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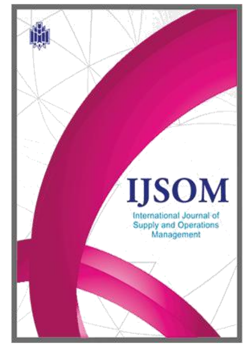

A Goal Programming Based Bi-Stage Network Design for COVID-19 Immunization Waste Management

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Abstract

The recent global efforts to control the spread of highly contagious COVID-19 pandemic have been successful, largely due to extensive vaccination campaigns. However, these campaigns have generated an enormous amount of infectious medical waste. This paper presents a weighted goal programming-based optimization model for managing medical waste generated from COVID-19 vaccination efforts. The model proposes an efficient system by integrating decisions of locating treatment centers and the routing of generated waste to these centers and eventually to disposal sites, with a focus on cost reduction, risk mitigation for the environment and the nearby population. The objectives include minimizing the setup and transportation costs, reducing risks to the population, limiting the number of installed units, and ensuring environmental sustainability of disposal sites. A set of randomly selected test instances is used to test the model's effectiveness. The results indicate that the compromised solution provides both cost benefits and reduced risk to the population. Specifically, the cost objective was compromised by only 5.98% and the risk objective by 1.54%, while the environmental sustainability objective was fully achieved. This approach effectively supports strategic choices in recycling healthcare waste generated from COVID-19 immunization. The study is expected to aid municipal managers and decision-makers of healthcare facilities in managing vaccination related waste more efficiently.

Keywords: Multi-objective optimization; Goal programming; COVID-19; Vaccination; Medical waste; Sustainability

1. Introduction

The recent outbreak of the novel Corona Virus Disease (COVID-19) has caused severe damage to public health globally. Nearly 105 million people have been affected, accompanied by 23 million deaths (WHO, 2021). It has posed a significant challenge not only to the healthcare system but also to the socioeconomic fabric of societies (Manning et al., 2021). The pandemic has also led to the generation of large volumes of medical waste from patient diagnosis and treatment across healthcare establishments (Haque et al., 2021; Tirkolaee et al., 2021). The extensive use of personal protective equipment (PPE), such as face masks, gloves, test kits, and sanitizers, has further exacerbated the problem of medical waste generation (Haque et al., 2021). Vaccination has emerged as one of the most effective ways to mitigate the impact of this infectious disease (Manning et al., 2021).

However, large-scale immunization campaigns have added to the existing burden of healthcare waste, including syringes, plastic containers, tissues, bandages, and so forth. Since most of this waste is plastic, responsible

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management is crucial to avoid environmental damage. From a circular economy perspective, recycling plastic is preferred over incineration or disposal due to its adverse ecological impact. Additionally, stainless steel waste from syringe needles and other surgical instruments can be reused after proper treatment of melting and reprocessing also (van Straten et al., 2021). In developing countries, where waste management systems are still nascent (Matete & Trois, 2008), the mismanagement of pandemic-led waste has further strained these systems. Therefore, the development and implementation of a safe and efficient medical waste management system are urgently needed to prevent the accumulation of waste stockpiles and the contamination of communities with potentially contagious waste, ensuring sustainability both during and post-COVID-19 period (Debnath et al., 2023; Tushar et al., 2023).

While several studies have addressed location-routing problems in healthcare waste contexts, limited attention has been given to COVID-19 vaccination waste (CVW) that would warrant immediate recycling choices. This research work is an attempt in this direction. Given the context of the preceding discussion, this research aims to explore the following research questions (RQs):

RQ1: How can healthcare waste from the COVID-19 vaccination drive be managed in terms of cost-effectiveness and environmental impact?

RQ2: What are the key variables and considerations in determining the optimal locations for vaccination centers to minimize healthcare waste generation and facilitate efficient waste routing?

RQ3: What practical implications and recommendations can be derived from the research findings to improve healthcare waste management from COVID-19 immunization?

To address these research questions, this study has set the following research objectives (ROs):

RO1: Develop an effective optimization model that integrates decisions on locating treatment centers and the routing of waste, aiming to minimize setup and transportation costs while ensuring environmental sustainability.

RO2: Gain a comprehensive understanding of the factors and considerations relevant to optimizing the management of healthcare waste generated from the COVID-19 vaccination.

RO3: Support decision-makers of healthcare facilities in making informed and efficient decisions regarding healthcare waste management from the COVID-19 vaccination.

To achieve these objectives, this study proposes a Multi-objective Goal Programming (MOGP) model to assist policymakers and decision-makers in making location-routing decisions related to setting up waste treatment centers and transporting the hazardous CVW from these centers to the disposal sites. The model aims to minimize conflicting objectives, including the number of centers to be established, the setup and transportation costs of CVW, the risk posed to the population, and the environmental sustainability of disposal sites. An illustrative dataset is used to demonstrate the model's effectiveness.

The remainder of the paper is structured as follows. Section 2 reviews relevant literature to identify the research gaps and study's contributions. Section 3 discusses the adopted methodology and model formulation. Section 4 demonstrates the formulation using an illustrative dataset. The analysis and discussion of the findings are reported in Section 5. Managerial and theoretical implications are discussed in Section 6, while Section 7 concludes the paper and provides future research directions.

2. Literature Review

Recent studies in waste management have increasingly focused on the application of various operations research techniques and modeling. These models predominantly addressed three key decisions: location, allocation or routing, and integrated network design (Yu, Sun, Solvang, Laporte, et al., 2020). The following sub-sections highlight recent investigations in waste management modeling across different segments, highlighting the existing research gaps.

