of distance, dis_{dr} is the distance between depot d and node r and y_{dr} is 1 if depot d is assigned to recycle center r. $Pcost$ shown in ***Eq.(1d)*** is the processing cost described as the total cost of processing wastes at recycling facilities where pr_{wqr} is the processing cost of each unit of waste w with technology q at recycling centers r, α_{wq} is the amount of waste required to produce one unit of product, which is generated from processing waste type w with technology q, pd_{rwqt} is The amount of product generated from processing waste w with technology q in recycling facility r in period t and com_{wq} is 1 if waste w is compatible with technology q.

$$Max\ z_2 = \sum_{r\in R}\sum_{q\in Q} nr_{iq} rr_{rq} \tag{2}$$

The second OF is to maximize the job opportunity in each recycling center, where nr_{iq} is the number of required labors on recycling processes at node $i \in r$ with technology q.

$$\sum_{d\in D}\sum_{r\in R}\sum_{k\in K} y_{dr} dis_{dr}\, em_k \le e_t \qquad \forall\, t \in T \qquad (3)$$

$$\sum_{j\in g} x_{ijkt} = 1 \qquad \forall\, i \in D, k \in K, t \in T \qquad (4)$$

$$\sum_{i\in D\cup G} x_{ijkt} = \sum_{i\in G\cup D} x_{jikt} \qquad \forall\, j \in G, k \in K, t \in T \qquad (5)$$

$$\sum_{K}\sum_{i\in g\cup d} x_{ijkt} = 1 \qquad \forall\, j \in G, t \in T \qquad (6)$$

$$\sum_{D} y_{dr} \le \sum_{w\in W}\sum_{q\in Q} veh_{kw}\, com_{wq} rr_{rq} \qquad \forall\, r \in R \qquad (7)$$

Eq.(3) guarantees that the amount of environmental impact of vehicles should not exceed the acceptable range in each period where em_k is the environmental impact of vehicle k per unit of distance and e_t is the acceptable amount for total environmental impact in each period.

Eq.(4) shows that the starting point for all vehicles at the beginning of each period is a depot where x_{ijkt} is 1 if vehicle k travels directly from node i to node j in period t. ***Eq. (5)*** guarantees the continuity of each vehicle's path through arriving and leaving the same generation node. ***Eq. (6)*** shows that all generation nodes are visited exactly once. ***Eq. (7)*** shows vehicle-waste and waste-technology compatibility. This constraint ensures that each type of waste should be transported by its related vehicle; equally, it shows that there are different types of technology that are compatible with different types of waste where veh_{kw} is 1 if waste type w is compatible with vehicle k.

$$u_{ikt} - u_{jkt} + GD * x_{ijkt} \le GD - 1 \qquad \forall\, i.j \in G, k \in K, t \in T \qquad (8)$$

$$\sum_{d\in D}\sum_{w\in W} dem_{iwt} veh_{kw} \le u_{ikt} \le \sum_{j\in D}\sum_{w\in W} veh_{kw}\, cap_{kw} \qquad \forall\, i \in G, k \in K, t \in T \qquad (9)$$

$$q_d^w = \sum_{i\in g}\sum_{k\in K}\sum_{t} x_{ijkt} \times dem_{iwt} \qquad \forall\, j \in D, w \in W \qquad (10)$$

$$pd_{rwqt} = d_{wqr} rr_{rq} com_{wq} \qquad \forall\, r \in R, w \in W, q \in Q, t \in T, r \in R \qquad (11)$$

$$\sum_{r\in R}\sum_{t\in T} xr_{rwt} = \sum_{d\in D}\sum_{r\in R}\sum_{q\in Q} q_d^w \times rr_{rq} \times com_{wq} \qquad \forall w \in W \qquad (12)$$

$$(st_{wn} + pt_{wn}) + MR(1 - yr_{wnw'n'o}) \le ft_{wn} \qquad w \in W, n \in N \qquad (13)$$

$$st_{wn'} \ge st_{wn} + pt_{wn} \qquad w \in W, n, n' \in N \qquad (14)$$

$$(st_{wn} + st_{w'n'}) + MR(1 - yr_{wnw'n'o}) \ge pt_{w'n'} \qquad w, w' \in W, n, n' \in N, o \in O \qquad (15)$$

$$\sum_{o\in O} z_{wno} \le 1 \qquad w \in W, n \in N \qquad (16)$$

$$yr_{wnw'n'o} \le z_{wno} \qquad w, w' \in W, n, n' \in N, o \in O, w \ne w', n \ne n' \qquad (17)$$

