

## RESEARCH ARTICLE

# Optimizing Healthcare Waste Management: Site Selection and Vehicle Routing Using Weighted P-Median and Multi depots Approaches

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## Abstract

Hazardous healthcare wastes management is considered as a major issue for the executive committee in developing countries. In order to eliminate hazardous healthcare wastes and to give sustainable solution, this study main to select an installation of a centralized and modern waste incinerator in Sfax, Tunisia. This paper presents a management methodology to identify a suitable location using a spatial analysis that employs geographic information system software (ArcGIS). Geographic Information Systems (GIS) techniques were used to find the best area from the whole part in order to eliminate areas of unsuitable land that didn't meet the social, environmental and economic criteria taken into account. After further evaluation, suitable sites were selected to install new incinerators. We propose a p-median problem where the objective is to determine the optimal locations of waste treatment facilities by minimizing the total weighted transportation distance from healthcare waste generators to treatment centers. The model is applied using real-world data collected from both public and private hospitals. The results demonstrate the effectiveness and practical relevance of the proposed approach.

**Keywords:** Hazardous Healthcare Waste; Sustainability; Geographic Information System; P-Median; Exact Method; Multi Depot Vehicle Routing Problem.

## Introduction

In recent decades, location–allocation analysis has played a crucial role in addressing spatial complexity in planning problems. In this context, this study investigates the sustainable centralized location of a healthcare waste incinerator as a solution to three key challenges. First, centralization contributes to reducing overall transportation and operational costs. Second, it mitigates environmental pollution by providing hospitals with a safer and more efficient system for the treatment of hazardous waste, including infectious and post-COVID-19 waste. Third, a centralized facility facilitates effective supervision and regulatory control by the competent authorities [9]. For countries, this issue is one of the priority actions among the axes of sustainable development. The absence of hospital's incinerators waste contributes more to pollution, to create enormous instability in healthcare and the difficulty of supervising authorities. On the contrary, the presence of a modern incinerator designed with emission control will help to reduce pollution, diseases and spread epidemics.

In our knowledge, the problem of uncontrolled spill of waste through a centralized incineration plant in Tunisia isn't well studied. In fact, we develop a novel approach to solve the main problem that use GIS and we propose some techniques to find the best area from the whole part. Moreover, we procedure to an exact method in order to optimize an allocation problem aiming to choose one location from a set candidate sites and to reduce total transportation cost.

## Literature Review

Nowadays, the problems of healthcare and solid wastes have become the most critical issues that are a sustainable and usual output of daily human activities. The amount of healthcare and solid waste has experienced a significant increase in the last decades. Besides, waste's characteristics have changed in line for the change in lifestyles of peoples, industrial developments, growth of population, and diseases like COVID-19 [17, 22, 4]. Over-all, wastes are categorized as municipal solid waste, healthcare waste (hazardous or not) and radioactive wastes. In the last decade, several studies have been carried out the field of site selection for the treatment of waste in different countries such as [1], Turkey [12], Japan [5], Kenya [16], Iran [17], India [22, 23, 35, 36] and Ethiopia [24, 32] and Poland [31]. Hence, it is indispensable to find out suitable site to install a new waste incinerator.

However, the type of hazardous healthcare wastes is not the same as other types of wastes (municipal waste and not hazardous healthcare waste). Consequently, it should not be treated together. Hazardous healthcare wastes must be managed in a sustainable and appropriate treatment and follow a medical waste rules due to the risk of infection and severe to affect the environment and human health [18].

Resolution of incinerator location problem encourage the majority of researchers to use Geographical Information System (GIS). This technique has been playing recently a main role in the process of decision-making. The advantages of using GIS tool are the saving time and the saving cost. Also, it provides a digital data catalogue for long term site monitoring [13].

Most of researches convenience from spatial allocation modelling methods and map overlay functions through representing independently criteria as layer maps then superimposed and a final map is produced for illustrate a location suitable zone of the study area. [22] Have identified 10 criteria to select the best healthcare waste disposal techniques and have indicated that incineration is the best method of waste treatment.

Based on research tests managed on real data, many articles prove that geographic and spatial information systems can be an useful and important source of information in decisions related to the evaluation of the location of an investment project having considerable function for environmental protection and keeping the principle of sustainable development [8, 39, 30, 2, 21, 25, 37, 1].

To the best of our knowledge, the location of waste treatment technique and disposal facilities has been the subject of a significant amount of work in the literature. But, studies dealing with hazardous healthcare waste are very rare.

Among the objectives of the present study was to identify suitable hazardous waste sites to install a new incinerator that are on the economic side is feasible, on the environmental side is respectful and on the social side is acceptable in the region of Sfax, applying Geographic Information System techniques. The following table summarize some studies whose context is selection of a new site for solid or healthcare waste incinerator.

**Table 1:** Related Paper Concerning Waste Site Selection

References	Context	S/H	L/I	Used methods	Country
Demirarslan, K.- O <i>et al.</i> (2016)	Selection of a new site for solid waste incinerator	S	I	GIS & MCDA	Turkey
Goulart Coelho, L.-M <i>et al.</i> (2016)	A critical review of current practices and methods of waste management	S	L	MCDA	–
Hariz, H.-A <i>et al.</i> (2017)	Sitting a new healthcare waste incinerator	H	I	GIS & MCDA	Kenya
Siejka, M and Mika, M (2017)	Determine the weights of factors decisive for the location of the municipal waste	S	L	AHP	Poland
Babalola, M.-A (2018)	Site selection for Anaerobic Digestion of Food and Biodegradable Waste	AD	L	GIS & MCDA	Japan
Mussa, A and Suryabagavan, K.-V. (2019)	Site selection of a solid waste dumping	S	L	GIS & MCDA	Ethiopia
Hazhir, K <i>et al.</i> (2020)	Site selection and environmental risks assessment of medical solid waste landfill	H	L	GIS & MCDA	Iran
Sisay, G <i>et al.</i> (2020)	Selecting an appropriate waste landfill site	S	L	AHP & MCDA	Ethiopia
Sk Ajim, A and Ateeque, A (2020)	Suitability analysis for municipal landfill site selection	S	L	Fuzzy AHP & GIS	India
Sk Ajim, A <i>et al.</i> (2020)	Selecting a sanitary waste landfill site	H	L	GIS & MCDA	India
Manupati, V.-k <i>et al.</i> (2021)	Selection of the best healthcare waste disposal techniques during and post COVID-19 pandemic era	H	I	MCDA	India
Mishra, A.-R and Rani, P (2021)	Selection healthcare waste disposal location	H	L	MCDA	India
Tripathi, A.- K <i>et al.</i> (2021)	Hospital site selection	–	L	GIS & MCDA	India

Notes: H: healthcare waste; S: solid waste; L: landfill site; I: incinerator sites and MCDA: multi criteria decision aid

In addition to GIS based approaches, several recent studies have applied the p-median optimization model to solve service or facility location problems, which is particularly relevant for locating waste treatment centers. The p-median model aims to select p sites in such a way as to minimize the sum of the weighted distances between demand points and the nearest facilities, thereby reducing transportation costs and improving operational efficiency in a given network. In the specific field of waste management, although the literature on p-median applied directly to incinerator location is still emerging, similar applications have been studied for the location of collection points and transfer stations for urban or rural waste. This work shows that the use of the p-median model helps minimize transport costs and improve facility accessibility, which is a crucial aspect for location decisions regarding sensitive treatment facilities such as incinerators.

**Table 2:** Related Paper Concerning P-Median Problem

References	Year	Application Context	Objective and Method
Shnaishel Cheetar, A.	2024	General location-allocation problems	Application of the <b>p-median problem</b> for optimal service design; optimizing facility allocation by minimizing service-to-demand distance.
Kwikima, M. M., and Ngole, F.	2025	Municipal Solid Waste Management (Tanzania)	Combination of <b>GIS</b> with p-median and p-center models to optimize collection point locations and routing, reducing distances and costs.
Badran <i>et al.</i>	2006	Municipal Solid Waste Management System	Implementation of a <b>facility location model</b> (transfer stations, incinerators, etc.) within a multi-criteria framework aimed at minimizing transportation costs and distances.
Abdulrasaq and Sule	2012	Location of waste bins / collection points (MSW)	Solving the <b>p-median problem</b> using GIS functionalities to optimize the placement of urban waste collection units.
Hakimi ( <b>Classic mathematical models</b> )	1970	Foundations of the p-median	Original formulation of the <b>p-median problem</b> for optimal facility location, minimizing weighted distances to demand (core concept used in many modern studies).

