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Article

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Solving multi-objective facility location problem using the fuzzy analytical hierarchy process and goal programming: a case study on infectious waste disposal centers



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ABSTRACT

The selection of a suitable location for infectious waste disposal is one of the major problems in waste management. Determining the location of infectious waste disposal centers is a difficult and complex process because it requires combining social and environmental factors that are hard to interpret, and cost factors that require the allocation of resources. Additionally, it depends on several regulations. Based on the actual conditions of a case study, forty hospitals and three candidate municipalities in the sub-Northeast region of Thailand, we considered multiple factors such as infrastructure, geological and social & environmental factors, calculating global priority weights using the fuzzy analytical hierarchy process (FAHP). After that, a new multi-objective facility location problem model which combines FAHP and goal programming (GP), namely the FAHP-GP model, was tested. The proposed model can lead to selecting new suitable locations for infectious waste disposal by considering both total cost and final priority weight objectives. The novelty of the proposed model is the simultaneous combination of relevant factors that are difficult to interpret and cost factors, which require the allocation of resources.

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1. Introduction

Infectious waste disposal (IWD) remains an important problem affecting the social and medical domains of nearly every nation, and infectious waste (IW) is one kind of hazardous waste. This waste, which is generated in the diagnosis, treatment or immunization of human beings or animals, needs to be handled with careful consideration to prevent the spread of pathogens and to protect environmental health [1,2]. At present in Thailand, there are more than 37,000 medical institutions, and the amount of infectious waste is about 23,725 tons per year, while this waste is expected to increase by 5.5 percent per year [3]. Although public hospitals in Northeastern Thailand have their own incinerators to dispose of their waste, because of environmental concerns and protests by local residents, many incinerators inside hospitals have been shut down, and these hospitals finally need to use services from outside waste disposal agencies. Existing agencies are not able to dispose of existing infectious waste effectively. Consequently, building new, suitable facilities for IWD more effectively

is becoming an issue that is particularly important to consider. In the past, infectious waste disposal has caused many problems, such as illegal dumping and lack of hygiene, and community hospitals are one of the medical institutions that have often found common problems because they are far from the locations of service providers or outside waste disposal agencies. For this reason, local governments of Thailand have set up a policy to encourage the establishment of new disposal centers by integration of neighborhoods, in order to increase the efficiency of IWD. The new disposal centers must be compatible with the requirements of governmental regulations, and at the same time must reduce economic, environmental, health and social impacts. Legally, municipalities are responsible for IWD. Therefore candidate locations will be selected from possible locations to serve medical institutions in municipalities. Choosing suitable locations (disposal centers) for this case poses complex problems, because we must consider social, environmental, cost and geological impact. The disposal site must not cause damage to the biophysical environment and the ecology of the neighboring area. In this problem, the maximization of satisfaction level regarding relevant impact, such as social and environmental impact, is as important as minimization of total cost. The satisfaction level regarding relevant impact can be evaluated from various qualitative and quantitative aspects, such as infrastructure,

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geological, environmental and social etc. The higher the satisfaction level, the lower the probability that sites cause damage to the biophysical environment and the ecology of the neighboring area. Certainly, both perspectives of total cost and relevant impact definitely must be considered in designing an optimal location network.

From the literature reviewed, location selection for IWD centers is an issue with many relevant factors, including factors that are difficult to interpret, and cost factors that require simultaneous allocation of resources. In order to achieve an optimal location network, the fuzzy analytic hierarchy process (FAHP) is suitable for solving multi-criteria/objective decision making (MCDM) problems that are difficult to interpret, and goal programming (GP) is suitable for solving multi-objective problems that require allocation of resources. Hence, choosing integrated FAHP and GP techniques (FAHP-GP model) to solve multi-objective facility location problems, while minimizing total cost and maximizing total location weight, are reasonable for use in this case. The multi-size location problem model (MSLP model) proposed in this study is different from the traditional facility location problem model (FLP model) because it can select both multiple sizes and locations simultaneously. In addition, the FAHP-GP model tries to minimize the total cost of the location network and maximize the satisfaction level of its stakeholders, under relevant constraints existing in the decision environment. Unlike the traditional FLP-based lowest total cost/minimum total distance, this can help the location network to reduce costs, increase efficiency and flexibility, and enhance the satisfaction level of stakeholders.

The rest of the paper is organized as follows. Section 2 is Related Literature. Section 3 is Methodology, Section 4 is Application of the proposed methodology and finally, Section 5 is the Conclusion.