2.1 Location Routing Models in Waste Management

Emek & Kara (2007) developed a cost-based mathematical model to locate hazardous waste disposal plants considering government air pollution standards. Berglund & Kwon (2014) addressed the routing of hazardous materials carriers by minimizing costs. In another study, Li et al. (2015) proposed a covering location model to collect and handle industrial hazardous waste, while another study used a homogenous capacitated truck fleet to handle the same (Paredes-Belmar et al., 2017). Ardjmand et al. (2015) used a genetic algorithm-based mathematical model to select hazardous waste generation and disposal facilities. Additionally, Lee et al. (2016) developed a mixed-integer programming model for Hong Kong municipal waste management.

Several studies have also proposed multi-objective approaches to hazardous waste management. Nema & Gupta (2003) employed a multi-objective model for planning and designing regional waste management systems, while Alumur & Kara (2007) focused on the selection of treatment and disposal centers, and associated technologies. Zografos & Androutsopoulos (2008) developed a decision support system for hazardous material routing and location of emergency response units. Das et al. (2012) utilized a Pareto Frontier-based decision tool to support transportation decisions. Furthermore, several approximation methods have also been proposed for hazardous waste network design problems (Asgari et al., 2017; Farrokhi-Asl et al., 2017; Rabbani et al., 2018).

2.2 Medical Waste Management Models

In addition to hazardous waste, some studies have specifically addressed medical waste in their formulations. Shih & Lin (2003) developed a multi-criteria optimization model for routing infectious medical waste in Taiwan. Taghipour & Mosaferi (2009) characterized medical waste in Iran concerning quantity, composition, and quality. Baati et al. (2014) applied the Analytic Hierarchy Process (AHP) to formulate a vehicle routing model for transporting infectious healthcare waste. Similarly, Chauhan & Singh (2016) employed a hybrid approach based to locate healthcare waste disposal centers. Nolz et al. (2014) formulated a collector-managed stochastic inventory routing problem for infectious medical waste, while Alshraideh & Abu Qdais (2017) developed a stochastic model for waste collection in Jordan. Budak & Ustundag (2017) proposed a mixed integer model for collecting and treating medical waste in Turkey. In a related study, Mantzaras & Voudrias (2017) formulated a cost-minimization model for locating transfer stations and routing vehicles. Moreover, Gergin et al. (2019) addressed the facility location problem in Turkey using an artificial bee colony algorithm, while Osaba et al. (2019) employed an improved bat algorithm to model a drug distribution problem in Spain. Kargar et al., (2020) adopted a fuzzy goal programming method to design a three-objective reverse supply chain for medical waste. Yazdani et al. (2020) introduced a new best-worst method to address the multi-criteria healthcare facility location problem.

2.3 COVID-19 medical waste models

Recent research has also focused on healthcare waste management during the COVID-19 pandemic. Yu, Sun, Solvang, & Zhao (2020) and Kargar et al. (2020) developed a multi-objective model to manage medical waste during COVID-19, tested in Wuhan, China. Tirkolaee et al. (2021) developed a multi-trip location routing problem for medical waste in COVID-19 contexts. Eren & Rıfat Tuzkaya (2021) employed a multi-objective traveling salesman problem to address the transportation of medical waste-carrying vehicles in Istanbul, while Valizadeh et al. (2021) proposed a leader-follower approach for managing government aid distribution and hazardous waste collection. Govindan et al. (2021) adopted a fuzzy goal programming approach for medical waste management. Another study by Valizadeh & Mozafari (2022) developed a mathematical model for healthcare waste and tested the results through four cooperative game theory methods.

A two-phase model was developed to transport medical waste in Chongqing (Cao, Xie, et al., 2023), and a digital twin-based framework was used for medical waste location transport (Cao, Liu, et al., 2023). Xin et al. (2023) proposed a hybrid model to forecast and transport medical waste. Hasija et al. (2022) provided a critical perspective on the impact of vaccination waste on the ecosystem and the marine environment. Another study proposed a decision support system for vaccine distribution in an urban setting (Shahparvari et al., 2022). Bertsimas et al. (2022) developed a prescriptive model to locate the vaccination sites and vaccine allocation. A study by Bani et al. (2022) developed a mixed integer mathematical programming model for the COVID-19 reverse logistics model, to minimize system's total cost and carbon emissions.

2.4 Research Gap and Study Contribution

From the extant literature, it is evident that while there are many studies on waste management, minimal attention has been paid to the waste generated from COVID-19 vaccination drives. Vaccination waste remains a critical issue in highly populated economies, with an estimated 9 billion vaccine doses generating significant waste globally (Crommelin et al., 2021). While the present study draws insights from existing research on medical and infectious waste management, it specifically focuses on the recyclable and hazardous components generated from COVID-19 vaccination waste. Given the risk associated with transporting infectious and hazardous components near populated areas, this study incorporates risk mitigation strategies for the population and emphasizes environmental sustainability. Table 1 summarizes related literature on medical waste management during COVID-19 using optimization methods, highlighting the novelty of this study in terms of its objective functions and constraints. This study aims to bridge this gap by proposing a multi-objective goal programming model that minimizes the number of recycling centers, reduces population, optimizes system costs, and maximizes sustainability.