After determining the optimal locations of hazardous healthcare waste treatment centers using a weighted p-median model, the next logical stage in the waste management planning process is the operational design of collection routes. While p-median focuses on strategic facility placement to minimize total weighted distances between generators and facilities, the Multi-Depot Vehicle Routing Problem (MDVRP) addresses the tactical and operational problem of routing collection vehicles from multiple depots to serve geographically dispersed healthcare facilities under capacity and service constraints. MDVRP is particularly relevant for waste collection systems involving several service bases and heterogeneous demand distributions.

**Table 3:** Related Paper Concerning MDVRP and Collection Waste

Reference	Year	Problem Variant	Context	Objective and Methods
Shi <i>et al.</i>	2020	MDVRP	Urban solid/household waste collection (multiple depots)	Minimize total transportation distance; heuristic + sector combination + merge head-drop tail strategy
Bouleft and Elhilali Alaoui	2023	Dynamic Multi-Compartment VRP (DM-CVRP)	Smart waste collection with sensors	Minimize transport + overflow penalty; GA/metaheuristic for dynamic routing
Yu <i>et al.</i>	2024	Multi-Depot Waste Collection VRP with Time Windows & Self-Delivery (MDWCVRPTW-SDO)	Recyclable waste collection, Yogyakarta, Indonesia	Minimize routing + compensation costs; MIP + simulated annealing
Lavigne <i>et al.</i>	2023	Rich Waste Collection Problem (multi-depot)	Brussels Capital Region, Belgium	Improve routing with memetic algorithm (MASS) for multi-depot, split pickup, intermediate facilities

## Case Study Description

Governorate of Sfax is the second industrial and economic capital. It is located on a Mediterranean coast loaded with an immense olive tree and is located north of the Gulf of Gabes with an area of 7,569 km<sup>2</sup>, or 4.6% of the country's area. It has a population of 955,421 inhabitants in 2014, which places it second behind the governorate of Tunis.

The current problem in most hospitals and health facilities in Sfax, Tunisia is the negligent dumping and uncontrolled burning of healthcare waste. Hazardous healthcare waste, in general, mixed and disposed-off with general waste or buried without treatment or burned in an open burning area. This is mainly due to non-existent or non-operational incinerators. This problem is solved by determining the location of collection site. Therefore, this work consists in determining the potential location of one site which depends on the economic, social, and environmental criteria. Then, an allocation problem was formulated to select

the optimal site from a set of candidate locations provided by the decision maker, aiming to minimize the total distance or cost of transporting waste from all healthcare facilities to the selected site. In this context, vehicles operating from a central depot collect waste from geographically dispersed healthcare establishments, ensuring that all known demands are met while respecting vehicle capacity constraints.

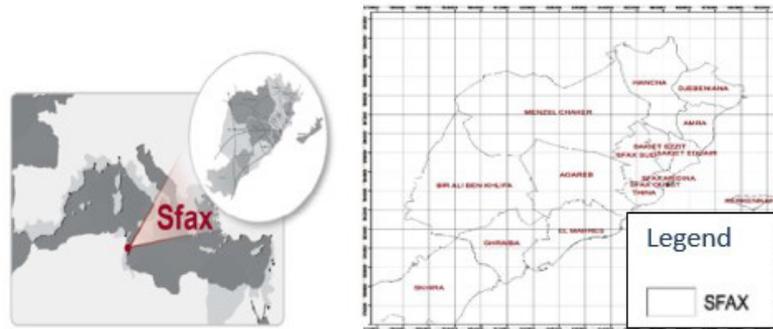


Figure 1: Sfax Area

### Spatial Site Selection Analysis Using GIS

This section focuses on a spatial assessment conducted to address the facility location problem. ArcGIS software was employed to identify the most suitable area within the Sfax governorate for the installation of a new incinerator.

#### Geographic Information System (GIS)

Identifying suitable sites for the installation of a hazardous healthcare waste incinerator is the first design and development challenge in this study. Geographic Information System (GIS) is a widely used tool in site suitability analysis. It involves identifying spatially referenced data in a problem solving environment. GIS is a digital database system which integrates geographically located data.

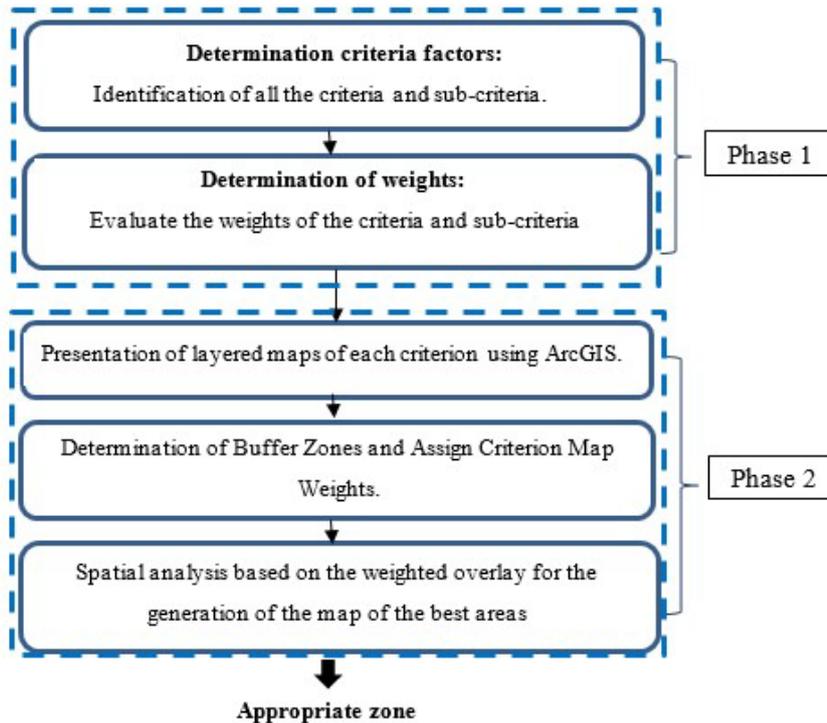
In general, several advantages provided by GIS. It is used to model the real world and moving from reality to geography in order to respond to specified problems and objectives. Then, it allows the visualization of information on an appropriate size.

The GIS designed during this study uses various attribute data relating to our study area and the high resolution and spatial precision of vector format layers with the aim of helping to choose the best sites to install a new incinerator in order to better manage hazardous healthcare waste.

#### Selection Criteria and Constraints

The methodology adopted in this article will be useful to decision makers for the efficient preparation of waste management guidelines and more particularly for choosing potential sites to locate an incinerator of hazardous healthcare waste and minimizing total distance (cost).

The following figure illustrates the methodology of the first stage of the study, which is structured into two main phases. In the first phase, a relevant set of criteria and sub-criteria is identified, and the corresponding weights are determined through consultation with decision makers. In the second phase, a spatial analysis is performed using ArcGIS to identify feasible locations for the installation of an incinerator. This analysis is based on three main criteria, each represented spatially as thematic map layers. Finally, these layers are overlaid to delineate the most suitable areas for incinerator siting



**Figure 2:** Flowchart of the Methodology

### Phase 1:

#### Determining criteria factors

In this study, a set of eight suitability criteria were considered. Several researchers in the sphere of healthcare waste incineration site selection show that decision making criteria in different countries proceed common goals such as economic, environmental and social desirability [24].

#### Economic Criteria

These criteria concern the economic cost of setting up an incinerator in the Sfax area. This criterion breaks down into two sub-criteria namely:

Road network: Installing the incinerator near the road network can significantly reduce investment costs.

Location of health establishments: Locating the facility close to health establishments can reduce the logistic costs of transportation.

#### Social Criteria

The social criteria consider the unwanted installation. Two criteria were taken into account:

Proximity to urban areas: The incinerator should be located at an adequate distance from residential areas to minimize noise and air pollution.