2. Related literature

The facility location problem (FLP) has been studied for one hundred years, but formally it is accepted by all scientists that Alfred Weber's book of 1909 is the essential origin of this theory [4]. Traditional FLP involves taking the cost minimization as a single objective/criterion, using a mathematical model to solve a location network or transportation network (depots, customers and arcs) problem. The location network that incurs the minimum total distance or lowest total cost is regarded as an optimal solution. In traditional FLPs, many researchers [5–10] have often proposed cost/distance minimization as a single objective/criterion using mathematical techniques (heuristic and optimization techniques) for solving these problems. However, with some special problems, such as choosing places to dispose of hazardous waste, selecting sites for nuclear power plants, site selection for garbage disposal and location selection for IWD, location selecting locations for these problems are very important decisions because they are costly and difficult to reverse. The location selection problems in these cases are multi-criteria/objective decision making (MCDM) problems, namely multi-criteria/objective facility location problems (MCFLPs/MOFLPs), and the selection needs to consider the importance of relevant factors such as social responsibility and environmental awareness simultaneously. Consequently, one of the most essential difficulties in dealing with these problems is to find a suitable approach by which to evaluate these criteria.

In recent years, many techniques to solve MCDM problems have been proposed, including mathematical techniques (mathematical programming techniques and artificial intelligence techniques) and MCDM techniques. A group of researchers [11–16] have proposed mathematical techniques in order to deal with environmental restrictions, whereas another group [17–20] have often proposed MCDM techniques to solve MCDM problems that are difficult to

interpret. One MCDM technique often suggested for solving these complex problems is AHP, because it is a simple and powerful approach [21,22]. Due to the complexity of the decision-making environment and ambiguity of each problem, some researchers [23–29] have proposed using AHP-only or combined AHP-other techniques for solving MCDM problems, because considering only the cost aspect will not handle these problems effectively. AHP has been widely used in the MCDM process by academics and practitioners [30–32] over the last 20 years. Since AHP alone will not be able to handle existing environmental restrictions, some researchers have combined AHP with mathematical techniques, in order to deal with environmental restrictions simultaneously. Linear programming (LP) and goal programming (GP), mathematical programming techniques, are often combined with the AHP in the literature. The LP model is used to solve single objective problems, but the GP model has been developed to solve multi-objective problems. GP was studied by Charnes, Cooper and Ferguson in 1955 for solving unsolvable LPs. For example, some researchers [33–38] have constructed combined AHP-mixed LP models for solving a single objective decision making problem, and combined AHP-mixed GP model for solving multi-objective decision making problems. Although AHP is a popular tool to solve MCDM problems, conventional AHP cannot reflect the human thinking style. The conventional AHP method is difficult in that it applies an exact value to express the decision maker's opinions in a comparison of alternatives, and the AHP method is often criticized because of its use of an unbalanced scale of judgment, and its inability to adequately handle the inherent uncertainty and imprecision in the pair-wise comparison process [39]. Later, the fuzzy analytic hierarchy process (FAHP), based on the fuzzy set theory of Zadeh [40], was developed in order to overcome this weak point, and this technique is often used to replace conventional AHP to solve MCDM problems that are difficult to interpret. Hence, recently, many researchers have used FAHP to solve MCDM problems instead of traditional AHP [41–46]. Although FAHP is widely used to solve MCDM problems, there are few papers that report combined FAHP-mathematical techniques to solve MCDM under existing environmental restrictions. For example, He et al. [47] proposed a FAHP-LP model for the multi-criteria transshipment problem to maximize customer service level, while minimizing logistics costs at the same time. Kannan et al. [48] presented an integrated fuzzy multi criteria decision making method and GP approach for supplier selection and order allocation in a green supply chain. Also, Bakeshlou et al. [49] proposed evaluating a green supplier selection problem using a hybrid MODM algorithm, in order to effectively consider existing environmental restrictions.

