Sustainable medical waste management in high-demand healthcare environments

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Abstract

The increase in medical and hospital waste production is a consequence of rising demand for medical services. A substantial increase in medical waste presents a dual challenge. The collecting and treatment system may struggle to manage the excess waste, potentially requiring the establishment of temporary treatment centers. Simultaneously, the rise in waste volume contributes to increased air, soil, and water pollution within the collecting system. This paper introduces a multi-objective mathematical model for medical waste management, addressing economic, environmental, and social sustainability pillars. It evaluates costs and environmental impact across diverse medical waste types and time periods to minimize damage from uncollected waste. Various locations, such as permanent and temporary hospitals, clinics, labs, residential areas, treatment centers, and landfills, are analyzed. Results demonstrate the efficacy of a three-objective model with weighted functions. This approach optimizes waste flow, installs new treatment centers, and establishes a balance between goals, enhancing medical waste management sustainably. The results indicate that increasing the amount of generated waste in waste production centers has the most significant impact on the quantity of uncollected waste and levels of water, soil, and air pollution. Changes in transportation and waste treatment costs have the most significant impact on the overall system cost

Keywords: Healthcare waste management, Sustainable logistics, Multi-objective optimization, Medical waste generation.

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Introduction

With the rapid advancement of medical science and technologies in recent decades, the volume of medical waste has increased dramatically. These wastes, comprising materials contaminated with viruses, bacteria, and potent chemicals, pose challenges to public health while offering an opportunity to enhance environmental management. While crucial for human health, they also significantly impact environmental balance. This article presents a mathematical model with the aim of improving current systems and methods in medical waste management, recognizing the paramount importance of this issue [1]. We witness the adverse impacts of the density of communicable and infectious diseases in global societies. There is a pressing need for an integrated approach to prevent the spread of these diseases and effectively manage medical waste [2].

This article delves into the intricacies of medical waste issues, presenting a mathematical model to enhance the management framework in this field. The subsequent sections provide a comprehensive analysis of the relevant literature and present the optimized results of the proposed model, along with future perspectives in medical waste management. The designed model comprises three levels of the chain: waste producers at the first level, waste collection and treatment centers at the second level, and a burial area at the last level. Sustainability, encompassing economic, environmental, and social aspects, serves as the guiding principle. Notably, the model's advantage lies in its consideration of medical waste within the three pillars of sustainability: economic, environmental, and social.

This article serves not only as a valuable source of information for researchers and scientists in the health and environmental fields but also plays a crucial role in formulating optimal policies and solutions for improved medical waste management. The contributions of this research can be summarized as follows:

1- Examining the three pillars of a sustainable logistics system (economic, social, and environmental aspects) in a medical waste management system.
2- Exploring the implementation of temporary treatment centers to manage the surge in waste production from hospitals, laboratories, clinics, residential areas, etc.
3- Balancing air, soil, and water pollution in the logistics system with the amount of uncollected waste during high-pressure situations.

The article conducts a thorough review of research literature in section 2. Section 3 introduces the problem description and the proposed mathematical model. Following this, section 4 provides numerical results obtained from model optimization and sensitivity analysis. The fifth section summarizes the research and presents some ideas for future studies.

Literature review

Recently in 2023, Mazzei and Specchia [3] provided an overview of the different technologies available for the treatment of solid medical waste (MW). The authors discussed the pros and cons of each technology, as well as their applicability to different types of MW. They also discuss the challenges and opportunities associated with the use of MW treatment technologies. Hou [4] investigates the factors that influence the generation of medical waste in China. The authors use a fixed-effects model to analyze data from eight cities in China from 2013 to 2019. They find that there is a non-linear N-shaped relationship between medical waste generation (MWG) and per capita gross domestic product (GDP). MWG will continue to increase with economic growth, but the growth rate will slow down from fast to slow, and then from slow to fast with economic growth.

Xu [5] in 2023 proposes an optimization model for a waste recycling network considering loading reliability to minimize the collective cost of location, vehicle usage, and transportation. The authors then propose a modified ant colony algorithm combined with the K-means clustering method based on a genetic algorithm to solve the optimal location problem and the vehicle routing problem. The numerical examples are then conducted in Xuzhou City, China to evaluate the performance of the proposed model. Kumar [6] reviews the use of life cycle assessment to assess the environmental impact of medical waste disposal. The authors discuss the different stages of the LCA process, as well as the different types of environmental impacts that can be assessed. They also provide examples of how LCA has been used to improve medical waste management practices. Yaspal [7] proposes a data-driven digital transformation approach for reverse logistics optimization in a medical waste management system. The authors use a multi-objective optimization model to minimize the total cost of the reverse logistics system, while also considering the risk of infectious waste spillages. They propose a data-driven approach to predict the demand for medical waste collection services.

Çelik [8] in 2023 proposes a multi-criteria decision-making method based on intuitionistic fuzzy sets to evaluate the medical waste management process in hospitals. The authors consider four criteria: qualified personnel, health institution infrastructure, control of waste, and environmental friendliness. They use the intuitionistic fuzzy technique for order preference by similarity to ideal solution (TOPSIS) method to rank the hospitals. The results show that the hospital with the highest ranking is the one that performs best in all four criteria. Cao [9] proposes a two-phase optimization model for COVID-19 medical waste handling. The first phase minimizes the total potential infection risks, the second phase minimizes the total environmental risks, and the third phase maximizes the total economic benefits. The authors use a lexicographic optimization approach and a linear weighted sum method to solve the model. The results show that the priority of sustainable objectives is society, economy, and environment in the first and second phases.