Proximity to industrial areas: Industrial areas are suitable locations for incinerators and similar facilities for waste treatment.

## Environmental Criteria

According to Sharma et al. (2013), the main problems raised by the construction of an incinerator concern the pollution generated by such facilities. Inappropriate location of an incinerator may lead to the contamination of food (WHO, 2005). Therefore, residual ash, fly ash and other emissions are dangerous and pose significant risks for agricultural products. In this work, three sub-criteria related to agricultural land and one coast line criterion are considered, namely:

Olive trees, Cereals and Vegetable crops

Close to the side line: the sea is at risk of being polluted by ash from incinerators. This can pose a risk to aquatic life, including fish and other marine animals.

## Weight Assessment and Decision-Maker Involvement

The weighting process was conducted through consultations with local authorities and experts to reflect the relative importance of each criterion in the site selection process. In accordance with the recommendations of the relevant governorate authorities in Sfax, the weights were assessed as follows. The aggregate weights assigned to the main criteria are: environmental criteria (0.48), economic criteria (0.44), and social criteria (0.08). The weights of the sub-criteria are presented in the following tables:

**Table 4: Environmental Criteria (48%)**

Sub-criteria	Relative weight	Overall weight
Distance from olive groves	0.51	0.2448
Distance from cereal fields	0.27	0.1296
Distance from vegetable crops	0.13	0.0624
Distance from the side line	0.09	0.0432

**Table 5: Economic Criteria (44%)**

Sub-criteria	Relative weight	Overall weight
Accessibility to the transportation network	0.75	0.33
Proximity to healthcare facilities	0.25	0.11

**Table 6: Social Criteria (8%)**

Sub-criteria	Relative weight	Overall weight
Distance from urban and residential areas	0.5	0.04
Proximity to existing industrial zones	0.5	0.04

The adopted weighting structure reflects the predominance of environmental and logistical constraints in healthcare waste facility location. In particular, olive groves and cereal fields were assigned higher importance due to their economic and ecological value, while coastal protection was considered a regulatory constraint. Economic efficiency was mainly driven by transportation accessibility, whereas social criteria were equally weighted to ensure balanced social acceptability.

## Phase 2: GIS maps and spatial analysis

### Spatial Analysis and Suitability Mapping

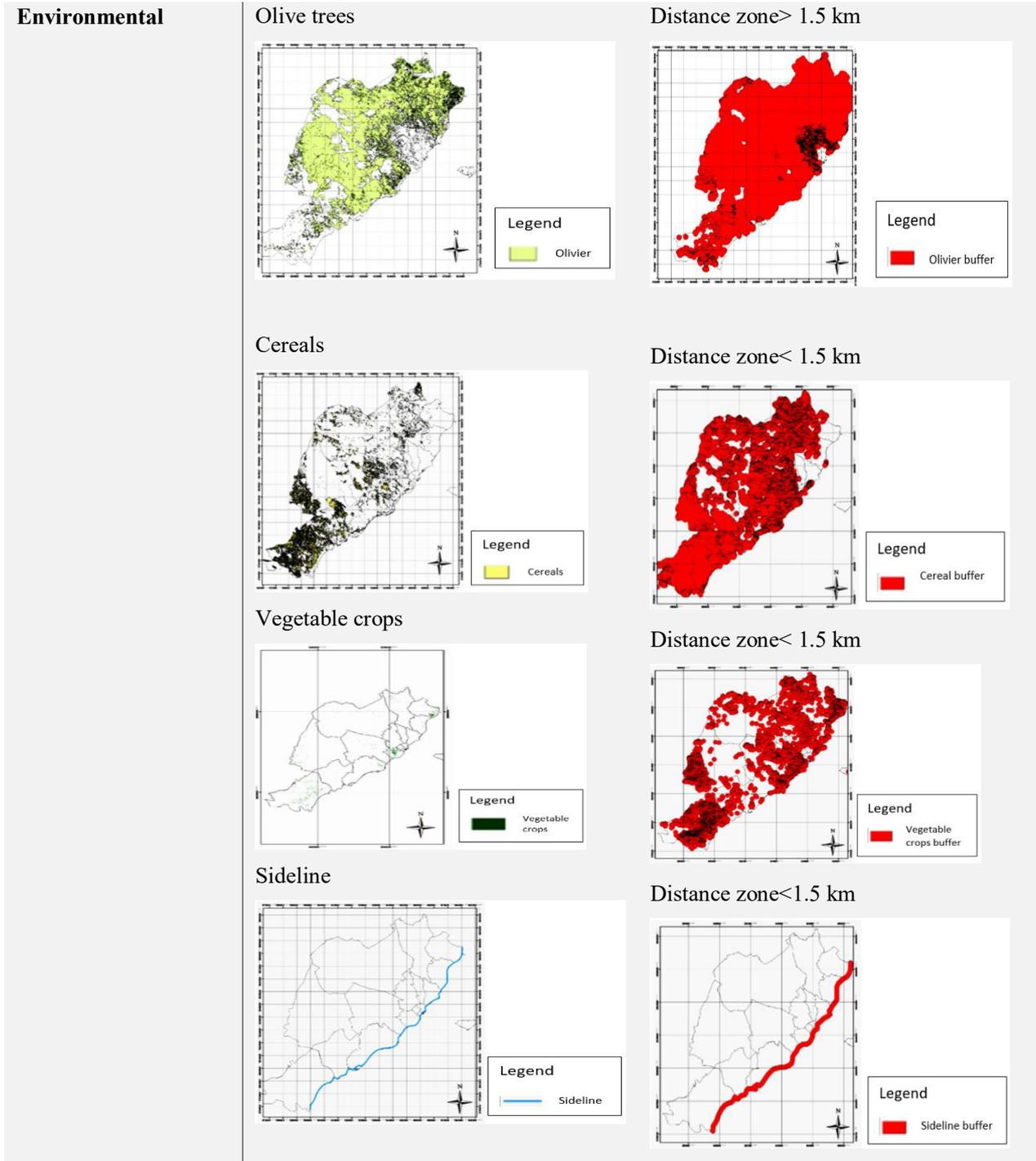
Georeferencing and digitizing are the first and second steps to obtaining the required maps. These maps are the digital topo-

graphic maps (1/ 25.000) that show roads, hospitals, urban and industrial areas, land used by olive trees, cereals vegetable crops and the sideline.

After presenting the maps of each sub-criterion as well as these weights and the determination of the buffer zones is the next step. The buffer zones are the spatial constraints constituted by the group of criteria according to the logic model in the decision-making tree. The buffers were calculated according to current legislation (Table 9).

To assign a weight to each criterion, the functionality of the weighted sum tool in ArcGIS was used. By applying the steps of the methodology flowchart, the suitability maps corresponding to each sub-criterion with their weights were obtained and presented in the following table.

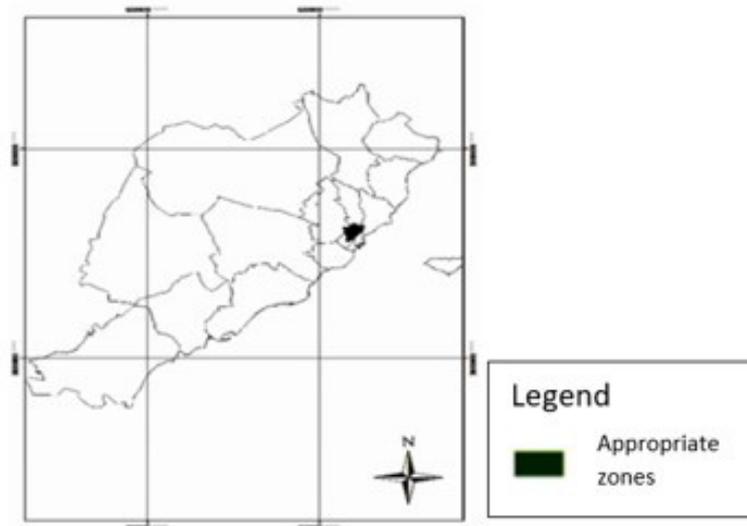
Criteria	Sub-criteria	Buffer zones
Economical	Health establishments	Distance zone <3 km
	Main routes	Distance zone <2 km
Social	Urban areas	Distance zone < 4 km
	Industrial areas	Distance zone >2 km



**Table 7:** Assessment and Buffer zones

### Identification of the Optimal Site

In the final step, the maps generated were integrated to produce the ultimate suitability map for selecting locations for hazardous hospital waste treatment and disposal centers. All restrictive data layers were overlaid within the GIS environment using tools such as ‘intersection,’ ‘buffer,’ and ‘erase,’ with weights previously provided by the governorate authorities. The remaining areas were then identified as suitable sites. Subsequently, the thematic layers representing environmental, social, and economic suitability were combined to define the final areas appropriate for the installation of such facilities (see Figure 5).