In MCFLPs/MOFLPs, some researchers have recently proposed to use the FAHP for solving the FLPs in many ways. For example, Önüt et al. [50] proposed a combined fuzzy MCDM approach based on the FAHP and fuzzy TOPSIS techniques for selecting a suitable shopping center location. Nazari et al. [44] applied Chang's fuzzy AHP-based multiple attribute decision-making (MADM) method for selection of the best site for landfills. Choudhary and Shankar [51] proposed the STEEP-fuzzy AHP-TOPSIS framework for evaluation and selection of thermal power plant locations. Safari, Faghih, and Fathi [52] proposed a fuzzy approach for selection of facility locations using technique for order preference by similarity to ideal solution (TOPSIS) method. Recently, Ozgen and Gulsun [53] proposed a combined probabilistic linear programming and fuzzy AHP for solving the multi-objective capacitated multi-facility location problem. Safari, Soufi and Aghasi [54] proposed the hybrid fuzzy MCDM approach (Hybrid of F-DELPHI, F-AHP, F-LLSM and F-PROMETHEE) and applied it to select the location for a Hypermart. Hanine et al. [55] proposed the comparison of the fuzzy TODIM and fuzzy AHP methods for landfill location selection.

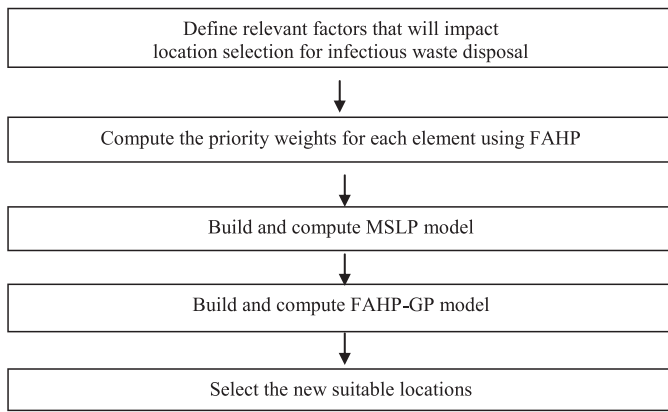


Fig. 1. The steps of the study process.

Although the FAHP is widely used at present, the application of this technique to solve MOFLPs is complex, depending on the nature of each problem. For this reason, choosing the appropriate technique will enhance the confidence of decision makers for selecting a suitable location network, by considering cost and environmental impact under available resources limitations.

According to the above literature review, the traditional FLP model is needed to improve decision making on location selection for the IWD problem. GP is used to solve multi-objective problems in the literature, and FAHP has often been used to solve MCDM problems which are difficult to interpret. In fact, FAHP cannot deal with the environmental restrictions of this problem. Hence, choosing the FAHP and GP techniques are reasonable in this case, because quantitative and qualitative objectives, under the limited resources available, should be included to achieve maximum stakeholder satisfaction with minimum total cost. Consequently, this article presents a new multi-objective model for location selection for IWD centers, namely the FAHP-GP model, which differs from the literature, in order to take advantage of the strengths of the methods detailed in the literature, while overcoming their weaknesses.

3. Methodology

The paper offers two methodologies for the selection of new suitable locations for IWD. The FAHP is presented first as a stand-alone methodology and then an integrated FAHP and GP model is presented as an extension for considering additional criteria in a new multi-objective facility location problem. The location selection process should have a model that is flexible and applicable to this case study, and the model should be able to respond to complex goals, both qualitative and quantitative. Therefore, this article presents several goals to be satisfied: cost and other relevant goals. Details of the conceptual framework are shown in Fig. 1.

The first step is to define relevant factors in order to select candidate locations. The selection of the new suitable locations for IWD from the candidate locations is made using legislation, regulation and expertise. For example, in Thailand, all municipality locations of will first be considered based on Thai legislation and encouragement of government policy. After that, locations that comply with Thai legislation and government policy will also be considered based on the regulations of each local government. Finally, experts will define relevant factors that impact location selection for IWD and then they will select candidate locations. There are important factors or general factors that impact the selection of new suitable locations in both Thailand and other nations. For example, total cost includes land, transportation, installation and maintenance cost. Infrastructure factors often include public utili-

ties and convenience to traffic systems. Geological factors often refer to area size of candidate locations, features of area, flooding in the past, and social & environmental factors often refer to population density, municipal administrators, capability of municipalities, distance from communities and distance from public water resources. The second step is to compute the priority weights for each element using FAHP. A high priority weight means that it is better than a low priority weight. The third step is to build and compute the multi-size location problem model (MSLP model) for IWD. The proposed model can be applied to solve the multi-size location problem using an optimization technique, differing from the literature. Another step is to build and compute a new FAHP-GP model. The priority weights of candidate locations using FAHP will be taken as input into the GP model as an extension in order to consider additional criteria in this problem. The final step is to select a new suitable location network for IWD, based on the optimal solution of the FAHP-GP model.