Wang [10] in 2023 proposes a bi-objective routing optimization model for medical waste collection. The objective is to minimize the maximum infectious risk and the transport cost simultaneously. The authors use an ε-constraint method incorporating weighting to obtain the entire Pareto front and an improved solution process. A fast approximation approach is proposed for solving large-scale instances efficiently. The results show that the proposed solution method is effective in finding the Pareto front. The priority of sustainable objectives is infectious risk, transport cost, and travel time. A decentralized decision mode is preferred to design a COVID-19 medical waste transport network at the province level. Bolan [11] reviews the distribution, fate, and management of potentially toxic elements (PTEs) in incinerated medical wastes. The authors discuss the sources of PTEs in medical waste, the types of PTEs that are found in medical waste, and the environmental impacts of PTEs from medical waste. They also discuss the different technologies that are used to treat medical waste and the challenges and opportunities associated with these technologies. Nengmin [12] in 2023 proposes a bi-objective routing optimization model for medical waste collection. The objective is to minimize the maximum infectious risk and the transport cost simultaneously. The authors use an ε-constraint method incorporating weighting to obtain the entire Pareto front and an improved solution process. A fast approximation approach is proposed for solving large-scale instances efficiently. The results show that the proposed solution method is effective in finding the Pareto front. The priority of sustainable objectives is infectious risk, transport cost, and travel time. A decentralized decision mode is preferred to design a COVID-19 medical waste transport network at the province level.

These studies collectively contribute valuable insights to the evolving field of medical waste management, addressing technological challenges through the exploration and evaluation of various treatment technologies. Additionally, they shed light on environmental aspects by assessing the environmental impact of medical waste disposal methods and proposing sustainable solutions. Moreover, these works offer solutions to logistical challenges by optimizing waste collection and recycling networks, considering factors such as loading reliability and efficient routing.

Problem description

The network structure comprises three main components: production, treatment, and disposal of medical waste, as explained earlier. These segments encompass various medical centers and facilities treating patients for various conditions. In the production section, waste from these centers is directed to treatment centers in the second part of the network, where it undergoes processing according to established treatment protocols. After purification, the waste is free of viruses, ensuring its safety. If the existing treatment centers are insufficient, network authorities may utilize new or temporary centers. The final part of the network structure involves specific landfills for treated medical waste, where the waste is buried according to specific sanitary guidelines.

As shown in Figure 1, three levels of the chain have been designed in this problem, where there are waste producers on the first level, waste collection and treatment centers are on the second level, and the disposal area is located on the last level. This supply chain seeks to minimize chain costs and environmental pollution and the amount of uncollected waste.

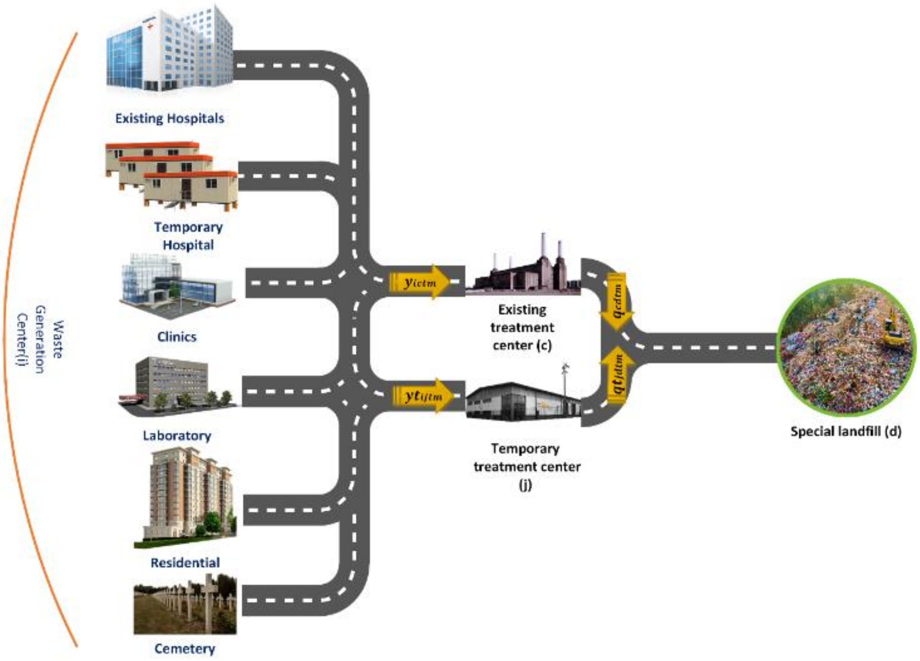

Figure (1) The framework of the medical waste supply chain network model

The main assumptions of this research are summarized below:

- Some of the hospital beds have been allocated to different patients and temporary hospitals may have been created by some hospitals to respond to potential demand.
- Medical waste is produced by few medical clinics dedicated for outpatient examinations of suspicious cases.
- Medical waste is also produced by laboratories that have the ability to diagnose.
- The efficiency of inactivating microbial spores must be possessed by the purification device. Therefore, other waste can be buried with medical waste after treatment with the Autoclave device and be safe.
- Patients diagnosed due to illness and are not in serious condition are in their homes. Medical waste is also produced by these patients, so their families have been asked to separate their waste from the waste produced by the patients by health officials. This waste is collected with a specific protocol and then transferred to transfer stations.
- The virus may be contained by their body after the death of the patients due to the virus or disease. In other words, viruses may be harbored by parts of the body that are still relatively preserved after death. The production of medical waste related to the death of patients is led by this situation.

Model formulation

This paper introduces a novel model aimed at minimizing the cost and risk associated with the collection, treatment, and prevention of potential harm caused by medical waste in any production facility. Designed as a three-goal mathematical model, it encompasses all conceivable centers, such as hospitals, clinics, laboratories, residential areas, and even cemeteries.