**Figure 3:** Final Aptitude Card

The final map presented in the figure above indicates that approximately 98% of the study area is unsuitable for the construction of incinerator facilities. More specifically, only 2% of the area meets the criteria for installing a healthcare waste incinerator. The primary limiting factors, which carry the highest weight in the analysis, include land occupied by olive groves and cereal fields, as well as the minimum required distance from industrial zones. The identified land falls within the most suitable class following the spatial analysis. According to ArcGIS verification, the selected site is located approximately 12 kilometers from the city center along the Tunis Road and is delineated by a circular area with a diameter of 4 kilometers. The application of this real case study demonstrates the effectiveness of the proposed methodology.

ArcGIS 10.5 was used to address the incinerator location problem for managing hazardous healthcare waste. The proposed approach enables the precise identification of optimal areas for sitting waste treatment facilities. The methodology presented in this study offers an effective and sustainable framework for the placement of undesired installations by considering multiple groups of criteria. The integration of geospatial analysis with weighted criteria provides higher precision and efficiency compared to traditional approaches. This study adopts a general method that ensures flexibility and sustainability in evaluating diverse criteria. However, a key limitation is the relatively small number of criteria considered.

### **Optimal Site Selection Using the $p$ -Median Model**

The Weighted  $p$ -median problem is a classical location–allocation optimization problem widely used in operations research, transportation, logistics, healthcare, and waste management systems. The objective of the main problem is to select exactly  $p$  ( $p=1$  and  $p=2$ ) facility locations from a set of candidate sites to minimize the total weighted distance between demand points (hospitals) and their assigned depot (incinerator) without exceeding facility capacities. Each demand point is associated with a weight (quantity of waste), which reflects its relative importance.

### **Candidate Sites Description**

We present the candidate sites identified from the ArcGIS analysis described in previous section and we integrate three additional sites proposed by the governorate authorities: Aguerreb, Mahres, and Thyna. These sites correspond to the current waste disposal zones, and they are considered potential locations for new hazardous healthcare waste treatment facilities.

### **Mathematical Formulation of the Capacitated, weighted P-Median Model**

Following the approach of Setiwan and Astuti (2024), the capacitated, weighted P median model is mathematically formulated to determine optimal facility locations while considering both demand weights and vehicle capacity constraints.

Note that:

I: set of demand nodes (privet and public hospitals), indexed by  $i$

J: set of candidate facility locations (sites to install incinerator for trait dangerous healthcare waste), indexed by  $j$

Parameters:

$w_i$ : demand or waste volume (weight) associated with node  $i$  (of each hospital)

$d_{ij}$ : distance or unit transportation cost between demand node (hospital)  $i$  and candidate facility  $j$  (depot)

$Q_j$ : maximum service capacity of depot  $j$

$p$ : prescribed number of facilities to be located

Decision variables:

$$x_{ij} = \begin{cases} 1, & \text{if waste quantity of node } i \text{ is assigned to depot } j \\ 0, & \text{otherwise} \end{cases}$$

$$y_j = \begin{cases} 1, & \text{if site } j \text{ is selected} \\ 0, & \text{otherwise} \end{cases}$$

The full healthcare waste weighted P-median Problem formulation is expressed as follows:

$$\text{Objective function :} \quad \text{Min } \sum_{i \in I} \sum_{j \in J} w_i d_{ij} x_{ij} \quad (1)$$

$$\text{Constraints:} \quad \sum_{j \in J} x_{ij} = 1 \quad \forall i \in I \quad (2)$$

$$x_{ij} \leq y_j \quad \forall i \in I, j \in J \quad (3)$$

$$\sum_{i \in I} w_i x_{ij} \leq Q_j y_j \quad \forall j \in J \quad (4)$$

$$\sum_{j \in J} y_j = p \quad (5)$$

$$x_{ij}, y_j \in \{0, 1\} \quad \forall i \in I, j \in J \quad (6)$$

Equation (1) minimizes the total weighted transportation cost between hospitals and their assigned incinerator location. Constraint (2) ensures that each hospital is assigned to exactly one depot. It guarantees full coverage of all demand points without splitting demand among multiple depots. Constraint (3) enforces logical consistency between assignment and location decisions. Each hospital can only be assigned to a depot if it is opened. While, constraint (4) limits the total demand assigned to each depot to its maximum capacity. Equation (5) specifies that exactly  $p$  depot must be opened among all candidate locations. Finally, constraints (6) define the binary nature of the decision variables.

### Scenario Design and Experimental Setup

To evaluate the optimal location of the incinerator under different operational scenarios, two propositions of the p-median model are considered.

Proposition 1: The location of hazardous healthcare waste treatment centers is formulated as a single-facility ( $p = 1$ ) p median problem, aiming to select the most suitable site among the four candidate locations while minimizing total transportation costs under capacity constraints. This proposition considers five demand  $D_k \in \{D1, D2, D3, D4, D5\}$ . This setup allows the evaluation of the model’s performance for each candidate site under varying demand.

Proposition 2: The two-facility ( $p = 2$ ) p median problem extends the analysis by selecting the best pair of candidate sites to jointly serve all healthcare facilities. In this scenario, combinations of sites are evaluated for the demand levels  $D_k=49, 50, 55$  with incinerator capacities  $Q \in \{60,80\}$ , reflecting realistic operational constraints. Each combination considers a two-cluster partition of healthcare facilities corresponding to the p median structure. This scenario-based approach allows a systematic assessment of transportation costs and model robustness when serving dispersed healthcare facilities with multiple incinerator locations.

### Results and Comparative Analysis

The table below describes the different criteria and sub-criteria for each proposed site. In Proposition 1, we consider only one site as a central depot, whereas in Proposition 2, two sites are selected simultaneously, combining candidate locations to evaluate their joint performance under varying demand and capacity scenarios.

**Table 8:** Comparative Assessment of Candidate Sites Using Weighted Criteria

Criteria	Sub-criteria	Global weight	ArcGIS	Agareb	Mahres	Thyna
Environmental	Distance from olive groves	0.2448	1	1	0	0
	Distance from cereal fields	0.1296	1	1	0	0
	Distance from vegetable crops	0.0624	1	1	0	0
	Minimum setback distance from coastal and shoreline areas	0.0432	1	0	0	1
Economic	Accessibility to the transportation network	0.33	1	1	0	1
	Proximity to healthcare facilities	0.11	1	0	0	1
Social	Distance from urban and residential areas	0.04	1	1	1	0
	Proximity to existing industrial zones	0.04	1	0	0	1
Total weighted score		1	1	0.744	0.04	0.5232

1 means the site favors the sub-criterion.

0 means the site is unfavorable with respect to the sub-criterion.

The candidate sites were evaluated using environmental, economic, and social criteria with weighted scores assigned by the gov-

ernorate authorities, as presented in Table 7. The site identified through ArcGIS achieved the highest overall suitability score (1.0000), as it satisfies all environmental constraints related to agricultural land use and coastal setbacks, while also offering good accessibility, proximity to healthcare facilities, and compliance with social criteria.

Among the sites proposed by the governorate authorities, Agureb obtained a relatively high score (0.744) due to its compliance with most environmental and accessibility criteria, although it shows limitations regarding coastal setbacks and proximity to healthcare and industrial zones. Thyna achieved a moderate score (0.5232), benefiting from good accessibility and proximity to healthcare facilities and industrial zones, but it fails to meet several environmental and social constraints. Mahres recorded the lowest score (0.04), reflecting poor performance across most criteria.