3.1. FAHP

There have been many different techniques for MCDM problems that are difficult to interpret, such as the Analytic Hierarchy Process (AHP) [18], Analytic Network Process (ANP) [56], Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [57] and Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) [58]. One traditional MCDM tool often suggested for solving complex problems is AHP, because it is a simple and powerful technique [21,22]. However, AHP has the weakness, that it cannot reflect the human thinking style. Later, Laarhoven and Pedrycz [59] proposed the Fuzzy Analytic Hierarchy Process (FAHP), in 1983, which was an application of the combination of AHP and the fuzzy set theory of Zadeh [40]. The FAHP was developed in order to overcome the weak points of AHP, and nowadays this contemporary tool is often used to solve MCDM problems which are difficult to interpret, instead of the traditional AHP. Hence, in this case study, the FAHP will be proposed in this section in order to define the global priority weights of each candidate location.

In this paper, Triangular Fuzzy Numbers (TFNs) are used to evaluate priority weights with fuzzy arithmetic operations, which are shown in Eqs. (1–5). Let $\tilde{A} = \{\tilde{a}_{ij}\}$ be the TFN judgment matrix containing all pair-wise comparisons between each criterion i and each alternative j . \tilde{A} can be defined by Eq. (1).

$$\tilde{A} = \begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & \tilde{a}_{nn} \end{bmatrix}, i \in \{1, 2, \dots, n\}, j \in \{1, 2, \dots, n\} \tag{1}$$

where $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ is TFN and l_{ij}, m_{ij} and u_{ij} are the least possible value, modal value and highest possible value respectively. The fuzzy arithmetic operations on TFN can be expressed as follows:

$$\text{Addition : } F_1 \oplus F_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{2}$$

$$\text{Multiplication : } F_1 \otimes F_2 = (l_1 \cdot l_2, m_1 \cdot m_2, u_1 \cdot u_2) \tag{3}$$

$$\text{Division : } F_1 / F_2 = (l_1 / u_2, m_1 / m_2, u_1 / l_2) \tag{4}$$

$$\text{Reciprocal : } F_1^{-1} = (1/u_1, 1/m_1, 1/l_1) \tag{5}$$

In this paper, TFN will be applied in order to compare a priority scale between each criterion i and each alternative j as shown in Table 1.

Table 1
The 9 - point scale of FAHP.

TFN	Definition
(1,1,1)	Equal importance
(2,3,4)	Moderate importance
(4,5,6)	Strong importance
(6,7,8)	Very strong importance
(8,9,9)	Extreme importance
$\bar{2}, \bar{4}, \bar{6}, \bar{8}$	Intermediate values between the two adjacent judgments

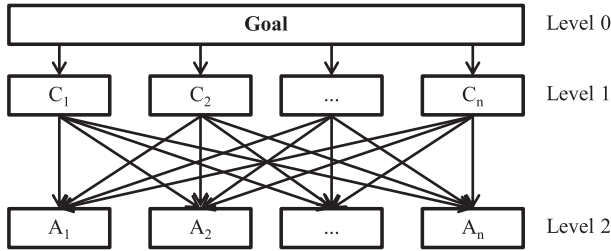


Fig. 2. Multi-level hierarchy for location selection.

Like the classical AHP, in this paper, the steps of the FAHP are as follows:

- Construct the hierarchy

To define relevant factors, the n decision factors can be defined by asking questions of experts or decision makers, about which criterion is more important with regard to the goal. The problem will be decomposed into a multi-level hierarchy. In Fig. 2, the hierarchical structure is based upon the traditional AHP Methodology. At level “0”, the goal is to select new suitable locations. At level “1”, the main criteria are C_1, C_2, \dots, C_n , and at level “2”, the alternatives are location 1 (A_1), location 2 (A_2) and location n (A_n).

- Construct the comparison matrices of each decision maker

The answers for each decision maker k can be constructed using pair-wise comparison matrices as follows:

$$\tilde{A}_k = \begin{bmatrix} \tilde{a}_{11k} & \tilde{a}_{12k} & \dots & \tilde{a}_{1nk} \\ \tilde{a}_{21k} & \tilde{a}_{22k} & \dots & \tilde{a}_{2nk} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1k} & \tilde{a}_{n2k} & \dots & \tilde{a}_{nnk} \end{bmatrix}, k = 1, 2, \dots, K \quad (6)$$

where \tilde{A}_k are fuzzy pair-wise comparison matrices for each decision maker k, and K is the number of decision makers.