(Indices)

$i \in I$	$I = \{1,2,\dots,\hat{I}\}$	:	Medical waste production centers
$c \in C$	$C = \{1,2,\dots,\hat{C}\}$	:	Fixed waste treatment centers
$j \in J$	$J = \{1,2,\dots,\hat{J}\}$	:	Temporary waste treatment centers
$d \in D$	$D = \{1,2,\dots,\hat{D}\}$	:	Waste disposal centers
$t \in T$	$T = \{1,2,\dots,\hat{T}\}$	:	Time periods
$m \in M$	$M = \{1,2,\dots,\hat{M}\}$	:	Types of waste

(Parameters)

ct_c	:	The cost of purification in fixed treatment center *c*
ctt_j	:	The cost of purification in temporary treatment center *j*
dc_d	:	The cost of burial of waste in disposal center *d*
co_{im}	:	The cost of collecting a unit of waste *m* from the waste production center *i*
R	:	Transportation cost in medical waste production centers

Rt	:	Transportation cost in treatment centers
wuw_{im}	:	The weight assigned to the severity of damage of waste *m* not collected at waste production center *i*
ins_j	:	The cost of constructing a temporary treatment center in place *j*
$fict_j$	:	Operating cost of temporary treatment center *j*
dic_{ic}	:	Distance between medical waste production centers *i* and fixed treatment center *c*
dit_{ij}	:	Distance between medical waste production center *i* and temporary treatment center *j*
did_{cd}	:	The distance between fixed treatment center *c* and disposal center *d*
$didt_{jd}$	:	The distance between temporary treatment center *j* and disposal center *d*
cac_c	:	Maximum capacity of fixed treatment center *c*
$cact_j$	:	Maximum temporary treatment capacity *j*
fic_c	:	Fixed treatment plant operating cost *c*
de_{itm}	:	Amount of waste *m* generated in medical facility *i* in time period *t*
ce_{im}	:	Amount of soil pollution per kilogram of waste *m* in waste production center *i*
cte_{ij}	:	Amount of carbon produced during transportation from production center *i* to temporary treatment center *j*
cee_{ic}	:	Amount of carbon produced during transportation from production center *i* to the fixed treatment centers *c*
ces_{cd}	:	Amount of carbon produced during transportation from fixed treatment center *c* to disposal center *d*
cts_{jd}	:	Amount of carbon produced during transportation from temporary treatment center *j* to disposal center *d*
fc_{cm}	:	Water pollution per kg of waste m for treatment operation in fixed treatment center *c*
ffc_{jm}	:	Water pollution per kilogram of waste *m* for the treatment operation in the temporary disposal center *j*
l_1	:	The coefficient of conversion of air pollution to soil
l_2	:	Water to soil pollution conversion factor
U_1	:	The assimilation coefficient of the first objective function
U_2	:	The assimilation coefficient of the second objective function
U_3	:	The assimilation coefficient of the third objective function

(Decision variables)

w_j	:	Binary variable for construction or non-construction of temporary waste center *j*
zct_{jt}	:	Binary variable for operation of temporary treatment center *j* in period *t*
zc_{ct}	:	Binary variable for establishment of fixed treatment *c* in period *t*
wz_{jt}	:	Variable zero and one if the temporary waste center *j* is built and put into operation
y_{ictm}	:	Amount of waste *m* transferred from waste production center *i* to fixed waste center *c* in period *t*
yt_{ijtm}	:	Amount of waste *m* transferred from waste production center *i* to temporary waste center *j* in period *t*
tq_{ctm}	:	Amount of waste *m* treated in fixed waste center *c* in period *t*
tqt_{jtm}	:	Amount of waste *m* treated in temporary waste center *j* in period *t*
q_{cdtm}	:	Amount of waste *m* transferred from fixed treatment center *c* to disposal center *d* in period *t*
qt_{jdtm}	:	Amount of waste *m* transferred from temporary treatment center *j* to disposal center *d* in period *t*
uq_{itm}	:	Amount of waste *m* not collected in medical waste generation center *i* in time period *t*
muq	:	Maximum amount of uncollected waste

(Objective functions)

$$\begin{aligned} Min\ z_1 = & \sum_{j,t}(fict_j\,.\,zct_{jt}) + \sum_{c,t,m}(ct_c\,.\,tq_{ctm}) + \sum_{j}(ins_j\,.\,w_j) + \sum_{c,t}(fic_c\,.\,zc_{ct}) + \sum_{j,t,m}(ctt_j\,.\,tqt_{jtm}) \\ & + R\left(\sum_{i,c,t,m}(dic_{ic}\,.\,y_{ictm}) + \sum_{i,j,t,m}(dit_{ij}\,.\,yt_{ijtm})\right) \\ & + Rt\left(\sum_{c,d,t,m}(did_{cd}\,.\,q_{cdtm}) + \sum_{j,d,t,m}(didt_{jd}\,.\,qt_{jdtm})\right) + \sum_{i,t,m}(co_{im}\,.\,de_{itm}) \end{aligned} \tag{1}$$

$$\begin{aligned} Min\ z_2 = & \sum_{i,t,m}(uq_{itm}\,.\,ce_{im}) + l_1\left(\sum_{i,j,t,m}(yt_{ijtm}\,.\,cte_{ij}) + \sum_{i,c,t,m}(y_{ictm}\,.\,cee_{ic})\right) \\ & + l_1\left(\sum_{c,d,t,m}(q_{cdtm}\,.\,ces_{cd}) + \sum_{j,d,t,m}(qt_{jdtm}\,.\,cts_{jd})\right) \\ & + l_2\left(\sum_{c,t,m}(tq_{ctm}\,.\,fc_{cm}) + \sum_{j,t,m}(tqt_{jtm}\,.\,ffc_{jm})\right) \end{aligned} \tag{2}$$