Eq. (8) and ***Eq. (9)*** are MTZ sub-tour eliminations. Also, these constraints guarantee that a load of collection vehicles does not Exceed from their given capacity where GD is the total number of generation nodes and depots, u_{ikt} is the continuous variable for sub-tour elimination constraints, dem_{iwt} is the amount of waste type w at node $i \in g$ in period t and cap_{kw} is capacity of vehicle k that is compatible with waste type w. ***Eq. (10)*** calculates the amount of each type of waste that enters each depot where q_d^w is the amount of waste type w that enters each depot. ***Eq. (11)*** indicates that demand for products assigned to recycling centers should be fulfilled in each period. ***Eq. (12)*** calculates the amount of each type of waste that enters each recycling center where xr_{rwt} is the amount of waste w that enters recycling facility r in period t. ***Eq. (13)*** states the completion of time operating type n on the waste type w where st_{wn} is starting time of operation waste type w, pt_{wn} is the processing time of recycling operation on waste type w, MR is number of vehicles for transfer component types w to recycle center, ft_{wn} is finishing time of operation waste type w and $yr_{wnw'n'o}$ is 1, if the recycled operation of waste type w before the operation waste type w' by robot o; 0 otherwise. ***Eq. (14)*** represents the sequence of recycling operations of each waste. ***Eq. (15)*** ensures two operations do not do at the same time by one robot. ***Eq. (16)*** determines the maximum number of robots that must be processed on each waste where z_{wno} is 1, if the recycling operation of waste type w is done by robot o; 0 otherwise ***Eq. (17)*** specify a set of operations to do by any robot.

$$\sum_{q\in Q} rr_{rq} \le 1 \qquad \forall\, r \in R \qquad (18)$$

$$\sum_{r\in R} rr_{rq} \ge com_{wq} \qquad \forall\, w \in W, q \in Q \qquad (19)$$

$$\sum_{i\in D}\sum_{j\in D} x_{ijkt} = 0 \qquad \forall k \in K, t \in T \qquad (20)$$

$$x_{ijkt}, rr_{rq}, y_{dr}, z_{wno}, yr_{wnw'n'o} = \{0,1\} \qquad \forall\, i,j \in g, d \in D, r \in R, w \in W, n \in N, o \in O \qquad (21)$$

$$u_{ikt}, ft_{wn}, st_{wn}, xr_{iwt} \ge 0 \qquad \forall\, i \in g, k \in K, t \in T, w \in W, n \in N \qquad (22)$$

Eq. (18) represents that only one type of technology could be applied to each recycling facility. ***Eq. (19)*** ensures that for each product that has demanded, its compatible facility should be established. ***Eq. (20)*** represents those vehicles that should not move between depots. ***Eq. (21) to (22)*** shows the range of each variable.

3. Solution methodology

3.1. LP-metric approach

The LP-metric approach is one of the well–known approaches in the literature on multi-objective problems. In this approach, we seek to minimize the deviations of the OF s from their optimal values.

In the comprehensive criterion method, first, individual solutions are calculated for each OF's optimality, and then the aggregated OF (23) is minimized. The optimal value of the *j*-th OF is f_j^*, and W_j shows the importance of the *j*-th OF. The LP-metric mathematical model is shown as follows.