**Table 9:** Total Transportation Costs for Each Candidate Site Under The 1-Median Scenario

	Sites	Results
1-Median	site ArcGIS	889,8
		876,2
		891,2
		874,6
		978
	site Agureb	1222,3
		1199,4
		1220,9
		1198,9
		1349,2
	site Mahres	1974,8
		1939,5
		1976,2
		1938,9
		2175,7
	site Thyna	420
		415,9
		421,1
		415,1
		465,5

Five demand scenarios were considered to capture the variability of waste generation across the 16 healthcare facilities. Scenario 1 totals 50 units (2, 1, 5, 13, 12, 1, 1, 1, 1, 3, 1, 1, 2, 3, 2), Scenario 2 totals 49 units (2, 1, 5, 12, 10, 1, 1, 1, 1, 1, 3, 1, 1, 3, 3), Scenario 3 totals 50 units (2, 1, 5, 12, 13, 1, 1, 1, 1, 1, 2, 1, 1, 3, 2, 3), Scenario 4 totals 49 units (2, 1, 5, 12, 10, 1, 1, 2, 1, 1, 2, 1, 1, 2, 1, 1, 3, 3, 3), and Scenario 5 totals 55 units (2, 1, 5, 13, 13, 1, 1, 2, 1, 1, 3, 2, 1, 3, 3, 3).

The comparative analysis of the GIS-based multi-criteria evaluation and the 1-median optimization results reveals both complementary and contrasting insights into site suitability. From the GIS perspective, the ArcGIS-identified site achieved the highest

overall suitability score (1.0000), as it satisfies all environmental, economic, and social criteria with weights assigned by the governorate authorities. This result highlights its strong compliance with land-use restrictions, accessibility, and social acceptability. Agureb and Thyna obtained intermediate scores (0.7440 and 0.5232, respectively), while Mahres was identified as largely unsuitable (0.0400) due to significant environmental and economic constraints.

In contrast, the 1-median optimization results, which focus exclusively on minimizing transportation costs, identify Thyna as the most cost-efficient site across all demand instances, followed by the ArcGIS-identified site. Agureb and Mahres consistently exhibit higher transportation costs, with Mahres performing the worst.

Taken together, these findings underline a trade-off between regulatory–environmental suitability and pure transportation efficiency. While Thyna minimizes transport costs, its lower GIS suitability score reflects environmental and social limitations. Conversely, the ArcGIS-identified site offers a balanced solution by combining high spatial suitability with competitive transportation costs, making it a robust and sustainable candidate when both planning constraints and logistical efficiency are considered.

**Table 10:** Total Transportation Costs for Each Candidate Site under the 2-Median Scenario

Sites	Demand	Sites capacities	Total Usage Rate		Clusters and Loads	Cost
		Q				
ArcGis/Thyna	D1	60	0.83	30/30	Cluster 1 (0-1-4-8-11-14) à66.7%	579.3
					Cluster 2 (2-3-5-6-7-9-10-12-13-15) à100%	
				45/15	Cluster 1(0-1-3-4-8-11-14-15) à77.8%	729.1
		Cluster 2(2-5-6-7-9-10-12-13) à100%				
		15/45	Cluster 1(0-1-8-11) à33.3%	442.2		
			Cluster 2(2-3-4-5-6-7-9-10-12-13-14-15) à100%			
	80	0.62	40/40	Cluster 1(0-1-8-11-14-15) à25%	484.9	
				Cluster 2(2-3-4-5-6-7-9-10-12-13) à100%		
	D2	60	0.8166	30/30	Cluster 1(0-1-4-7-8-11-14) à63.3%	565.4
					Cluster 2(2-3-5-6-9-10-12-13-15) à100%	
					45/15	Cluster 1(0-1-3-4-7-8-11-14-15) à75.6%
		Cluster 2(2-5-6-9-10-12-13) à100%				
		15/45	Cluster 1(0-8-11) à26.7%	430		
			Cluster 2(1-2-3-4-5-6-7-9-10-12-13-14-15) à100%			
80	0.6125	40/40	Cluster 1(0-1-7-8-11-14) à22.5%	472.4		
			Cluster 2(2-3-4-5-6-9-10-12-13-15) à100%			
D3	60	0.83	30/30	Cluster 1(0-1-4-8-11-14) à66.7%	581.2	
				Cluster 2(2-3-5-6-7-9-10-12-13-15) à100%		
				45/15	Cluster 1(0-1-3-4-8-11-14-15) à77.8%	729.4

					Cluster 2(2-5-6-7-9-10-12-13) à100%		
				15/45	Cluster 1(0-1-8-11) à33.3%	443.3	
	80	0.62	40/40		Cluster 2(2-3-4-5-6-7-9-10-12-13-14-15) à100%		
					Cluster 1(0-1-8-11-14-15) à25%	486.1	
	D4	60	0.8166	30/30		Cluster 2(2-3-4-5-6-7-9-10-12-13) à100%	
						Cluster 1(0-1-4-8-9-11-14) à63.3%	564
				45/15		Cluster 2(2-3-5-6-7-10-12-13-15) à100%	
						Cluster 1(0-1-3-4-8-9-11-14-15) à75.6%	712.9
				15/45		Cluster 2(2-5-6-7-10-12-13) à100%	
						Cluster 1(0-8-11)à26.7%	429.2
	80	0.6125	40/40		Cluster 2(1-2-3-4-5-6-7-9-10-12-13-14-15) à100%		
					Cluster 1(0-1-8-9-11-14) à22.5%	471.7	
	D5	60	0.9166	30/30		Cluster 2(2-3-4-5-6-7-10-13-13-15) à100%	
						Cluster 1(0-1-4-8-11-14-15) à83.3%	665.2
				45/15		Cluster 2(2-3-5-6-7-9-10-12-13) à100%	
						Cluster 1(0-1-3-4-7-8-11-14-15) à88.9%	815.4
				15/45		Cluster 2(2-5-6-9-10-12-13) à100%	
						Cluster 1(0-1-8-9-11-14) à66.7%	527.4
	80	0.6855	40/40		Cluster 2(2-3-4-5-6-7-10-12-13-15) à100%		
					Cluster 1(0-1-7-8-9-11-14-15) à37.5%	570.8	
ArcGis/Aguereb	D1	60	0.83	30/30		Cluster 2(2-3-4-5-6-10-12-13) à100%	
						Cluster 1(0-3-4-7-8-11) à100%	997.1
				45/15		Cluster 2(1-2-5-6-9-10-12-13-14-15) à66.7%	
						Cluster 1(0-1-3-4-5-6-7-8-9-10-11-12-13-14-15) à100%	905.8
				15/45		Cluster 2(2) à33.3%	
						Cluster 1(0-1-7-8-9-10-11-14-15) à100%	1097.7
	80	0.62	40/40		Cluster 2(2-3-4-5-6-12-13) à77.8%		
					Cluster 1(0-1-3-4-7-8-9-10-11-14-15) à100%	931.3	
	D2	60	0.8166	30/30		Cluster 2(2-5-6-12-13) à25%	
						Cluster 1(0-1-3-4-7-8-9-11-12) à100% %	973.3
45/15					Cluster 2(2-5-6-10-13-14-15) à63.3%		
				Cluster 1(0-1-3-4-5-6-7-8-9-10-11-12-13-14-15) à97.8%	892.2		