$$Min\ z_3 = muq \tag{3}$$

(Constraints)

$$uq_{it-1m} + de_{itm} = \sum_c y_{ictm} + \sum_j yt_{ijtm} + uq_{itm} \quad \forall i,t,m \tag{4}$$

$$\sum_i \sum_m y_{ictm} \leq cac_c\ .zc_{ct} \quad \forall c,t \tag{5}$$

$$\sum_i y_{ictm} = tq_{ctm} \quad \forall c,t,m \tag{6}$$

$$\sum_i yt_{ijtm} = tqt_{jtm} \quad \forall j,t,m \tag{7}$$

$$q_{cdtm} = tq_{ctm} \quad \forall c,d,t,m \tag{8}$$

$$qt_{jdtm} = tqt_{jtm} \quad \forall j,d,t,m \tag{9}$$

$$muq \geq \sum_t \sum_m (wuw_{im}\ .uq_{itm}) \quad \forall i \tag{10}$$

$$\sum_i \sum_m yt_{ijtm} \leq (capct_j\ .wz_{jt}) \quad \forall j,t \tag{11}$$

$$wz_{jt} - zct_{jt} - w_j + 1.5 \geq 0 \quad \forall j,t \tag{12}$$

$$1.5 \times wz_{jt} - zct_{jt} \leq 0 \quad \forall j,t \tag{13}$$

$$y_{ictm}\ , yt_{ijtm}\ , tq_{ctm}\ , tqt_{jtm}\ , q_{cdtm}\ , qt_{jdtm}\ , uq_{itm}\ , muq \geq 0 \quad \forall i,j,t,c,m,d \tag{14}$$

$$wz_{jt}\ , zct_{jt}\ , zc_{ct}\ , w_j \epsilon \{0.1\} \quad \forall j,t,c \tag{15}$$

The first objective, aiming to minimize the overall system costs, is expressed by equation (1). This function incorporates fixed operating costs for both fixed and temporary treatment centers, construction costs for temporary treatment centers, operational costs for waste treatment in both fixed and temporary centers, transportation costs from production centers to treatment centers, and the cost of transporting treated waste from treatment centers to burial centers. The second objective, focused on minimizing environmental pollution, is defined by equation (2). It accounts for soil pollution during waste collection at production centers, air pollution from vehicles transporting waste to temporary and permanent treatment centers, air pollution during transportation from fixed and temporary treatment centers to waste disposal centers, and water pollution resulting from waste treatment in treatment centers. The unit for this function is kilograms. The third objective, outlined in equation (3), involves minimizing the maximum amount of uncollected waste in medical waste production centers, measured in kilograms.
Equation (4) ensures a balanced flow between medical waste production centers, fixed treatment centers, and temporary treatment centers. It establishes the relationship between the decision variables for uncollected waste in medical waste production centers and the waste flow between production centers and treatment centers. Equation (5) guarantees that the input of waste to fixed treatment centers does not exceed their capacity. If a fixed treatment center is not operational, no waste is sent to it, as indicated by the binary decision variable in this equation. Equations (6) and (7) equalize the incoming flow of waste with the amount treated in fixed and temporary treatment centers, respectively. Equations (8) and (9) ensure equality between treated waste output from fixed and temporary treatment centers and the treated waste within these centers.
Equation (10) defines the maximum amount of uncollected waste. Equation (11) ensures that the input of waste to temporary treatment centers does not exceed their capacity, with no waste sent if the temporary treatment center is not built. Equation (12) linearizes the multiplication of two binary variables, ensuring the possibility of sending waste to a temporary treatment center if it is built and operational. Equation (13) further linearizes equation (12), ensuring the operational status of a temporary treatment center if it is assigned to receive any waste. This prevents the situation where a temporary treatment center is built but not operated, as stipulated in equation (11). Positive variables are denoted in equation (14), and binary variables are represented in equation (15).

Solution approach
Maintaining a balance among various objectives is crucial in multi-objective problems. Each objective requires attention and weighting to fully optimize the problem, and achieving a proper balance is facilitated through the weighted combination method. The combination of weights with the overall objective function proves effective in resolving multi-objective problems. Unique weights are assigned to each objective within the overall objective function. The mathematical formulation of this approach is presented in equation (16).

$$F(x) = \sum_{i=1}^{k} U_i \, . \tilde{f}_i(x) \qquad (16)$$

Equation (16) shows the final objective function $F(x)$, the i[th] normalized objective function $\tilde{f}_i(x)$, and the weight U_i associated with each objective function. Normalization of each objective is achieved by dividing it by its maximum possible value. The combined objective function of the proposed mathematical model is given by equation (17), where objectives z_1 to z_3 are calculated in equation (1) to (3) and different wights are examined in the following section.

$$Min \ Z_U = U_1 \, . z_1 + U_2 \, . z_2 + U_3 \, . z_3 \qquad (17)$$

Numerical results

This section begins by presenting the values of the indices and parameters of the mathematical model, followed by the results of its solution. The problem is formulated with 18 medical waste production centers (WPC), 3 permanent waste treatment centers, 3 temporary waste treatment centers, and one disposal center, considered over 6 time periods. In accordance with Kargar's paper [13], Tables 1 to 4 provide the values of model parameters, including demand, capacity, amount of waste sent, and costs. Notably, the cost of collecting waste from medical waste production centers is zero for centers 1 to 10, 17, and 18.