Table 1. Summary of model formulations on COVID-19 medical waste management

Reference	Objective Function				Model		Parameters and Constraints					
	No. of centers	Risk	Cost	Env. Sust.	Stages	Type	Utilization	Toll charges	Route Vulnerabilit	Accident prob.	Population exposure	Vehicle routing
(Yu, Sun, Solvang, & Zhao, 2020)	-	ü	ü	-	2	M	-	-	-	-	-	ü
(Kargar, Pourmehdi, et al., 2020)	ü	ü	ü	-	2	M	-	-	-	-	-	ü
(Govindan et al., 2021)	-	ü	ü	ü	1	M	-	-	-	-	ü	ü
(Tirkolaee et al., 2021)	-	ü	-	-	2	M	-	-	-	-	-	ü
(Valizadeh et al., 2021)	-	-	ü	-	2	M	-	-	-	-	-	ü
(Cao, Xie, et al., 2023)	ü	ü	ü	-	2	M	-	-	ü	ü	ü	ü
(Tasouji Hassanpour et al., 2023)	-	ü	ü	-	2	M	-	-	-	-	-	ü
(Xin et al., 2023)	-	ü	ü	-	1	M	-	-	-	-	-	-
(Rattanawai et al., 2024)	-	-	-	-	1	S	-	-	-	-	-	ü
This paper	ü	ü	ü	ü	2	M	ü	ü	ü	ü	ü	ü

S: Single stage; M: Multi-stage; '-' represents either No or Unclear

Thus, this study makes valuable contributions to the COVID-19 vaccination waste management research by addressing key gaps identified in existing literature. While previous studies primarily focus on risk, cost, and vehicle routing, this study adopts a more comprehensive approach by incorporating key factors, including environmental sustainability, population exposure, and accident probability. It proposes a multi-objective goal programming model that optimizes the number of recycling centers, reduces costs, mitigates risks, and enhances sustainability. These elements have not been collectively considered in prior models. Furthermore, it also incorporates parameters such as utilization rates, toll charges, and route vulnerability, ensuring a holistic waste management framework. By expanding upon existing medical waste management models and introducing a more inclusive optimization framework, this research contributes to more efficient and sustainable decision-making in COVID-19 vaccination waste disposal, particularly in highly populated regions.

3. Mathematical Model formulation

3.1 Problem Description

This study addresses the complex decision of identifying optimal locations of treatment centers that separate recyclable and hazardous components from vaccination waste generated at immunization centers. It also tackles the logistics of transporting the waste generated from immunization centers to treatment centers, followed by the movement of hazardous and infectious waste from these treatment centers to disposal sites. Several factors including cost reduction, risk mitigation for nearby populations, and environmental sustainability guide these decisions. The problem considers various parameters such as accident probabilities along the routes, vulnerability, toll charges, fixed setup cost of treatment centers and the variable transportation costs. The schematic representation of the network is shown in Figure 1. Since model proposed in the study uses an illustrative waste management system, it has several assumptions.

i. The treatment centers are assumed to be equipped to segregate hazardous and recyclable waste components.
ii. The accident probabilities and route vulnerabilities are constant and can be quantified.
iii. Transportation costs are proportional to the distance travelled and amount of waste transported.
iv. The risk to the population is a function of the distance of the route from populated areas

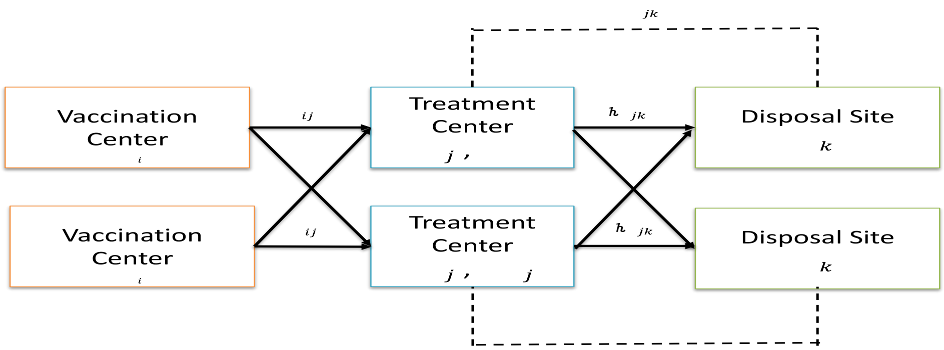

Figure 1. Network Representation

3.2 Model Formulation

The problem formulation comprises parameters, decision variables, objectives or goals, and constraints. The model inputs are referred to as parameters, while the values to be solved by the model are represented as decision variables. These decision variables are used to formulate the objective function and the model constraints. The present paper employs two types of decision variables: binary and integer. Binary variables determine the location of the treatment centers, whereas integer variables determine the quantities of vaccine waste transported from the healthcare centers to the recycling centers, and to the disposal sites.

The goal programming model is formulated by computing the best values G_n^+ of all four objectives (goals) by solving four integer programming models individually. The model parameters are provided as follows:

Sets

I : Set of vaccination centers

J : Set of treatment centers

K : Set of disposal sites

N : Set of objectives or goals

Parameters

WG_i : Quantity of immunization waste generated at center i

C_j : Capacity of treatment center j

C_k : Capacity of disposal site k

D_{ij}: Distance between vaccination center i and treatment center j

D_{jk}: Distance between treatment center j and disposal site k

FCT_j : Fixed setup cost of treatment center j

VCT_j : Variable treatment cost per unit at the treatment center j

VCD_k : Variable disposal cost per unit at the disposal site k

FCD_k : Fixed setup cost of disposal site k

POP_j : Population around the treatment center j

EX_j : Population exposure around the treatment center j

PrT_j : Accident probability at the treatment center j

PrT_{jk} : Accident probability along the route from the treatment center j to disposal site k

EX_{jk} : Exposure or vulnerability along the route from treatment center j to disposal site k

POP_{jk} : Population around the route $j\ to\ k$

V_{jk} : Toll charges along the route from the treatment center j to the disposal site k

$UT_{min\,j}$: Minimum utilization of the treatment center j

UD_{mink}: Minimum utilization of the disposal site k

R_k : Rank of disposal sites for their environmental sustainability

α : Fraction of hazardous waste segregated at treatment centers

G_n^+ : Best value for goal n

G_n^- : Worst value for goal n

w_n^g : Weight associated with goal n

M : Distance to cost multiplier factor

§: Multiplier for unrestricted assignment of values subjection to selection

Decision Variables

y_j : Binary variable, 1 if the treatment center j is selected, 0 otherwise

y_k : Binary variable, 1 if the disposal site k is selected, 0 otherwise

z_{jk} : Binary variable, 1 if the route between j and k is selected, 0 otherwise

q_{ij} : Quantity of vaccination waste transported from center i to treatment center j

hq_{jk} : Quantity of hazardous vaccination waste from treatment center j to disposal site k.