					Cluster 2(2) à33.3%	1075.2	
					15/45		Cluster 1(0-1-5-7-8-9-10-11-12-14) à100%
	80	0.6125	40/40	Cluster 2(2-3-4-6-13-15) à75.6%		910	
				Cluster 1(0-1-3-4-5-7-8-9-10-11-12-13-15) à100%			
				Cluster 2(2-6-13) à22.5%			
	D3	60	0.83	30/30	Cluster 1(0-3-4-7-8-11) à100%		996
					Cluster 2(1-2-5-6-9-10-12-13-14-15) à66.7%		
				45/15	Cluster 1(0-1-3-4-5-6-7-8-9-10-11-12-13-14-15) à100%		907.2
					Cluster 2(2) à33.3%		
				15/45	Cluster 1(0-1-7-8-9-10-11-12-14-15) à100%		1096.8
					Cluster 2(2-3-4-5-6-13) à 77.8%		
	80	0.62	40/40	Cluster 1(0-1-3-4-7-8-9-10-11-12-14-15) à100%		930.7	
				Cluster 2(2-5-6-13) à 25%			
	D4	60	0.8166	30/30	Cluster 1(0-1-3-4-7-8-9-11) à100%		971.3
					Cluster 2(2-5-6-10-12-13-14-15-13) à 63.3%		
				45/15	Cluster 1(0-1-3-4-5-6-7-8-9-10-11-12-13-14-15) à97.8%		890.6
					Cluster 2(2) à33.3%		
				15/45	Cluster 1(0-1-5-7-8-9-10-11-12-14) à100%		1073.6
					Cluster 2(2-3-4-6-13-15) à75.6%		
	80	0.6125	40/40	Cluster 1(0-1-3-4-5-7-8-9-1-11-12-14-15) à100%		908.4	
				Cluster 2(2-6-13) à22.5%			
	D5	60	0.9166	30/30	Cluster 1(0-1-3-5-7-8-9-10-11-12-14)30/30à100%		1114.9
					Cluster 2(2-4-6-13-15)25/30à83.3%		
45/15				Cluster 1(0-1-3-4-7-8-9-10-11-12-14-15) à100%		1017.5	
				Cluster 2(2-5-6-13) à66.7%			
15/45				Cluster 1(0-1-7-8-9-10-11-14) à100%		1215.3	
				Cluster 2(2-3-4-5-6-12-13-15) à88.9%			
80	0.6855	40/40	Cluster 1(0-3-4-7-8-9-10-11-14) à100%		1049.2		
			Cluster 2(1-2-5-6-12-13-15) à37.5%				
ArcGis/Mahres	D1	60	0.83	30/30	Cluster 1(0-1-4-7-8-9-10-11-12-13-14-15) à100%	1298.2	

					Cluster 2(2-3-5-6) à66.7%								
					45/15		Cluster 1(0-1-3-4-5-6-7-8-9-10-11-12-13-14-15) à100%	986.8					
							Cluster 2(2) à33.3%						
					15/45		Cluster 1(0-1-7-8-9-10-11-14-15) à100%	1621.9					
							Cluster 2(2-3-4-5-6-12-13) à77.8%						
					80		0.62	40/40	Cluster 1(0-1-3-4-7-8-9-10-11-14-15) à100%	1087.3			
									Cluster 2(2-5-6-12-13) à25%				
					D2		60	0.8166	30/30	Cluster 1(0-1-4-7-8-9-10-11-12-13-14-15) à100%	1263.6		
										Cluster 2(2-3-5-6) à63.3%			
									45/15	Cluster 1(0-1-2-3-4-5-7-8-9-10-11-12-14-15) à100%	956.1		
										Cluster 2(6-13) à26.7%			
									15/45	Cluster 1(0-1-7-8-10-11-14-15) à100%	1586.2		
										Cluster 2(2-3-4-5-6-9-12-13) à75.6%			
									80	0.6125	40/40	Cluster 1(0-1-3-4-5-7-8-9-10-11-12-14-15) à100%	1053.1
												Cluster 2(2-6-13) à22.5%	
					D3		60	0.83	30/30	Cluster 1(0-1-4-7-8-9-10-11-13-14-15) à100%	1299.7		
										Cluster 2(2-3-5-6-12) à66.7%			
									45/15	Cluster 1(0-1-3-4-5-6-7-8-9-10-11-12-13-14-15) à100%	988.2		
										Cluster 2(2) à33.3%			
									15/45	Cluster 1(0-1-7-8-9-10-11-12-14-15) à100%	1623.5		
Cluster 2(2-3-4-5-6-13) à77.8%													
80	0.62	40/40	Cluster 1(0-1-3-4-7-8-9-10-11-12-14-15) à100%	1088.1									
			Cluster 2(2-5-6-13) à25%										
D4	60	0.8166	30/30	Cluster 1(0-1-4-7-8-9-10-11-12-13-14-15) à100%	1262								
				Cluster 2(2-3-5-6) à 63.3%									
			45/15	Cluster 1(0-1-2-3-4-5-6-7-8-9-10-11-12-14-15) à100%	954.5								
				Cluster 2(3) à26.7%									
15/45	Cluster 1(0-1-7-8-9-11-12-14-15) à100%	1583.9											

	D5	80	0.6125	40/40	Cluster 2(2-3-4-5-6-10-13) à75.6%	151.5
					Cluster 1(0-1-3-4-5-7-8-9-10-11-12-14-15) à100%	
		Cluster 2(2-6-13) à22.5%				
		Cluster 1(0-1-4-7-8-10-11-14-15) à100%	1491			
		Cluster 2(2-3-5-6-9-12-13) à83.3%				
		45/15	Cluster 1(0-1-3-4-7-8-9-10-11-12-14-15) à100%	1174.9		
	Cluster 2(2-5-6-13) à66.7%					
	15/45	Cluster 1(0-1-7-8-9-11-14-15) à100%	1816			
		Cluster 2(2-3-4-5-6-10-12-13) à88.9%				
	80	0.6855	40/40	Cluster 1(0-1-3-4-7-8-11-14-15) à100%	1281.6	
				Cluster 2(2-5-6-9-10-12-13) à37.5%		
	Aguereb/Mhres	D1	60	0.83	30/30	Cluster 1(0-1-2-4-7-8-12-13-14-15) à100%
Cluster 2(3-5-6-9-10-11) à66.7%						
45/15			Cluster 1(0-1-2-3-4-8-10-12-13-14-15) à100%	1290.8		
			Cluster 2(5-6-7-9-11) à33.3%			
15/45			Cluster 1(0-1-2-13-14-15) à100%	1732.1		
			Cluster 2(3-4-5-6-7-8-9-10-11-12) à77.8%			
80		0.62	40/40	Cluster 1(0-1-2-3-4-13-14-15) à100%	1363.9	
				Cluster 2(5-6-7-8-9-10-11-12) à25%		
D2		60	0.8166	30/30	Cluster 1(0-1-2-4-7-8-12-13-14-15) à100%	1467.4
					Cluster 2(3-5-6-9-10-11) à63.3%	
		45/15	Cluster 1(0-1-2-3-4-7-8-10-12-13-14-15) à100%	1253.5		
			Cluster 2(5-6-9-11) à26.7%			
		15/45	Cluster 1(1-2-13-14-15) à100%	1696.6		
			Cluster 2(0-3-4-5-6-7-8-9-10-11-12) à75.6%			
80		0.6125	40/40	Cluster 1(0-1-2-3-4-12-13-14-15) à100%	1326.2	
				Cluster 2(5-6-7-8-9-10-11) à22.5%		
D3		60	0.83	30/30	Cluster 1(0-1-2-4-12-13-14-15) à100%	1503.6
					Cluster 2(3-5-6-7-8-9-10-11) à66.7%	
	45/15	Cluster 1(0-1-2-3-4-8-10-12-13-14-15) à100%	1289.4			
		Cluster 2(5-6-7-9-11) à33.3%				
	15/45	Cluster 1(0-2-13-14-15) à100%	1733.4			
		Cluster 2(1-3-4-5-6-7-8-9-10-11-12) à77.8%				