Table 1. Values of parameters used in solving the model

Parameters	Center 1	Center 2	Center 3
The cost of treatment in fixed centers	0.7	0.7	0.7
The cost of treatment in temporary centers	0.7	0.7	0.7
The cost of constructing a temporary treatment center	20000	20000	20000
Operating cost of the temporary treatment center	300	300	300
Fixed treatment plant operating cost	400	400	400
Maximum fixed filtration capacity	550	500	200
Maximum temporary treatment capacity	400	400	150

Table 2. Values of parameters used in solving the model

parameters	Value
Transportation cost in medical waste production centers	0.53
Transportation cost in treatment centers	0.022
The coefficient of conversion of air pollution to soil	0.2
Water to soil pollution conversion factor	0.3
The distance between the fixed treatment center 1 and the burial center	32.9
The distance between the fixed treatment center 2 and the burial center	31
The distance between the fixed treatment center 3 and the burial center	34.7
Distance between temporary treatment center 1 and burial center	32.9
Distance between temporary treatment center 2 and burial center	31
Distance between temporary treatment center 3 and burial center	30

Table 3. Values of parameters used in solving the model

Distance between medical waste production centers and fixed treatment centers		Fixed treatment center 1	Fixed treatment center 2	Fixed treatment center 3	The distance between medical waste production centers and temporary treatment centers		Temporary treatment center 1	Temporary treatment center 2	Temporary treatment center 3
	WPC 1	0	2	3.8		WPC 1	0	2	2
	WPC 2	2	0	3.7		WPC 2	2	0	1.5
	WPC 3	1.9	3.6	3.9		WPC 3	1.9	3.6	2
	WPC 4	2	3.8	4		WPC 4	2	3.8	2.1
	WPC 5	1.1	3	3		WPC 5	1.1	3	1.2
	WPC 6	0.2	2	3.85		WPC 6	0.2	2	2.1
	WPC 7	1.9	0.6	3.7		WPC 7	1.9	0.6	1.4
	WPC 8	2.1	3.6	3.9		WPC 8	2.1	3.6	2
	WPC 9	1.7	3.5	3.7		WPC 9	1.7	3.5	2.8
	WPC 10	2	1.7	3.7		WPC 10	2	1.7	1.4
	WPC 11	4.2	3.9	6.1		WPC 11	4.2	3.9	3.1
	WPC 12	2.8	5.4	5.6		WPC 12	2.8	5.4	6.1

WPC 13	4.1	6.1	5.9	WPC 13	4.1	6.1	6.4
WPC 14	2	1.8	1.2	WPC 14	2	1.8	0.5
WPC 15	5.1	5	2.9	WPC 15	5.1	5	4
WPC 16	3.4	5.8	2.4	WPC 16	3.4	5.8	4.7
WPC 17	3.4	5.8	2.4	WPC 17	3.4	5.8	4.8

Table 4. Values of parameters used in solving the model

		Garbage type 1	Garbage type 2	Garbage type 3	Garbage type 4	Garbage type 5	Garbage type 6
Weight assigned to severity of damage of uncollected waste in medical waste generation facility	WPC 1	2.2	2.4	2.8	1.9	3.1	2.2
	WPC 2	2.5	2.7	3.1	2.2	3.4	2.5
	WPC 3	2	2.2	2.6	1.7	2.9	2
	WPC 4	2	2.2	2.6	1.7	2.9	2
	WPC 5	4.5	4.7	5.1	4.2	5.4	4.5
	WPC 6	4.2	4.4	4.8	3.9	5.1	4.2
	WPC 7	4	4.2	4.6	3.7	4.9	4
	WPC 8	4	4.2	4.6	3.7	4.9	4
	WPC 9	4.1	4.3	4.7	3.8	5	4.1
	WPC 10	3	3.2	3.6	2.7	3.9	3
	WPC 11	5.2	5.4	5.8	4.9	6.1	5.2
	WPC 12	5.4	5.6	6	5.1	6.3	5.4
	WPC 13	5.5	5.7	6.1	5.2	6.4	5.5
	WPC 14	5.3	5.5	5.9	5	6.2	5.3
	WPC 15	5.1	5.3	5.7	4.8	6	5.1
	WPC 16	5.2	5.4	5.8	4.9	6.1	5.2
	WPC 17	1.3	1.5	1.9	1	2.2	1.3
	WPC 18	1.5	1.7	2.1	1.2	2.4	1.5
		Garbage type 1	Garbage type 2	Garbage type 3	Garbage type 4	Garbage type 5	Garbage type 6
Cost of waste collection unit from medical	WPC 11	0.4	0.4	0.4	0.4	0.4	0.4
	WPC 12	0.4	0.4	0.4	0.4	0.4	0.4
	WPC 13	0.4	0.4	0.4	0.4	0.4	0.4
	WPC 14	0.4	0.4	0.4	0.4	0.4	0.4
	WPC 15	0.4	0.4	0.4	0.4	0.4	0.4
	WPC 16	0.4	0.4	0.4	0.4	0.4	0.4

The input information is fed into the GAMS software to derive the optimal solution. The model was executed on a personal computer equipped with an Intel 2.7 GHz CPU and 8 GB of RAM. The determination of weights (U_i) involves a sensitive process that can be approached in various ways. Table 5 presents various combinations of weights for the three objective functions. For the remainder of this paper, our focus will be on the last scenario, where equal weights are assigned to objectives. Given that all objectives pursue minimization, this choice establishes several trade-offs between them. Notably, the improvement of an objective value is observed as its weight increases.