Mixed Integer Linear Programming (MILP) Formulation

$$Z = COST_{min}\ , RISK_{min}\ , NUM_{min}\ , ENVS_{max} \tag{1}$$

Where,

$$COST_{min} = \sum_j FCT_j y_j + VCT_j \sum_i q_{ij} + M \sum\sum q_{ij}\, D_{ij} + \sum_k FCD_k y_k + \sum_k VCD_k hq_{jk} + M \sum\sum hq_{jk}\, D_{jk} + \sum\sum V_{jk}\, z_{jk}$$

$$RISK_{min} = \sum_j POP_j * EX_j * PrT_j * y_j + \sum\sum PrT_{jk} *\ POP_{jk} *\ EX_{jk} *\ z_{jk}$$

$$NUM_{min} = \ \sum_j y_j$$

$ENVS_{max} = \sum_k R_k y_k$

Subject to:

$$\sum_i q_{ij} \leq y_j C_j \quad \forall j \tag{2}$$

$$\sum_j q_{ij} = WG_i \quad \forall i \tag{3}$$

$$\alpha \sum_i q_{ij} \geq \sum_k hq_{jk} \quad \forall j \tag{4}$$

$$\sum_k hq_{jk} \leq C_k y_k \quad \forall j \tag{5}$$

$$hq_{jk} \leq \S * z_{jk} \quad \forall \text{ i}, j, k \tag{6}$$

$$\sum_i q_{ij} \geq UT_{\min j} \quad \forall j \tag{7}$$

$$\sum_j hq_{jk} \geq UD_{\min k} \quad \forall k \tag{8}$$

Eq. (1) outlines the four objective functions derived from the MILP models, which will subsequently inform the target values used in the goal programming formulation. The first objective is to minimize the total costs ($COST_{min}$) associated with the vaccination waste management network. These costs include the fixed setup expenses of treatment centers and disposal sites, variable treatment and disposal costs, transportation costs from vaccination centers to treatment centers and then to disposal sites, as well as toll charges along the routes. The second objective is to minimize the total risk ($RISK_{min}$) posed to the population near the treatment centers and along the hazardous waste transport routes. The risk is computed using the product of probability, vulnerability and the population (Trivedi & Singh, 2017; Willis et al., 2006). The third objective focuses on minimizing the total number of treatment sites (NUM_{min}) that are opened, while the fourth objective aims to select disposal sites with the highest environmental sustainability rating ($ENVS_{max}$).

Eq. (2-8) exhibit the constraints used in the MILP formulations. Eq. (2) ensures that the waste quantities transported to a treatment center do not exceed its capacity and allows transportation only when the treatment center is established. Eq. (3) indicates the transportation of all vaccination waste generated at the vaccination centers. The constraint in Eq. (4) shows the flow conservation of the waste generated and the hazardous waste transported to the disposal sites. It also considers hazardous waste as a fraction of the total generated waste. The constraint given by Eq. (5) states that the waste reaching a selected disposal site should not exceed its capacity. Eq. (6) ensures transportation along a route only if that route is selected. The binary selection variable is further used to compute the toll charges of the routes. Eq. (7-8) are required to meet the conditions of minimum capacity utilizations at the treatment centers and disposal sites.

4. Solution Approach- Goal Programming

Goal programming is a popular approach within the multi-objective decision-making realm. It extends linear programming by focusing on multiple conflicting objectives (Charnes & Cooper, 1957). It minimizes the deviations of achieved levels from the target values. The extant literature presents multiple variations of classical goal programming, including Archimedean sum of deviations, lexicographic goal programming, and Min-Max goal programming (Flavell, 1976; Tamiz et al., 1998). This paper adopts a Min-Max weighted goal programming approach due to its varied applicability in various domains including supplier selection, disaster recovery projects (Ho, 2019; Trivedi & Singh, 2017), and so forth.

The target or goal values for all the four objectives are determined by solving the MILP models. Additionally, the anti-ideal solution values are also obtained from the MILP model outputs. These best and the worst values are then used in the denominator to normalize the deviations. Finally, a multi-objective model based on a weighted goal programming approach is developed to optimize all the goals simultaneously (Trivedi & Singh, 2017). The goal values obtained from the four MILP models, and the GP model, along with constraints, are represented below:

Minimize

$$Z = \sum_k \frac{d_n^* \times w_n^g}{|G_n^+ - G_n^-|} \tag{9}$$

Where d_n^* refers to the deviation variable denoting deviations from the target values.

d_n^+ : Over-achievement of goal n

d_n^- : Under-achievement of goal n

$d_n^* = d_n^+$ $for\ minimization\ goals$ (positive deviation)

$d_n^* = d_n^-$ $for\ maximization\ goals$ (nagative deviation)