		80	0.62	40/40	Cluster 1(0-2-3-4-13-14-15) à100%	1364.1	
					Cluster 2(1-5-6-7-8-9-10-11-12) à25%		
	D4	60	0.8166	30/30	Cluster 1(0-1-2-4-8-9-12-13-14-15) à100%	1466.8	
					Cluster 2(3-5-6-7-10-11) à63.3%		
					45/15	Cluster 1(0-1-2-3-4-7-8-10-12-13-14-15) à100%	1253
						Cluster 2(5-6-9-11) à26.7%	
					15/45	Cluster 1(1-2-13-14-15) à100%	1696
						Cluster 2(0-3-4-5-6-7-8-9-10-11-12) à75.6%	
	80	0.6125	40/40	Cluster 1(0-1-2-3-4-12-13-14-15) à100%	1325.6		
				Cluster 2(5-6-7-8-9-10-11) à22.5%			
	D5	60	0.9166	30/30	Cluster 1(0-1-2-4-13-14-15) à100%	1701.7	
					Cluster 2(3-5-6-7-8-9-10-11-12) à83.3%		
				45/15	Cluster 1(0-1-2-3-4-8-12-13-14-15) à100%	1487.5	
					Cluster 2(5-6-7-9-10-11) à66.7%		
15/45				Cluster 1(1-2-13-14-15) à100%	1932.8		
				Cluster 2(0-3-4-5-6-7-8-9-10-11-12) à88.9%			
80	0.6855	40/40	Cluster 1(0-1-2-4-5-6-7-8-9-10-12-13-14-15) à100%	1557.6			
			Cluster 2(3-11) à37.5%				
Aguereb/Thyna	D1	60	0.83	30/30	Cluster 1(0-1-2-8-9-10-13-14-15) à66.7 %	724.2	
					Cluster 2(3-4-5-6-7-11-12) à100%		
				45/15	Cluster 1(0-1-2-4-5-7-8-9-10-12-13-14-15) à77.8 %	963.8	
					Cluster 2(3-6-11) à100%		
	15/45	Cluster 1(14-15) à33.3 %	494				
		Cluster 2(0-21-2-3-4-5-6-7-8-9-10-11-12-13) à100%					
	80	0.62	40/40	Cluster 1(2-14-15) à25 %	568		
				Cluster 2(0-1-3-4-5-6-7-8-9-10-11-12-13) à100%			
	D2	60	0.8166	30/30	Cluster 1(0-1-2-8-9-13-14-15) à63.3 %	701	
					Cluster 2(3-4-5-6-7-10-11-12) à100%		
45/15				Cluster 1(0-1-2-4-7-8-9-10-12-13-14-15) à75.6 %	941.1		
				Cluster 2(3-5-6-11) à100%			
15/45	Cluster 1(1-15) à26.7 %	475.2					

		80	0.6125	40/40	Cluster 2(0-2-3-4-5-6-7-8-9-10-11-12-13-14) à100%	549.2
					Cluster 1(0-1-14-15) à22.5 %	
	D3	60	0.83	30/30	Cluster 2(2-3-4-5-6-7-8-9-10-11-12-13) à100%	724
					Cluster 1(0-1-2-8-9-10-13-14-15) à66.7%	
		45/15	Cluster 2(3-4-5-6-7-11-12) à100%	962.6		
			Cluster 1(0-1-2-4-7-8-9-10-12-13-14-15) à77.8 %			
			Cluster 2(3-5-6-11) à100%			
			Cluster 1(14-15) à33.3 %			
		15/45	Cluster 2(0-1-2-3-4-5-6-7-8-9-10-11-12-13) à100%	495.1		
			Cluster 1(2-14-15) à25 %			
	80	0.62	40/40	Cluster 2(0-1-3-4-5-6-7-8-9-10-11-12-13) à100%	569.1	
				Cluster 1(0-1-2-10-13-14-15) à63.3 %		
	D4	60	0.8166	30/30	Cluster 2(3-4-5-6-7-8-9-11-12) à100%	700
					Cluster 1(0-1-2-4-7-8-9-10-12-13-14-15) à75.6 %	
		45/15	Cluster 2(3-5-6-11) à100%	940.6		
			Cluster 1(1-15) à26.7 %			
			Cluster 2(0-2-3-4-5-6-7-8-9-10-11-12-13-14) à100%			
			Cluster 1(0-1-14-15) à22.5 %			
		15/45	Cluster 2(2-3-4-5-6-7-8-9-10-11-12-13) à100%	548.4		
			Cluster 1(0-1-2-4-14-15)25/30à83.3 %			
D5	60	0.9166	30/30	Cluster 2(0-3-5-6-7-8-9-10-11-12-13)30/30à100%	884.6	
				Cluster 1(0-1-2-4-5-6-7-8-9-10-12-13-14-15) à88.9 %		
	45/15	Cluster 2(3-11) à100%	1089.8			
		Cluster 1(0-2-15) à66.7 %				
		Cluster 2(1-3-4-5-6-7-8-9-10-11-12-13-14) à100%				
		Cluster 1(1-2-13-14-15) à 37.5%				
	15/45	Cluster 2(0-3-4-5-6-7-8-9-10-11-12) à100%	613.5			
		Cluster 1(1-2-13-14-15) à 37.5%				
80	0.6855	40/40	Cluster 2(0-3-4-5-6-7-8-9-10-11-12) à100%	688.2		
			Cluster 1(0-1-2-5-7-8-9-10-14-15) à66.7 %			
Mahres/Thyna	D1	60	0.83	30/30	Cluster 2(3-4-6-11-12-13) à100%	1039.3
					Cluster 1(0-1-2-5-7-8-9-10-14-15) à66.7 %	

				45/15	Cluster 1(0-1-2-4-5-7-8-9-10-11-13-14-15) à77.8 %	1506		
					Cluster 2(3-6-12) à100%			
				15/45	Cluster 1(0-10) à33.3 %	574.2		
					Cluster 2(1-2-3-4-5-6-7-8-9-11-12-13-14-15) à100%			
				80	0.62	40/40	Cluster 1(0-1-7-9-10-15) à25%	729.1
							Cluster 2(2-3-4-5-6-8-11-12-13-14)à100%	
	D2	60	0.8166	30/30	Cluster 1(0-1-2-7-9-10-14-15) à63.3%	1004		
					Cluster 2(3-4-5-6-8-11-12-13) à100%			
				45/15	Cluster 1(0-1-2-4-5-7-9-10-11-13-14-15) à75.6 %	1470.8		
					Cluster 2(3-6-8-12) à100%			
				15/45	Cluster 1(9-10) à26.7%	539.2		
					Cluster 2(0-1-2-3-4-5-6-7-8-11-12-13-14-15) à100%			
	80	0.6125	40/40	Cluster 1(0-9-10-15) à22.5 %	694			
				Cluster 2(1-2-3-4-5-6-7-8-11-12-13-14) à100%				
	D3	60	0.83	30/30	Cluster 1(0-1-2-5-7-8-9-10-11-14-15) à66.7%	1040.7		
					Cluster 2(3-4-6-12-13) à100%			
				45/15	Cluster 1(0-1-2-4-5-7-9-10-11-13-14-15) à77.8 %	1507.5		
					Cluster 2(3-6-8-12) à100%			
				15/45	Cluster 1(0-9-10) à33.3 %	575.4		
					Cluster 2(1-2-3-4-5-6-7-8-11-12-13-14-15) à100%			
80	0.62	40/40	Cluster 1(0-1-7-9-10-15) à25 %	930.4				
			Cluster 2(2-3-4-5-6-8-11-12-13-14) à100%					
D4	60	0.8166	30/30	Cluster 1(0-1-2-7-9-10-14-15) à63.3 %	1003.4			
				Cluster 2(3-4-5-6-8-11-12-13) à100%				
			45/15	Cluster 1(0-1-2-4-5-7-9-10-11-13-14-15) à 75%	1470.2			
				Cluster 2(3-6-8-12) à100%				
			15/45	Cluster 1(0-10) à26.7 %	538.5			
				Cluster 2(1-2-3-4-5-6-7-8-7-9-11-12-13-14-15) à100%				
80	0.6125	40/40	Cluster 1(0-1-9-10-15) à22.5 %	693.4				
			Cluster 2(2-3-4-5-6-7-8-11-12-13-14) à100%					