- Combine the comparison matrices of each decision maker

The pair-wise comparison matrices can be aggregated with the fuzzy geometric mean method and can be defined by Eq. (7) [60],

$$\tilde{G} = \left(\prod_{i=1}^K \tilde{a}_{ijk} \right)^{1/K} = \begin{bmatrix} \tilde{g}_{11} & \tilde{g}_{12} & \dots & \tilde{g}_{1n} \\ \tilde{g}_{21} & \tilde{g}_{22} & \dots & \tilde{g}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{g}_{n1} & \tilde{g}_{n2} & \dots & \tilde{g}_{nn} \end{bmatrix} \quad (7)$$

where \tilde{G} is the aggregated comparison matrix.

- Estimate priority weights of each level

After aggregation of the pair-wise comparison matrices, the aggregated matrix will be normalized with Eq. (8).

$$Nor(\tilde{G}) = \begin{bmatrix} \frac{\tilde{g}_{11}}{\sum_{i=1}^n \tilde{g}_{i1}} & \frac{\tilde{g}_{12}}{\sum_{i=1}^n \tilde{g}_{i2}} & \dots & \frac{\tilde{g}_{1n}}{\sum_{i=1}^n \tilde{g}_{in}} \\ \frac{\tilde{g}_{21}}{\sum_{i=1}^n \tilde{g}_{i1}} & \frac{\tilde{g}_{22}}{\sum_{i=1}^n \tilde{g}_{i2}} & \dots & \frac{\tilde{g}_{2n}}{\sum_{i=1}^n \tilde{g}_{in}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\tilde{g}_{n1}}{\sum_{i=1}^n \tilde{g}_{i1}} & \frac{\tilde{g}_{n2}}{\sum_{i=1}^n \tilde{g}_{i2}} & \dots & \frac{\tilde{g}_{nn}}{\sum_{i=1}^n \tilde{g}_{in}} \end{bmatrix} \quad (8)$$

After that, the priority weights of each level can be defined by calculating the mean of each row i of the normalized matrix, as shown in Eq. (9). The fuzzy priority weights are TFN, which can be converted to crisp priority weights using Eq. (10) [61].

$$\tilde{W}_i = \begin{bmatrix} \tilde{w}_1 \\ \tilde{w}_2 \\ \vdots \\ \tilde{w}_n \end{bmatrix} = \begin{bmatrix} \left[\frac{\tilde{g}_{11}}{\sum_{i=1}^n \tilde{g}_{i1}} + \frac{\tilde{g}_{12}}{\sum_{i=1}^n \tilde{g}_{i2}} + \dots + \frac{\tilde{g}_{1n}}{\sum_{i=1}^n \tilde{g}_{in}} \right] / n \\ \left[\frac{\tilde{g}_{21}}{\sum_{i=1}^n \tilde{g}_{i1}} + \frac{\tilde{g}_{22}}{\sum_{i=1}^n \tilde{g}_{i2}} + \dots + \frac{\tilde{g}_{2n}}{\sum_{i=1}^n \tilde{g}_{in}} \right] / n \\ \vdots \\ \left[\frac{\tilde{g}_{n1}}{\sum_{i=1}^n \tilde{g}_{i1}} + \frac{\tilde{g}_{n2}}{\sum_{i=1}^n \tilde{g}_{i2}} + \dots + \frac{\tilde{g}_{nn}}{\sum_{i=1}^n \tilde{g}_{in}} \right] / n \end{bmatrix} \quad (9)$$

$$df\tilde{a}_{ij} = [(u_{ij} - l_{ij}) + (m_{ij} - l_{ij})] / 3 + l_{ij} \quad \forall i, \forall j \quad (10)$$

- Check for CR values

\tilde{W} is defined by Eq. (11). After that, using Eq. (10), the crisp numbers of \tilde{W} can be defined by Eq. (12).

$$\tilde{W}_i = \begin{bmatrix} \tilde{w}_1 \\ \tilde{w}_2 \\ \vdots \\ \tilde{w}_n \end{bmatrix} = \begin{bmatrix} (w_1 \times \tilde{g}_{11} + w_2 \times \tilde{g}_{12} + \dots + w_n \times \tilde{g}_{1n}) / w_1 \\ (w_1 \times \tilde{g}_{21} + w_2 \times \tilde{g}_{22} + \dots + w_n \times \tilde{g}_{2n}) / w_2 \\ \vdots \\ (w_1 \times \tilde{g}_{n1} + w_2 \times \tilde{g}_{n2} + \dots + w_n \times \tilde{g}_{nn}) / w_n \end{bmatrix} \quad (11)$$

$$\tilde{w}_i = df \begin{bmatrix} \tilde{w}_1 \\ \tilde{w}_2 \\ \vdots \\ \tilde{w}_n \end{bmatrix} = \begin{bmatrix} \tilde{w}_1 \\ \tilde{w}_2 \\ \vdots \\ \tilde{w}_n \end{bmatrix} \quad (12)$$