Additional constraints:

$$\sum_j FCT_j y_j + VCT_j \sum_i q_{ij} + M \sum\sum q_{ij} D_{ij} + \sum_k FCD_k y_k + \sum_k VCD_k hq_{jk} + M \sum\sum hq_{jk} D_{jk} + \sum\sum V_{jk} z_{jk} + d_1^- - d_1^+ = G_1^+ \quad (10)$$

$$\sum_j POP_j * EX_j * PrT_j * y_j + \sum\sum PrT_{jk} * POP_{jk} * EX_{jk} * z_{jk} + d_2^- - d_2^+ = G_2^+ \quad (11)$$

$$\sum_j y_j + d_3^- - d_3^+ = G_3^+ \quad (12)$$

$$\sum_k R_k y_k + d_4^- - d_4^+ = G_4^+ \quad (13)$$

$$y_j \in Binary \quad (14)$$

$$y_k \in Binary \quad (15)$$

$$z_{jk} \in Binary \quad (16)$$

$$q_{ij} \in Integer \quad (17)$$

$$hq_{jk} \in Integer \quad (18)$$

The objective functions of the previous models are converted into constraints using the deviational variables representing the goals' overachievement and underachievement. They are represented by Eq. (10-13). The goal programming model employs the weighted values of unfavorable deviational variables to be minimized. It attempts to minimize the overachievement of minimization goals and the underachievement of maximization goals.

5. Numerical Example

An illustrative dataset is used to demonstrate the applicability of the proposed multi-objective model. Five vaccination centers were considered as the source of vaccination waste. The generated waste must be transported to eight treatment centers and segregated into hazardous and non-hazardous components. All the treatment centers require fixed setup costs and have different proximities from the vaccination centers. The treatment cost also varies across the treatment centers. Moreover, different accident probabilities were associated with each, impacting the surrounding population in their respective zones. The exposure and the probabilities are used to compute the risk to the nearby population.

5.1 Input Parameters

Table 2 shows the distance between the vaccination centers (VC1-VC5) and the treatment centers (TC1-TC8), along with the fixed and variable setup and operation costs.

Table 2. Distance (in Kilometers) between waste treatment and vaccination centers

Vaccination Centers	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8
VC1	3	3	15	5	5	5	4	15
VC2	15	2	4	3	5	13	5	5
VC3	6	12	6	14	3	4	7	6
VC4	18	3	9	2	8	14	15	15
VC5	9	10	10	21	5	6	13	14

Accident probabilities, exposure, and nearby population information are employed to compute the risk from each treatment center (Trivedi & Singh, 2017; Willis et al., 2006). The risk parameters, capacity, and cost parameters for each treatment center are provided in Table 3.

Table 3. Capacity, Cost & Risk Parameters

Parameters	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8
Capacity ('00 Kg)	6000	5000	5500	4200	4500	6000	8000	2500
Accident Probability	0.4	0.35	0.65	0.7	0.2	0.5	0.6	0.1
Pop exposure	0.8	0.6	0.3	0.4	0.5	0.6	0.1	0.2
Population	50000	60000	57000	34000	45000	56000	100000	45000
Variable treatment cost (USD/kg)	3	5	4	7	5	8	2	5
Fixed cost ('00 USD)	4000	6000	4500	5300	6800	3400	5500	5400

In the second stage of the transportation network, the hazardous waste generated at the treatment centers is transported to the six disposal sites (DS1-DS6). The distance of the disposal sites from the treatment centers is given in Table 4.

Table 4. Distance between treatment centers and disposal sites

Treatment Centers	DC1	DC2	DC3	DC4	DC5	DC6
TC1	8	8	7	4	4	4
TC2	6	3	5	7	1	6
TC3	4	3	7	8	9	3
TC4	7	10	4	11	3	7
TC5	2	11	7	3	9	5
TC6	4	3	7	12	8	6
TC7	6	14	11	5	7	11
TC8	6	4	5	7	4	10

All the disposal sites are assessed regarding their environmental sustainability and environmental impact. The sites are rated on a scale of 1-6, with a higher rating implying a lesser adverse environmental impact. The environmental sustainability values, fixed and variable costs associated with the disposal sites, and capacities are reported in Table 5.

Table 5. Costs and capacity of disposal sites

Criteria	DC1	DC2	DC3	DC4	DC5	DC6
Capacity ('00 Kg)	3000	2500	4500	2200	1600	2300
Variable disposal cost (USD/kg)	4	5	2	3	6	1
Fixed cost ('00 USD)	8000	7800	5600	4500	7600	4000
Environmental sustainability rating	5	6	4	2	1	3

In the second stage, the risk profile of all the routes transporting hazardous waste from the treatment centers to the disposal sites is computed. The risk is computed by the accident probability along a route, vulnerability, and impact (represented by the population living along the route) (Trivedi & Singh, 2017). The probability, exposure, and population values are shown in Table 6, Table 7, and Table 8, respectively.

Table 6. Accident probability along the routes

Treatment Centers	DC1	DC2	DC3	DC4	DC5	DC6
TC1	0.08	0.08	0.07	0.04	0.04	0.04
TC2	0.06	0.03	0.05	0.07	0.01	0.06
TC3	0.04	0.03	0.07	0.08	0.09	0.03
TC4	0.07	0.1	0.04	0.11	0.03	0.07
TC5	0.02	0.11	0.07	0.03	0.09	0.05
TC6	0.04	0.03	0.07	0.12	0.08	0.06
TC7	0.06	0.14	0.11	0.05	0.07	0.11
TC8	0.06	0.04	0.05	0.07	0.04	0.1

Table 7. Exposure/vulnerability along the routes

Treatment Centers	DC1	DC2	DC3	DC4	DC5	DC6
TC1	0.2	0.8	0.4	0.5	0.3	0.4
TC2	0.2	0.2	0.3	0.9	0.8	0.5
TC3	0.4	0.9	0.2	0.7	0.1	0.1
TC4	0.7	0.7	0.7	0.2	0.5	0.2
TC5	0.2	0.5	0.5	0.4	0.3	0.4
TC6	0.4	0.4	0.7	0.6	0.2	6
TC7	0.6	0.6	0.2	0.5	0.7	11
TC8	0.6	0.5	0.4	0.3	0.5	10

