A multi-objective network design for recycling healthcare waste from large-scale immunization

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Abstract. This paper presents a Goal programming-based optimization model for managing the recycling operations of healthcare waste generated from large-scale vaccination drives. The model proposes an efficient system by integrating the decisions of locating recycling units and the routing of generated waste to them, considering the risks to the environment and the associated population. The objectives include the minimization of setup and transportation costs, risks to the population, and the number of installed units. A set of randomly selected test instances is used to test the effectiveness of the model. The results reveal that a compromised solution offers cost advantages and population risk mitigation. The approach effectively supports the strategic choices in recycling healthcare waste generated from immunization.

1 Introduction

The pandemic outbreak, such as the novel Corona Virus Disease (COVID-19), has led to serious damage to public health across the world. Nearly 105 million people have been affected by the pandemic so far, accompanied by 23 million deaths [1]. This poses a serious threat and challenge not only to the healthcare system but also the socio-economic system [2]. The control and further spread of the pandemic have become a critical issue [3]. The pandemic has led to the generation of large volumes of medical waste from the diagnosis and treatment of patients at various healthcare establishments [3], [4]. The enormous use of personal protective equipment (PPE), such as face masks, gloves, test kits, and sanitizers, has contributed further to medical waste generation [4]. Vaccination has proved to be one of the most effective ways of reducing or eliminating the effects of infectious diseases [2]. The nations have started preparing themselves by rolling out large-scale and urgent vaccination drives, such as the recent pandemic, that aim to contain the spread and impact of the pandemic. The large-scale immunization across nations in the coming time is bound to add to the already existing burden of healthcare waste in the form of syringes, plastic containers, tissues, bandages, and so forth. Since a majority of this waste is made of plastic, it becomes imperative to handle it responsibly to avoid environmental damage. From a circular economy

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perspective, recycling plastic is preferred over incineration or disposal due to its adverse ecological impact. Additionally, the stainless steel waste in the form of syringe needles and other surgical instruments can be reused after proper treatment of melting and reprocessing [5]. In developing countries, waste management systems are still at a nascent stage [6] and are further taxed by the mismanagement of pandemic-led waste. With the global population gearing up for large-scale vaccination to combat potential situations like pandemics in the future, careful and proper planning for the consequential healthcare waste needs attention. Although there are several studies that have addressed location-routing problems in healthcare waste contexts, no study has attempted to consider the ramifications of an increased generation of vaccination waste that would warrant immediate recycling choices. The nations, especially developing countries, need to come up with timely strategies to handle this upcoming waste. The present research work is a first attempt in this direction. The main contribution of this paper is to support the strategic decisions of locating the temporary recycling centers for vaccination waste as well as the transportation route choices, keeping in mind the cost and risk implications. A multi-objective Goal Programming (MOGP) model is proposed that assists the policy-makers in location-routing decisions related to setting up recycling centers and transporting the vaccination waste from the healthcare establishments to the recycling centers. The conflicting objectives to be minimized include the number of recycling centers to be set up, the cost of setup as well as transporting the vaccination waste, and the risk to the population and the environment. An illustrative dataset is used to demonstrate the effectiveness of the proposed model.

2 Literature Review

The waste management literature has found numerous applications of Operations Research techniques in the recent past. The mathematical models have predominantly focused on three key decisions, including location, allocation or routing, and an integrated network design [7]. The location-routing models integrate the decisions of location and routing [3]. The following section reports some of the recent investigations in waste management modeling literature to highlight the research gaps therefrom.

Emek and Kara [8] proposed a cost-based mathematical model to site the hazardous waste disposal plant considering the air pollution standards set by the government. Another study by Berglund and Kwon [9] addressed the routing of hazardous materials carriers by minimizing the costs. Li et al. [10] 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 [11]. Ardjmand et al. [12] applied a genetic algorithm-based mathematical model to select the facilities for hazardous waste generation and disposal. In another study by Lee et al. [13], a mixed-integer programming model was developed for Hong Kong municipal waste management.

Several works have proposed a multi-objective approach to address hazardous waste management. Nema and Gupta [14] used a multi-objective model for planning and designing regional waste management systems. A similar work by Alumur and Kara [15] addressed the selection of treatment centers, disposal centers, and associated technology. Zografos and Androutsopoulos [16] developed a decision support system for hazardous material routing and emergency response unit location problems, while Das et al. [17] used a Pareto Frontier-based decision tool to support transportation decisions. Several approximation methods have also been proposed for hazardous waste network design problems [18]–[20]. Yu et al. [7] developed a bi-objective stochastic network design for hazardous waste management.

In addition to hazardous waste management, some of the studies have emphasized medical waste in their formulations. Shih and Lin [21] developed a multi-criteria optimization model for routing of infectious medical waste in Taiwan. Another study applied Analytic Hierarchy

Process (AHP) and formulated a vehicle routing model for the transportation of infectious healthcare waste [22]. Similarly, Chauhan and Singh [23] employed a hybrid approach based on AHP, fuzzy Technique for Order Preference by Similarity to Ideal Solution, and Interpretive structural modeling to locate healthcare waste disposal centers. Nolz et al. [24] formulated a collector-managed stochastic inventory routing problem of infectious medical waste. In another study, Kargar et al. [25] adopted a fuzzy goal programming method to design a three-objective reverse supply chain for medical waste. Another study optimized reverse logistics for the collection and disposal of waste in Turkish health centers.
To the best of the authors' knowledge, there is a very limited investigation in the context of waste generated from large-scale immunization, comprising plastic, stainless steel, and hazardous waste elements. The following model aims to effectively manage the large scale vaccination waste from the cost and risk perspectives.