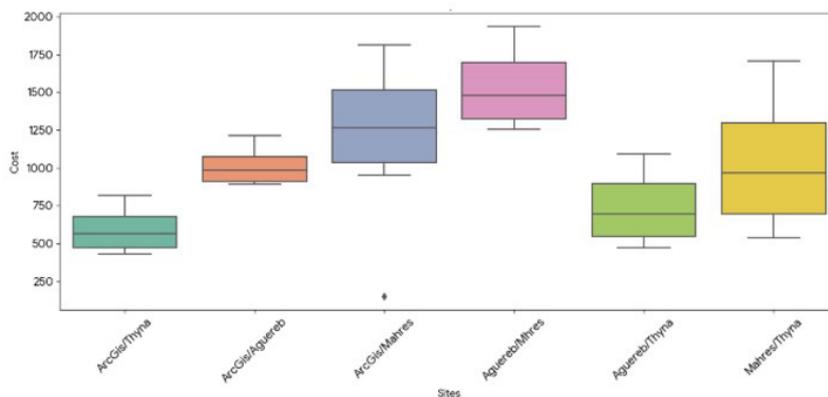
	D5	60	0.9166	30/30	Cluster 1(0-1-2-5-7-8-9-10-13-14-15) à83.3%	1240.4
					Cluster 2(3-4-6-11-12)30/30à100%	
				45/15	Cluster 1(0-1-2-4-5-7-8-9-10-11-13-14-15) à88.9%	1706.9
		Cluster 2(3-6-12) à100%				
	80	0.6855	40/40		Cluster 1(0-1-9-10-15) à66.7 %	774.6
					Cluster 2(2-3-4-5-6-7-8-11-12-13-14) à100%	
					Cluster 1(0-1-2-9-10-15) à37.5%	929.6
		Cluster 2(3-4-5-7-6-7-8-11-12-13-14) à100%				

The comparative analysis of the p-median (p = 2) scenarios highlights clear differences in performance among site combinations under varying demand levels and capacity configurations. Overall, combinations involving the ArcGIS-identified site and Thyna consistently achieve the lowest transportation costs, while maintaining acceptable utilization rates. These scenarios exhibit stable behavior across all demand, indicating strong robustness with respect to demand variability.

Scenarios combining ArcGIS and Agueréb result in moderate transportation costs, reflecting reasonable spatial coverage but less favorable geographic proximity compared to Thyna-based combinations. While capacity utilization remains satisfactory, these configurations are generally less cost-efficient, especially under higher demand levels. In contrast, combinations involving Mahres, either paired with ArcGIS or Agueréb, consistently generate the highest transportation costs, despite often achieving full or near-full capacity utilization. This indicates that Mahres is geographically less suitable for minimizing transportation distances, even when cluster assignments are optimized.

Across all scenarios, increasing facility capacity from Q=60 to Q=80 reduces overall utilization rates but generally leads to lower or more stable transportation costs, suggesting improved flexibility in waste allocation. Moreover, imbalanced cluster configurations, for instance when one facility serves approximately 15 units of demand while the other serves about 45 units, tend to minimize transportation costs but result in uneven load distribution, whereas balanced configurations provide better operational equity at a slightly higher cost.

In summary, the results confirm that the ArcGIS–Thyna combination offers the best trade-off between cost efficiency, capacity utilization, and robustness, reinforcing the consistency between the GIS-based suitability analysis and the p-median optimization outcomes.



**Figure 4:** Distribution of Costs Per Site Combination

The figure 4 analysis reveals that the ArcGIS / Thyna combination is not only the most cost-effective scenario but also the most stable. It exhibits the lowest median cost and a narrow interquartile range, indicating that its performance remains consistent regardless of fluctuations in demand or variations in capacity allocation. In contrast, combinations involving Mahres or Agureb as primary hubs show significantly higher dispersion and numerous outliers, suggesting a high sensitivity to operational changes. Specifically, the Agureb / Mahres scenario shows the highest variance, making it a high-risk choice for long-term planning. Consequently, the ArcGIS / Thyna scenario is confirmed as the most robust configuration, offering predictable economic performance and minimizing the risk of budget overruns under peak demand conditions.

**Healthcare Waste Collection Routing Problem**

This section presents the healthcare waste collection routing problem, which focuses on the design of efficient vehicle routes to collect hazardous waste from multiple hospitals while respecting depot capacities and operational constraints. The problem is formulated as a Multi-Depot Vehicle Routing Problem (MDVRP), where selected treatment facilities serve as depots and each vehicle must return to its originating depot after completing its assigned route.

**Problem Description**

This study investigates a MDVRP applied to the collection of hazardous healthcare waste. Waste is generated by 16 geographically dispersed hospitals within the study area. Collection operations are conducted from multiple depots, which correspond to the optimal treatment sites previously selected through the location–allocation analysis, each with a depot capacity of  $Q = 60$ . Each depot operates a dedicated fleet of vehicles that depart from and return to the same depot after completing their assigned routes. The objective is to design cost-efficient vehicle routes that ensure the collection of waste from all healthcare facilities while satisfying known demand levels and vehicle capacity constraints. The problem aims to minimize the total transportation cost (or distance) while guaranteeing full service coverage and operational feasibility.

The distance matrices between ArcGIS-selected depots and hospitals, as well as inter-hospital distances, are adopted from Daoud et al. (2020). The following table presents the distances between the Thyna depot and the 16 hospitals considered in the study.

**Table 11:** Distance Matrix Between the Thyna Depot And Healthcare Facilities (Km)

Hospital	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Thyna depot	12	9.7	8.9	7.4	8	6.8	5.4	8.2	9	8	9	10	7.2	8.9	9.8	10.4

Table 11 reports the distances between the Thyna depot and the 16 healthcare facilities, extracted from the ArcGIS-based distance matrix. These distances are used as input parameters for the multi-depot vehicle routing model. The mathematical formulation of the MDVRP applied in this study follows the model proposed by Ouertani et al. (2023), which provides a robust framework for designing optimal routes while accounting for depot capacities, vehicle constraints, and service requirements.

**Computational Results**

This study adopts an exact solution approach implemented through the CPLEX solver to optimally resolve the proposed optimization problem.

**Table 12:** Results for The Exact Method

Demand	Loads	Total cost	CPU
D1	Route 1: 76.7%	57.3	604.54
	Route 2: 90%		
D2	Route 1: 83.3%	57.3	941.29
	Route 2: 80%		
D3	Route 1: 76.7%	57.3	602.62
	Route 2: 90%		
D4	Route 1: 83.3%	57.3	603.44
	Route 2: 80%		
D5	Route 1: 90%	57.3	602.61
	Route 2: 93.3%		

The analysis of vehicle loads shows that Route 1 utilizes between 76.7 % and 90 % of the maximum vehicle capacity, while Route 2 ranges from 80 % to 93.3 %. These values indicate a high level of vehicle utilization, ensuring an efficient allocation of fleet resources. However, certain routes, particularly Route 2 for D5 (93.3 %), are approaching full capacity, suggesting the need for monitoring in case of future demand increases.

The CPU time varies from 602.61 to 941.29 units, reflects the computational effort required to solve each demand optimally. The total transportation cost per demand remains stable (57.3 km) across all demands, demonstrating the robustness and efficiency of the exact model for the studied instances, despite variations in vehicle loads.

Overall, the results confirm that the MDVRP model provides optimal routing solutions that ensure full service coverage while respecting vehicle capacity constraints. This approach offers a powerful tool for planning hazardous healthcare waste collection, reducing transportation costs and maximizing vehicle utilization. These findings can assist decision-makers in resource allocation and fleet optimization for economically and environmentally sustainable waste collection operations.

## Conclusion

The current healthcare waste management situation in Sfax, Tunisia, is far from optimal, presenting significant environmental and health risks. This study demonstrates the effectiveness of combining GIS-based spatial analysis, a weighted p-median model, and Multi-Depot Vehicle Routing Problem (MDVRP) optimization to design a sustainable healthcare waste management system.

The GIS analysis identified suitable sites for incinerator placement by integrating environmental, economic, and social criteria, while the p-median optimization minimized transportation costs from hospitals to treatment facilities. Scenario-based evaluations revealed trade-offs between environmental suitability and operational efficiency: while the ArcGIS site achieved the highest overall suitability score, Thyna consistently minimized transportation costs, highlighting its logistical efficiency.

The integration of MDVRP further optimized waste collection routes from multiple healthcare facilities to the selected incinerator sites, ensuring all demand points are serviced within vehicle capacity constraints and providing robust cluster configurations against demand fluctuations. The results emphasize that careful capacity planning and route optimization are crucial for

sustainable and cost-effective healthcare waste management.

Future research should address multi-period demand modeling, uncertainty in waste generation, and the integration of environmental impact assessments, further enhancing the decision-making framework for hazardous waste treatment facility planning.

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