Since it is not necessary to present nomenclature at the beginning of the paper, each variable or symbol used in the text must be clearly defined after its first appearance in the text.

$$\left.\begin{array}{l} min\ \ f_1(x) \\ min\ \ f_2(x) \\ \vdots \\ min\ \ f_k(x) \\ s.t: \\ \underline{X} \in x \end{array}\right\} \rightarrow \left\{\begin{array}{l} min\ \ D_p = \left(\sum_{j=1}^{k} w_j . \left(\frac{f_j(x) - f_j^*}{f_j^*} \right)^p \right)^{1/p} \\ s.t: \\ \underline{X} \in x \end{array}\right. \quad (23)$$

3.2. Lagrangian relaxation approach

In mathematical optimization approaches, the relaxation approach known as LR uses a simpler problem to approximate a challenging restricted optimization issue. A solution to the relaxed problem is an approximate solution to the main problem and provides useful information. The method imposes a cost on violators and uses a Lagrange coefficient to punish violations of inequality requirements. The strong inequality constraints in the model are replaced by these additional costs. Most of the time, this relaxed problem is simpler to solve than the original one. The LR approach is shown as follows:

$$\begin{array}{l} \max c^T x \\ s.t \\ (1) A_1 x \le b_1 \\ (2) A_2 x \le b_2 \\ \vdots \end{array}$$

Constraint (2) can be introduced into the OF:

$$\begin{array}{l} \max c^T x + \lambda^T (b_2 - A_2 x) \\ s.t \\ (1) A_1 x \le b_1 \end{array}$$

If the weight of λ become nonnegative, the OF is penalized and if constraint (2) is satisfied, we are also rewarded. The LR of our main problem is the system that was just explained. ***Table 1*** shows the pseudo-code of the algorithms.

Table 1. LR algorithm

Lagrangian relaxation
1) Calculate an initial upper bound (UB) and $LB^* = -\infty$, initial Lagrange coefficient vector λ
2) Solving relaxation problems and calculating LB
3) If $LB > LB^*$ then $LB = LB^*$
4) $\lambda^{(t)} = \lambda^{(t-1)} + k(b - Ax)$ while $k = \theta \frac{UB - LB^*}{\sum_{i=1}^{n}(b_i - a_i x^*)^2}$
5) If there is no improvement in the value of the best bound after m consecutive iterations, then θ = θ/2
6) Refer to step 2

4. Numerical examples

4.1. Computational experiments

To prove the effectiveness of the proposed model, ten sample problems are generated and solved. The problems have different sizes. All parameters follow a uniform distribution to get closer to reality, and we round these parameters to illustrate the resulting numbers better. The characteristics of the problems we are considering are given in ***Table 2***, and the values of the parameters are specified in ***Table 3***. Each problem is solved by the LP-metric method. To obtain the values of the OFs, we first solve each problem separately, and then, each problem is examined by the LP-metric method with different weights. The proposed method is implemented with the GAMS commercial software on a system with Intel Core (TM) i3 CPU, M 450 @ 2.30 GHz, 2.00 GB of RAM.

Table 2. Test problem

Index	Description	Sample problem									
		1	2	3	4	5	6	7	8	9	10
i,j	No. of generation node	7	8	9	10	11	11	12	13	14	15
d	No. of depot	3	3	4	5	5	6	6	7	7	8
w	No. of waste	4	4	4	4	4	4	4	4	4	4
k	No. of vehicle	3	3	3	4	4	4	4	4	5	5
t	No. of time periods	3	4	4	5	6	6	7	8	9	10
r	No. of recycling center	4	4	5	6	6	6	6	7	8	9
q	No. of technologies	3	3	3	3	3	3	3	3	3	3
o	No. of robots	3	3	4	4	4	4	5	5	6	6
n	No. of operation	3	3	5	5	5	5	5	5	5	5