Table 8. Population along the routes

Treatment Centers	DC1	DC2	DC3	DC4	DC5	DC6
TC1	4500	4000	3400	9380	5000	4000
TC2	4600	1000	2400	6700	6000	3000
TC3	7000	9000	7200	9380	6000	9000
TC4	5600	3000	9600	5360	5600	8000
TC5	2300	9000	9600	9380	3000	7000
TC6	4600	8000	10800	9380	9000	4000
TC7	2500	7000	6000	12000	8000	3000
TC8	3000	4000	8400	6700	7000	3200

The toll charges along the transportation routes from the treatment centers to the disposal sites are given in Table 9. It is further assumed that the fraction of hazardous waste out of the total generation is 0.5. It is also ensured that the minimum utilization of the selected treatment center and the disposal site is 50 percent.

Table 9. Toll charges (cumulative) along the routes

Treatment Centers	DC1	DC2	DC3	DC4	DC5	DC6
TC1	900	400	1876	750	480	450
TC2	920	100	1340	850	120	340
TC3	1400	900	1876	1250	1080	560
TC4	1120	300	1072	750	360	700
TC5	460	900	1876	2250	1080	900
TC6	920	800	1876	2000	960	800
TC7	500	700	2400	1750	840	700
TC8	600	400	1340	1000	480	400

5.2 Results, Analysis & Discussion

This paper developed a transportation model that supports the location, allocation, and routing decisions involved in COVID-19 vaccination waste management. In the first stage, the key decisions included selecting treatment centers and the quantities of waste transported from each vaccination center to the chosen treatment centers. In the second stage, the decisions involved the selection of a disposal site and transporting the hazardous waste from the treatment centers to it.

In the initial step, four mixed integer linear programming problems were solved, each corresponding to one of the objectives: cost, risk, environmental sustainability, and the number of treatment centers to be opened. This step was essential to identify target goal values of all each objective, which would later be used in the goal programming model. The models were run using the MS Excel solver on a PC equipped with an Intel core i5 processor and 8GB RAM. The target values for all the objective functions are given in Table 9.

Table 9. MILP Outputs with the Target Values

	COST	RISK	NUM	ENVS
COST	**348152**	486100	507586	420876
RISK	49448	**35598.4**	51210.8	53662
NUM	5	5	**4**	5
ENVS	15	21	18	**21**

The target values for the goals were determined as follows: 348152 for cost, 35598 for risk, 4 for the number of treatment centers opened, and 21 for the environmental sustainability rating of the disposal sites. The corresponding anti-ideal values were also extracted from Table 9. In the second step, a goal programming model was formulated using the Eq. (9-18), with an equal weight assigned to all four goals. The solution indicated the selection of treatment centers 2,3,5,7, and 8. The quantities of waste transported from the vaccination centers to the selected treatment centers are shown in Table 10.

Further, in the second stage, the hazardous waste obtained from the treatment centers was transported to the disposal sites. All six sites were selected for the disposal of hazardous waste. The transportation routes and waste quantities are reported in Table 11.

Table 10. Waste quantities transported to the treatment centers

Vaccination Center	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8
VC1	0	0	0	0	0	0	5000	0
VC2	0	500	3400	0	0	0	2600	0
VC3	0	0	2100	0	1100	0	0	2500
VC4	0	4500	0	0	0	0	0	0
VC5	0	0	0	0	3400	0	0	0

Table 11. Hazardous waste transported to disposal sites

Treatment Centers	DC1	DC2	DC3	DC4	DC5	DC6
TC1	0	0	0	0	0	0
TC2	0	900	0	0	1600	0
TC3	0	1300	0	0	0	1450
TC4	0	0	0	0	0	0
TC5	1400	0	0	0	0	850
TC6	0	0	0	0	0	0
TC7	1600	0	0	2200	0	0
TC8	0	0	1250	0	0	0

It can be seen from Table 10 and Table 11 that since treatment centers 1, 4, and 6 were not selected in the first stage, no hazardous waste was transported from these centers to any disposal site. The total waste received by each selected treatment center was reduced by 50%, owing to recyclable component separation, and only the hazardous component was transported onward. Thus, the waste transported from treatment centers was half of the total waste they initially receive. Further, the compromised solution obtained by the goal programming model reports that the cost objective is compromised by 5.98%, the risk objective by 1.54%, number of centers by 25%, whereas the environmental sustainability objective was fully achieved. The tornado chart depicted in Figure 2 represents how sensitive is the objective function (represented by cell M33) to the other parameters. The highest sensitivity is attributed to the ideal and non-ideal difference values of sites (G30), followed by the weight of the number of sites objective (L30) and its positive deviation from the target value (D30).

A sensitivity analysis is also carried out to test the sensitivity of the results vis-à-vis the selective preference given to the four objectives. In the first scenario S1, equal importance is assigned to the objectives. The scenarios and the weights of the objectives are as follows: S2 (10%, 20%, 30%, and 40%); S3 (40%, 30%, 20%, and 10%); S4 (20%, 20%, 30%, and 30%); S5 (20%, 30%, 30%, and 20%). The deviations of all the objectives in different scenarios are represented in Figure 3.