Table 5. Different scenarios for weights of the objectives

Scenario No.	U_1	U_2	U_3	z_1	z_1	z_1
1	0	0.5	0.5	56517	117415	6
2	0.5	0	0.5	9572	521811	13505
3	0.5	0.5	0	47670	121950	760
4	0.33	0.33	0.33	47734	122016	450

Table 6 shows the amount of uncollected waste in medical waste production centers in the last period (t = 6). In the Sensitivity Analysis section, we will perform a comprehensive examination of the impact of variations in the amount of waste produced on the occurrence of uncollected waste. Figure 2 shows the amount of sending types of waste for period 6. The quantities of each of the six types of waste are depicted as a vector with six elements on each arc in this figure. Some of the transported values are omitted in this figure to simplify and enhance clarity.

Table 6. Amounts of uncollected waste from medical waste production centers in period 6

	Garbage type 1	Garbage type 2	Garbage type 3	Garbage type 4	Garbage type 5	Garbage type 6
WPC 1	43.754	0	0	0	0	40.748
WPC 2	0	0	53.774	0	0	0
WPC 3	0	0	27.388	0	24.382	23.380
WPC 4	0	0	0	26.720	25.050	24.048
WPC 5	0	0	0	0	0	1.598
WPC 6	1.292	0	0	0	0	1.156
WPC 7	0	0	0	0	0	0.816
WPC 8	0.986	0.952	0	0.884	0	0
WPC 9	0	0	0	0	0	1.088
WPC 10	2.600	2.600	0	0	2.600	0
WPC 11	43.358	3.415	0	0	13.024	24.472
WPC 12	0	0	0	29.526	26.646	24.472
WPC 13	53.998	0	0	0	0	27.930
WPC 14	0	37.772	16.140	29.526	0	0
WPC 15	34.846	28.603	0	25.270	0	0
WPC 16	0	29.260	21.228	0	0	0
WPC 17	4.342	0	4.342	0	4.342	4.342
WPC 18	5.678	0	0	5.678	0	5.678

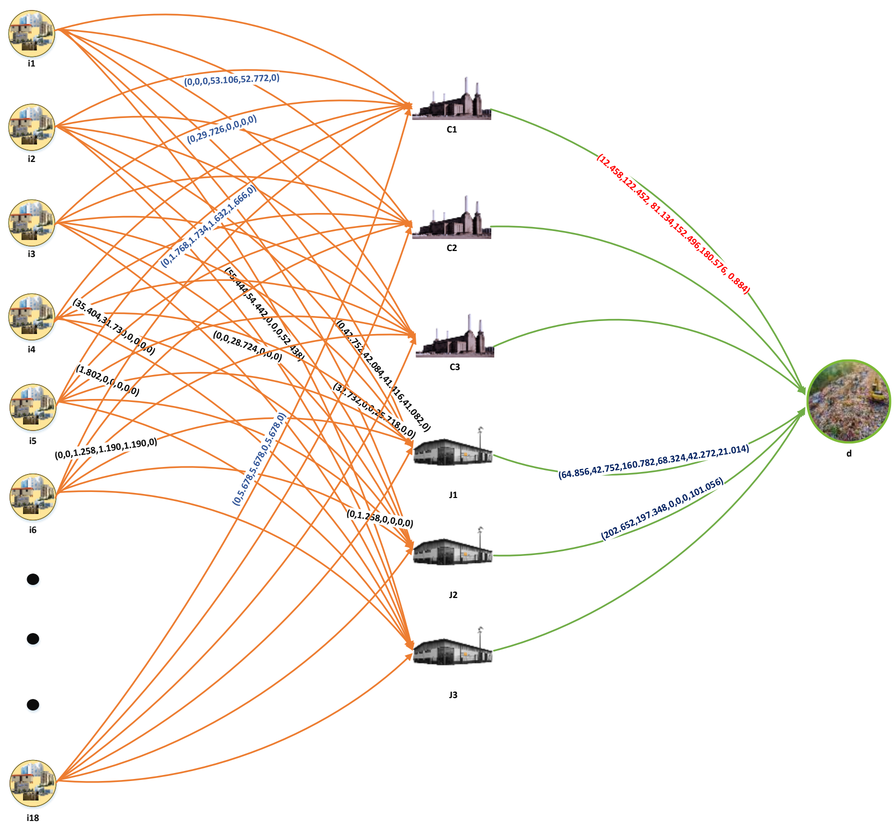

Figure (2) The results obtained from solving the model in the period of time 6

Sensitivity analysis

The effect of changing the values of different parameters on the value of the objective function is investigated in this section, and the influence of each parameter on the objective function is shown. The parameters examined in this section are: the amount of waste produced, the cost of waste collection, and the weight assigned to the severity of the damage of the waste. Different coefficients are used for the mentioned parameters in the sensitivity analysis method to evaluate the changes in the objective functions by changing the parameters.

Figure 3 shows the results of the sensitivity analysis for the amount of waste *m* produced in the medical center *i* in time period *t*. The sensitivity analysis on the amount of waste produced reveals that the objective functions attain better values in each optimal state when the amount of waste is reduced. Figure 3 also shows that the amount of environmental pollution produced has a direct relationship with the amount of waste produced in the sensitivity analysis. An increase in the amount of waste produced does not lead to significant changes in costs due to limitations in transportation capacities; however, the quantity of uncollected waste sees a drastic increase.