Table 3. Parameters in test problems

Parameters	Value	Parameters	Value
dis_{ir}(kilometers)	~uniform (10,50)	cap_{kw} (kilogram)	~uniform (2000,3000)
c_{o} (dollar)	~uniform (300,1000)	mr (number)	~uniform (50,200)
pr_{wqr} (dollar)	~uniform (300,1500)	em_{k}(ppm)	~uniform (10,50)
fr_{rq} (dollar)	~uniform (1000,2500)	rc_{r} (kilogram)	~uniform (300,2000)
so_{wqr} (dollar)	~uniform (100,200)	alfa_{wq} (kilogram)	~uniform (10,500)
dem_{iwt} (kilogram)	~uniform (500,600)	dt_{wqtr} (number)	~uniform (100,200)
nr_{rq} (number)	~uniform (50,500)	e_{t}(ppm)	~uniform (2500, 2700)
GD(number)	~uniform (10,23)	pt_{wn} (min)	~uniform (10,50)

4.2. Results

In this section, the focus is on validating the suggested model by solving the five sample problems mentioned in the previous section.

Some parameters are changed and the response of the model is evaluated. To do so, numerical results obtained by the LP-metric approach are analyzed concerning the primary measures: first OF value (Z_1), second OF value (Z_2), the OF for LP-metric approach (Z_{LP}), and CPU–time. The numerical results are shown in ***Table 4.***

Table 4. Computational results obtained for small-sized problem

Test problem	OF			Time(s)
	Z_1	Z_2	Z_{LP}	
1	9.647117E+8	1296	0.066	003
2	1.134563E+9	1324	0.082	006
3	1.157713E+9	1371	0.064	065
4	2.654482E+9	1951	0.042	174
5	2.169672E+9	2087	0.083	260

This model is NP-hard so in large sizes has not had to answer or spent a long time to achieve the solution. For solving this model, an approach, namely LR is considered.
Each problem is solved by two LP-metric and LR methods. To obtain the values of the OF s, we first solve each problem separately, and then, each problem is examined by two different methods. The proposed methods are implemented with the GAMS commercial software on a system with Intel Core (TM) i3 CPU, M 450 @ 2.30 GHz, 2.0 GB of RAM. The numerical results are shown in ***Table 5***. It is clear that in this table, the GAMs Software can’t solve the problem after problem 5; whereas it can solve problems 1 to 5; however, the Lagrangian method has given solutions for problems 5 to 10. So, it is obtained that in upper size LR works better.

Table 5. The numerical results

The number of problems	Run with LR		Run with gams	
	OF	CPU-times	OF	CPU-times
1	9.647117E+8	006	9.647117E+8	008
2	1.154563E+9	007	1.134563E+9	025
3	1.187713E+9	012	1.157713E+9	065
4	2.754482E+9	028	2.654482E+9	174
5	2.189672E+9	038	2.169672E+9	260
6	2.734482E+9	045	-	-
7	2.856481E+9	069	-	-
8	4.654782E+10	122	-	-
9	5.264773E+10	247	-	-
10	7.554732E+10	605	-	-

5. Conclusion

This paper develops a new mixed-integer non-linear bi-objective mathematical model to design an efficient MSW network. MSW plays a major role in people's life. This environmental issue can pose a significantly greater threat to human health and ecosystem balance compared to the time before now. Thus, this paper has presented a new integrated multi-stage model for a comprehensive MSWM system in three levels of vehicle routing, disassembly sequence scheduling, and allocation of recycling centers to depot centers. The novelty of this paper is considering waste-vehicle and waste-technology compatibility as an effective and useful method to mitigate environmental issues. To measure the effectiveness of the suggested model, it was solved using two multi-objective methods, namely, LP-metric and LR methods. Moreover, to deal with the complexity of the introduced model, a LR heuristic based on a subgradient approach was proposed, and making use of some numerical examples in small and large sizes, the performance of the suggested heuristic was verified. The results showed that the proposed heuristic is capable to produce the results of small and also large-sized problems with negligible gaps and a reasonable time in comparison with the results of exact methods. Several numerical test problems from a small to a large extent were solved. The following matters are suggested for future work:

- Developing heuristic approaches, such as benders decomposition and meta-heuristic algorithms like genetic algorithms to solve large-scale problems is recommended;
- Applying stochastic optimization to solve the problem under uncertainty would also be meaningful;
- Considering the machine learning algorithm to forecast produced waste would also be useful;
- Considering queuing theory to decrease waiting time in generation node or depot.

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