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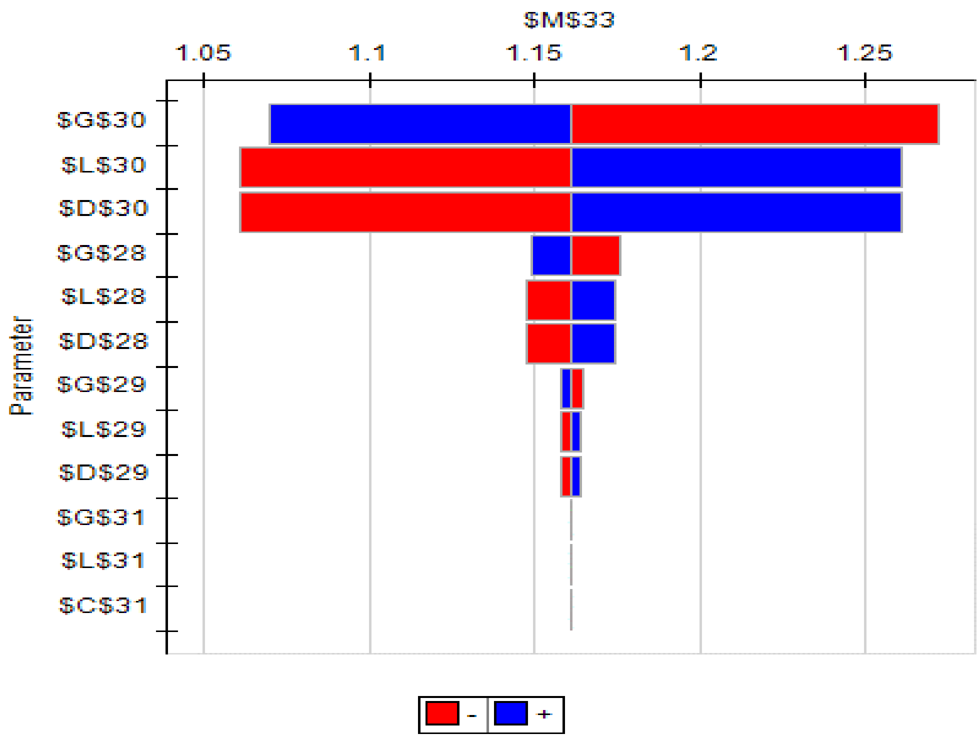

Figure 2. Tornado chart with the sensitivity of objective function

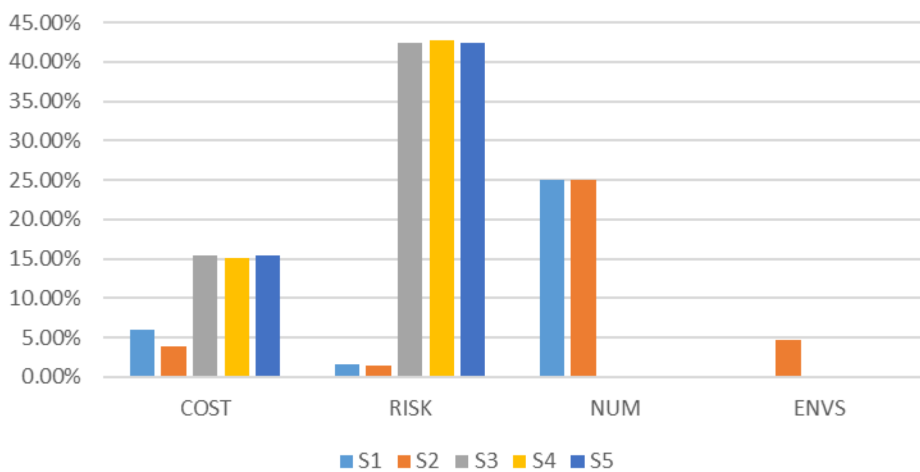

Figure 3. Deviations in targets under scenarios

The selection of treatment centers also varies under the five scenarios. The pictorial representation of the center selections in various scenarios is shown in Figure 4. It can be seen from Figure 3 that treatment center TC4 is not selected in all the scenarios, whereas center TC7 has been selected in all the scenarios. Further, it can also be seen that the centers TC1, TC3, TC6, and TC7 are selected in the scenarios that assign 30% weight to the number of center minimization objectives, thereby fully meeting the objective target.

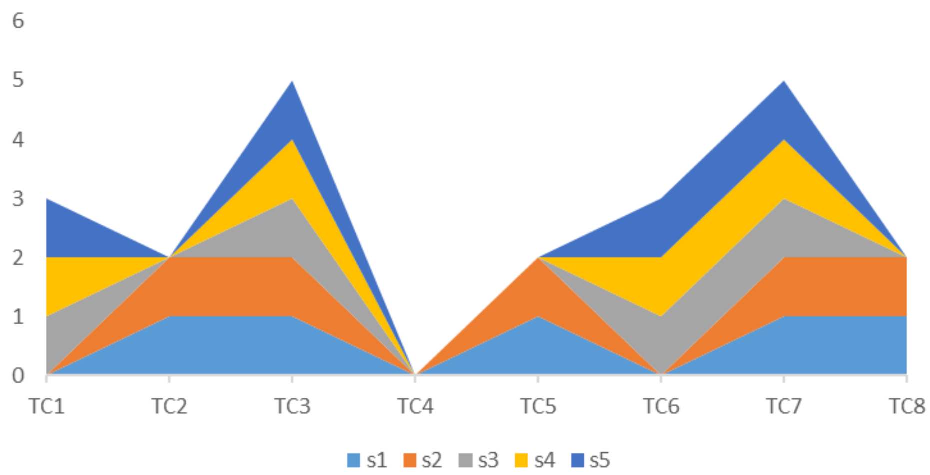

Figure 4. Selection of treatment centers in scenarios

The findings of this research substantially differ from those in related studies, particularly given the limited focus on managing vaccination waste. For example, the study by Bani et al. (2022) addressed this issue using a MILP model in a case study of Iran, focusing on reducing total cost and carbon emissions. In contrast, our work expands on this by incorporating additional dimension. Specifically, this paper accounts for setup costs of treatment centers, as well as the transportation costs involved in carrying the waste from the vaccination centers to the treatment centers and then to the disposal sites. Furthermore, in the second stage of the model, toll charges were also considered, which can have a substantial impact on decisions due to their potentially higher costs compared to transportation.