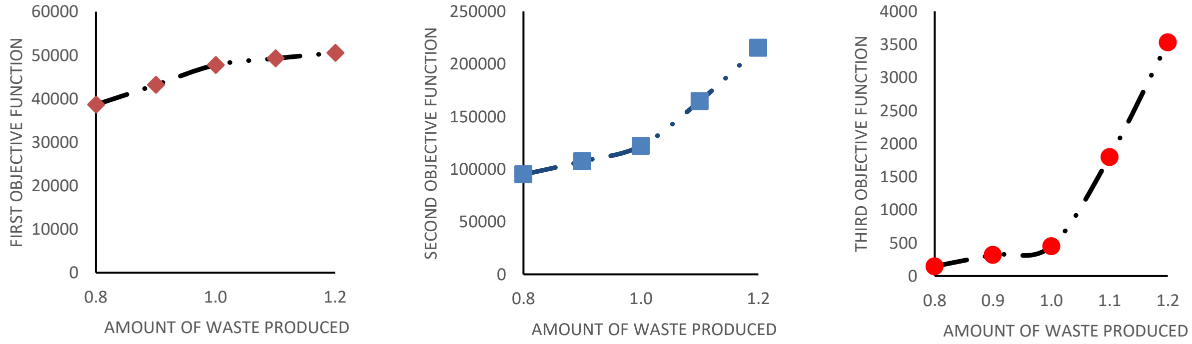

Figure (3) Sensitivity analysis on the amount of waste produced in WPCs

The sensitivity analysis presented in Figure 4, conducted on the cost of collecting waste from medical waste production centers, indicates that the first objective function, i.e., costs, achieves lower values when the cost of waste collection is reduced. Notably, the collection cost does not impact the other objective functions, signifying that alterations in collection costs mainly influence the overall system costs, without affecting environmental concerns or the amount of uncollected waste.

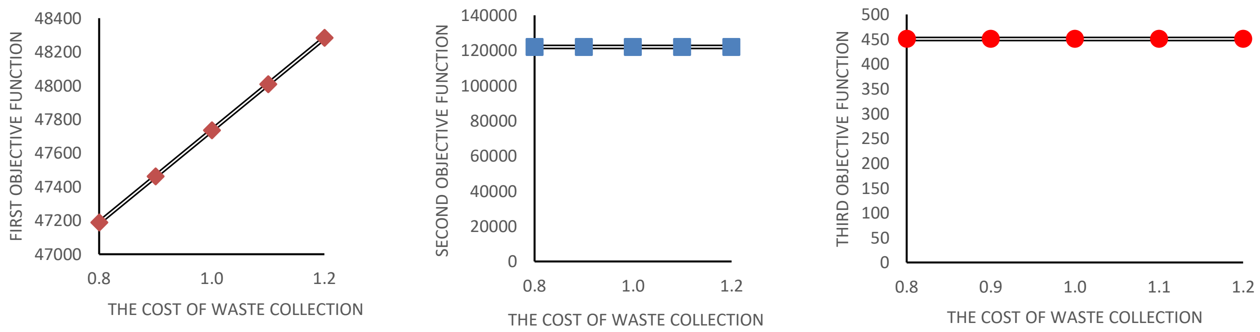

Figure (4) Sensitivity analysis on the costs of waste collection

The sensitivity analysis depicted in Figure 5, conducted on the weight assigned to the severity of the damage caused by the waste, reveals notable findings. As the weight of the damage factor increases, there is a concurrent decrease in the amount of uncollected waste, resulting in an increase in system costs. This outcome stems from the model's efforts to collect and treat a larger quantity of waste, consequently escalating associated costs. Notably, it is crucial to highlight that elevating the damage of waste factor up to 20% produces a positive impact on the environmental pillar of sustainability, as the environmental effects of the collecting system decrease.

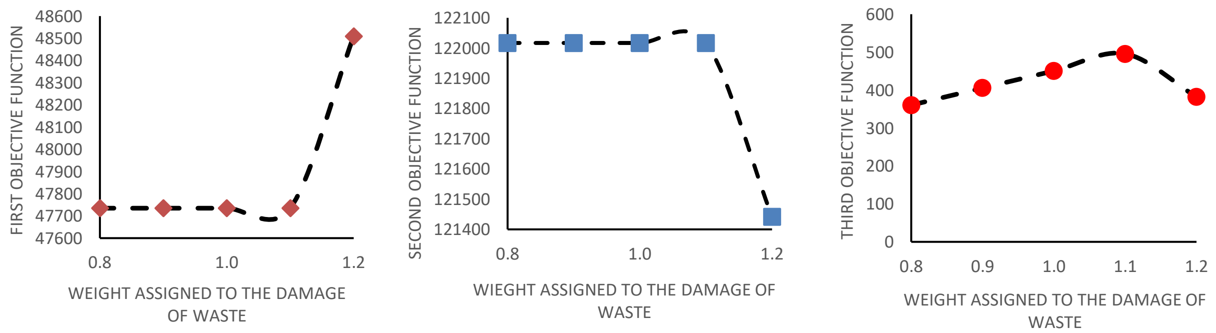

Figure (5) Sensitivity analysis on the weight assigned to the severity of the damage of the waste

Checking the conflict of objectives

The conflict of objectives was assessed by optimizing the mathematical model with three distinct aims: first, to reduce total costs; second, to minimize environmental pollution; and third, to minimize the maximum amount of uncollected waste. The results, presented in Table 7, clearly indicate that each objective is in conflict with the others due to their disparate nature, as illustrated schematically in Figure 6.