3 Model Formulation

The goal programming model is formulated by computing the best values G_k^+ of all three objectives (goals) by solving three integer programming models. The model parameters are shown below:

Sets

I : Set of healthcare centres

J : Set of recycling centres

K : Set of objectives or goals

Parameters

R_j : Capacity of recycling centre
D_{ij}: Distance between healthcare and recycling centres
FC_j : Fixed setup cost of recycling centre
VC_j : Variable recycling cost per unit at the recycling centre
POP_j : Population around the recycling centre
EX_j : Population exposure around the recycling centre
$PROB_j$: Accident probability at the recycling centre
DH_j : Distance of recycling centre to the nearest disposal centre
TD : Threshold distance to the nearest disposal facility
WG_i : Quantity of immunization waste generated at the healthcare centre i
G_k^+ : Best value for goal k
G_k^- : Worst value for goal k
w_k^g : Weight associated with goal k
M : Distance to cost multiplier factor

Decision Variables

y_j : Binary variable, 1 if the recycling centre j is selected, 0 otherwise
q_{ij} : Quantity transported from healthcare centre i to recycling centre j
d_k^+ : Over-achievement of goal k
d_k^- : Under-achievement of goal k

MILP Formulation

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

Where

$$COST_{min} = \sum_j y_j FC_j + (\sum_i q_{ij}) VC_j + \sum\sum q_{ij}\, D_{ij}\, M$$

$$RISK_{min} = \sum_j y_j FC_j * POP_j * EX_j * PROB_j$$

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

Subject to:

$$\sum_i q_{ij} \leq y_j R_j \tag{2}$$

$$\sum_j q_{ij} \geq WG_j \tag{3}$$

$$y_j \times DH_j \leq TD \tag{4}$$

$$y_j = Binary$$

$$\chi q_{ij} = Integer$$

Z computes target values for the goal programming model. The constraints represent that a recycling centre should handle the waste only when it is selected. Further, the next constraint mentions that all the generated waste must be handled by the recycling centres. The third constraint states that the selection of the recycling centre should keep in mind its distance to the nearest disposal centre within allowed limits. The GP model along with constraints are represented below:

Minimize

$$Z = \sum_k \frac{d_k^* \times w_k^g}{|G_k^+ - G_k^-|} \tag{5}$$

Where $d_k^* = d_k^+ \ for\ minimization\ goals$

Additional constraints:

$$\sum_j y_j FC_j + (\sum_i q_{ij}) VC_j + \sum\sum q_{ij}\, D_{ij}\, M + d_1^- - d_1^+ = G_1^+ \tag{6}$$

$$\sum_j y_j FC_j * POP_j * EX_j * PROB_j + d_2^- - d_2^+ = G_2^+ \tag{7}$$

$$\sum_j y_j + d_3^- - d_3^+ = G_3^+ \tag{8}$$

The deviation variables are employed to convert objective functions into constraints. The GP objective Z uses undesirable deviation factors, targets, and weights, and is minimized.

4 Illustration & Analysis

An illustrative dataset was used to run the model. There are six healthcare centres and ten recycling centres. Initially, individual three MILP models were run and finally, the goal programming model was solved giving equal preference to all the goals.

Table 1. Selection and allocation at recycling centres

RC1	RC2	RC3	RC4	RC5	RC6	RC7	RC8	RC9	RC10
5000	0	0	0	0	0	0	0	0	0
0	100	0	0	0	0	6400	0	0	0
1000	0	0	0	1100	0	1600	0	2000	0
0	4500	0	0	0	0	0	0	0	0
0	0	0	0	3400	0	0	0	0	0
0	0	0	0	0	0	0	2500	4200	0

Table I shows that 6 out of 10 recycling centres are chosen by the model along with the quantities of waste to be relocated from healthcare centres to recycling centres. Centres RC3, RC4, RC6, and RC10 are not chosen. Table II shows the percentage of target achievement.

Table 2. Deviation of objective from the target values

Objectives	Achieved value	Target value	% Deviation
Total Cost	297700	288240	3.2%
Total Risk	49280	47795	3.1%
Number of Centres	6	5	20%

Table II shows that the optimal number of centres obtained from the goal programming model is six instead of the ideal of five locations. Further, the cost and the risk objectives are met with only slight deviations from the ideal values. Further, a sensitivity analysis was also carried out with five scenarios. The varying weights of goals in different scenarios are depicted in Table III.

Table 3. Scenarios and weights of goals

Scenario	Weight of objectives
1	(0.33,0.33,0.33)
2	(0.2,0.4,0.4)
3	(0.1,0.5,0.4)
4	(0.5,0.3,0.2)
5	(0.4,0.2,0.4)

Table IV shows the deviations in cost, risk, and the number of centers for other scenarios

Table 4. Scenarios

Objectives	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Total Cost	3.2%	7.6%	7.6%	3.2%	3.2%
Total Risk	3.1%	0%	0%	3.1%	3.1%
Number of Centres	20%	20%	20%	20%	20%

Thus, we see from the solution obtained illustrative dataset that the goal programming model offers a compromise solution against the three conflicting objectives of cost, risk, and number of recycling centres. The solution also is robust in terms of assigning different preferences to different goals.

5 Conclusion

COVID-19 has proven to be a serious threat to the global population and every country, including India, is gearing up to combat the pandemic. Such a large-scale vaccination drives throughout the countries to prevent the effects of the virus release a large amount of recyclable waste that can pose a serious threat to the population if not carefully handled. The present model contributes by facilitating the selection and allocation of such a inoculation waste from the health centres to the recycling centres, keeping the total costs, risks and the number of recycling centres at a compromisingly minimum level. The model can find applicability in various geographies as future variants may lead to an increased number of vaccinations, specifically in high-population countries including India. Future works may formulate a stochastic equivalent to the proposed model considering the variability of a few parameters. Further, the model may also be tested on a real case study.

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