Further, the results from this study reveal that the high costs associated with setting up the treatment centers might discourage the selection of few centers, leading to better utilization of others. The study also factors in the risk associated with potential accidents and their impact on the surrounding population using the framework adopted by Trivedi & Singh (2017) and Willis et al. (2006). The risks of transporting hazardous waste are also accounted for in the present proposition. Moreover, the environmental sustainability rating for each disposal site was used to favor sites with minimal adverse environmental impact.

The reported results highlight the effectiveness of a weighted goal-programming model in achieving the desired objectives. Comparing model objectives under different scenarios and evaluating tradeoffs may lead to more efficient resource allocation. The proposed model offers decision-makers a systematic and scientific approach to making key decisions for waste management in a vaccination programs.

6. Implications

The study's findings offer several implications across theoretical, managerial, and sustainability dimensions. These implications are outlined in the following subsections:

6.1 Theoretical Implications

This study contributes several key theoretical advancements:

i. By establishing a systematic, data-driven approach to managing waste generated from the COVID-19 vaccination program, this study enhances the effectiveness of resource allocation.

ii. The study develops a comprehensive and economically conscious approach to waste management, incorporating multiple objectives of cost reduction, risk mitigation, optimal facility location, and environmental sustainability, particularly crucial in large-scale vaccination campaigns.

iii. It highlights the importance of integrating sustainability considerations into waste management strategies, especially during healthcare crises such as the COVID-19 pandemic.

iv. The findings illustrate practical relevance, demonstrating the potential to drive advancements in waste management practices and enhance decision-making processes.

6.2 Managerial Implications

The results provide several actionable insights for decision-makers and managers overseeing current and future vaccination drives during COVID-19 and other pandemics. First, the study presents a decision support framework that serves the key decisions of locating treatment sites, waste allocation, and transportation, considering conflicting goals such as cost, risk, number of sites, and environmental sustainability. Second, the proposed model addresses various cost dimensions associated with vaccination waste management, including setup costs, logistics costs, and toll charges. Third, the model emphasizes the importance of a comprehensive risk assessment, particularly focusing on the hazards associated with vaccination waste, including infectious substances, sharps, contaminated materials, and so forth, using a probability, vulnerability and consequence framework. Furthermore, it stresses the relevance of accurate assessment of quantities and nature of waste generated to effectively allocate resources for waste collection, treatment, and disposal. Another important dimension addressed in the present framework is the implementation of sustainable waste management practices, including the promotion of the treatment of waste as well as minimization of environmental impact of the disposal sites.

The sensitivity analysis of the proposed model may further provide some significant insights that help managers identify key ‘centers’ and critical parameters under various scenarios, providing a vital planning tool that would enhance the effectiveness of the vaccination drives.

6.3 Implications for Sustainability

The study underscores the ecological consequences of waste generated during COVID-19 vaccination. By including environmental sustainability as a goal, the study highlights the importance of minimizing environmental harm throughout the waste management procedure. This implication accentuates the commitment to adopting sustainable practices and ensuring responsible waste disposal, thereby safeguarding ecosystems and preserving vital natural resources in a profound and impactful manner. Sustainable waste management practices involve strategically selecting disposal sites based on proximity to sensitive ecosystems, appropriate waste treatment facilities, regulatory compliance, and environmental sustainability. Considering the environmental sustainability of disposal sites, the model aids decision-makers in planning for the future by identifying locations capable of accommodating waste from the current and future vaccination campaigns. This emphasizes the significance of adopting adaptable and sustainable waste management practices that accommodate changing circumstances and increased waste volumes. The model can drive resource efficiency and foster the adoption of recycling and reuse practices by optimizing cost reduction and risk mitigation and prioritizing the environmental sustainability of disposal sites.

7. Conclusion

The present paper proposed a multi-objective model based on weighted goal programming to effectively manage waste from COVID-19 vaccination drives. The model addressed the key decisions such as optimal placement of treatment centers, the transportation of vaccination waste from vaccination centers to treatment facilities, and finally to disposal sites.

The proposed decision support model offers two significant contributions. First, it facilitates the strategic selection of treatment sites and allocation of COVID-19 vaccination waste from healthcare facilities to treatment and disposal sites, while minimizing total costs, risks, and the number of centers. Additionally, it incorporates the environmental sustainability of disposal sites. The goal programming model reports that the cost objective was compromised by only 5.98% and the risk objective by 1.54%, while the environmental sustainability objective was fully achieved Second, the model explores the applicability of goal programming-based multi-objective decision-making in managing vaccination waste. The framework presented in this study is particularly relevant in various high-population geographies as future variants may lead to increased vaccinations.

This study, albeit noteworthy, acknowledges its limitations, highlighting the need for future research to surmount them and achieve greater strides. The model can be adopted to various case studies, and historical data can validate the results. Future works may formulate a stochastic equivalent to the proposed model considering the variability of a few parameters. Further, a hybrid approach comprising multi-attribute decision-making methods may be adopted to compute the environmental sustainability rankings of the disposal sites used in the model. Future studies may also test hypotheses and propose solution approaches to increase the generalizability of the proposed study in other pandemic contexts.

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