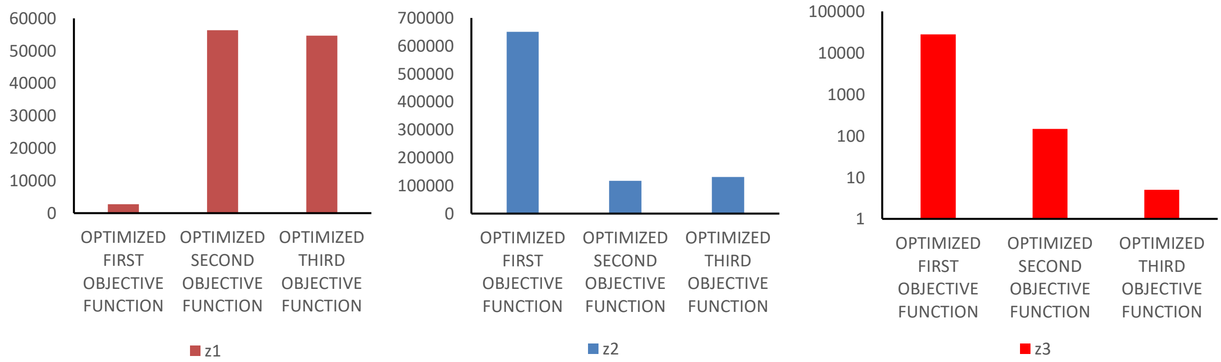

Figure (6) The conflict of goals in the optimization modes of each goal

In Figure 6, when optimizing the first objective function (total costs), there was a significant increase in the amount of uncollected waste. Although the decrease in waste transfer reduced air pollution, discontinuing the treatment process escalated water pollution, reaching its maximum value due to unmanaged waste. Optimizing the second objective function (air, water and soil pollution) resulted in a notable decrease in environmental pollution and uncollected waste compared to the first objective. However, this improvement came at the cost of a substantial increase in overall expenses. The optimization of the third objective function led to a remarkable reduction in uncollected waste, approximately a quarter of that from the second objective optimization. Nevertheless, this decrease in uncollected waste led to an increase in environmental pollution, with costs remaining high due to capacity constraints, compared to the optimization of the second objective function. The trade-offs between these objectives reveal the complex interplay within the system, underscoring the challenge of achieving a balanced and sustainable solution.

The initial rows of Table 7 illustrate the absolute values of objective functions z_1 to z_3 when each of them is separately optimized. The subsequent rows show the relative deviation of each objective from its optimized value. For instance, the costs of the waste management system are 19 times higher when attempting to minimize the amount of uncollected waste compared to the scenario where the costs are minimized directly.

The variation range for the third objective (uncollected waste) is higher than for the other objectives, indicating its greater sensitivity to optimization, whether focusing solely on itself or optimizing other objectives. Ensuring the effective collection of health waste in hospitals, clinics, laboratories, and other healthcare facilities is paramount for several critical reasons. Firstly, the proper and timely collection of health waste is essential to maintain a hygienic and safe environment within these centers, safeguarding the well-being of patients, healthcare professionals, and staff. Additionally, thorough waste collection is crucial for preventing the spread of infections and diseases, contributing significantly to public health efforts. Furthermore, effective waste collection in healthcare settings is imperative to comply with regulatory guidelines and standards. Proper waste disposal not only ensures adherence to legal requirements but also reflects the commitment of healthcare institutions to ethical and responsible practices.

Table 7. Objectives variation when optimizing each objective function

		Optimization of the first objective	Optimization of the second objective	Optimization of the third objective
Absolute values	z_1	2735	56326	54675
	z_2	649904	117382	131330
	z_3	28165	147	5
Relative gap from minimum value	z_1	0	19.6	19.0
	z_2	4.5	0	0.1
	z_3	5632	28.4	0

Conclusion

Establishing an efficient health waste collection system is of top importance as it directly impacts various aspects of public health and environmental sustainability. A well-designed system not only accounts for costs but also addresses the critical issue of uncollected medical waste, ensuring that no hazardous materials are left unattended within healthcare facilities. This collection process is vital for preventing potential health hazards and minimizing the risk of infections, contributing to overall community well-being. Also, a comprehensive health waste collection system considers the environmental implications of transportation and burial activities. By minimizing soil, water, and air pollution associated with waste management processes, such a system aligns with broader environmental conservation goals.

This paper introduces a multi-objective mathematical model for medical waste management, with a specific emphasis on economic, environmental, and social sustainability pillars. The model systematically evaluates the costs and environmental impact associated with diverse medical waste types and different time periods. The logistics system is organized into three levels. The first level encompasses waste production centers, including hospitals, clinics, residential areas, and laboratories. The second level comprises permanent and temporary treatment centers. The third level involves a disposal center dedicated to the burial of medical waste. The objective functions are threefold: first, to minimize transportation and operational costs; second, to minimize soil, air, and water pollution generated by the waste management system; and third, to minimize the amount of uncollected waste. This model evaluates six distinct types of medical waste across six time periods

The results of the sensitivity analysis indicate that when the amount of generated waste in waste production centers increases, it has the most significant impact on the quantity of uncollected waste and the levels of water, soil, and air pollution resulting from waste disposal (i.e., the objective functions related to environmental and social dimensions). Changes in transportation and waste treatment costs have the most significant impact on the overall system cost, namely the economic objective, and this impact follows a linear relationship, while the other two objectives are not significantly affected by these changes. Increasing the severity coefficient of waste damage has the most significant impact on costs, sharply increasing them. This is because the system tries to reduce environmental pollution caused by waste, and this process incurs additional costs. Examining the conflict of objectives reveals that the uncollected waste objective function exhibits the most significant range of change when the model transitions between the three objective functions. This underscores the importance of this objective in comparison to the others.

Several ideas for future research in this area are outlined below: 1) Investigating the application of alternative multi-objective methods, such as the epsilon-constraint method, could offer valuable insights into addressing the complexities of the problem. 2) Considering various types of vehicles within the fleet adds a layer of realism to the model, offering a more comprehensive understanding of the challenges associated with medical waste management. 3) Recognizing the inherent uncertainty in real-world scenarios, future research could delve into solving the problem under uncertain conditions by incorporating stochastic input parameters and employing robust optimization techniques. 4) As the dimensions of the problem increase, employing metaheuristic methods becomes increasingly relevant. Investigating the application of metaheuristic approaches could enhance the efficiency and scalability of the model for larger-scale applications.

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