λ_{max} is computed using Eq. (13).

$$\lambda_{max} = \sum_{i=1}^n \tilde{w}_i / n \quad (13)$$

CI is computed using Eq. (14).

$$CI = (\lambda_{max} - n) / (n - 1) \quad (14)$$

CR is computed using Eq. (13), and RI is defined using Table 2

$$CR = CI / RI \quad (15)$$

A Consistency Ratio (CR) of 0.10 or less is accepted as a fine consistency measure. If the value exceeds 0.10, it should be revised.

Table 2
List of random index values.

n	2	3	4	5	6	7	8	9
RI(n)	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

- Compute the final priority weights for each alternative

The final priority weights are calculated by adding the weights per candidate and multiplying by the weights of the corresponding criteria. A final score is obtained for each candidate location. The best alternative is the maximum value of the final priority weight, and a high value for a priority weight means that it is better than a low priority weight.

3.2. MSLP model

The first theoretical study on the facility location problem began in 1909 when Alfred Weber introduced a warehouse location problem to minimize the total distance between a warehouse and a set of customers [62]. Daskin [63] classified discrete facility location problems into three categories: covering-based problems, median-based problems, and other problems. Covering-based problems are divided into three basic types: set covering problems, maximal covering problems, and p-center problems; see details in the literature [62,63]. This study aims to achieve lowest total cost, which is similar to set covering problems. Therefore, based on set covering problems, a location selection model was formulated to solve the location selection for infectious waste disposal in this case, with details are as follows.

The multi-size location problem model (MSLP model) is formulated to solve the optimization problem of K sizes of incinerators and multiple locations. The candidate municipalities are assumed to have enough space, budget and staffing, and the locations of the incinerators can be made anywhere within the candidate municipalities. Details of the mathematical model of this problem are shown below.

Indices:

- i is the index of each municipality, $i = 1, 2, \dots, m$, ($m = 3$).
- j is the index of each hospital, $j = 1, 2, \dots, n$, ($n = 40$).
- k is the size of each incinerator, $k = 1, 2, \dots, K$, ($K = 2$).

Parameters:

- f_k is facility cost (baht/day).
- o_k is operating cost (baht/day).
- c_{ij} is transportation cost between municipality i and hospital j (baht/day)
- dt_{ij} is actual distance between municipality i and hospital j (km).
- u is unit transportation cost (baht/km).
- s_k is the size of each incinerator i .
- d_j is the demand of hospital j (kg/day).

Decision variables:

- X_{ij} is a binary decision variable; $X_{ij} = 1$ if the hospital j is served by municipality i ; $X_{ij} = 0$ otherwise.
- Y_i is a non-negative integer decision variable; $Y_i = 1$ if municipality i is opened, $Y_i = 0$ otherwise.
- Z_{ik} is a binary decision variable; $Z_{ik} = 1$ if the municipality i is opened by selecting incinerator k , $Z_{ik} = 0$ otherwise.

Objective function:

$$Min.Z = \sum_{i=1}^m \sum_{k=1}^K f_k \cdot Z_{i,k} + \sum_{i=1}^m \sum_{k=1}^K o_k \cdot Z_{i,k} + \sum_{i=1}^m \sum_{j=1}^n u \cdot dt_{ij} X_{ij} \quad (16)$$

Constraints:

$$\sum_{i=1}^m X_{ij} = 1 \quad \forall j \quad (j = 1, 2, \dots, n) \quad (17)$$

$$\sum_{j=1}^n d_j \cdot X_{ij} \leq \sum_{k=1}^K s_k \cdot Z_{ik} \quad \forall i \quad (i = 1, \dots, m) \quad (18)$$

$$\sum_{i=1}^m \sum_{k=1}^K s_k \cdot Z_{i,k} \geq \sum_{j=1}^n d_j \quad (19)$$

$$\sum_{k=1}^K Z_{ik} = Y_i \quad \forall i \quad (i = 1, \dots, m) \quad (20)$$

$$X_{ij} \in \{0, 1\} \quad (21)$$

$$Y_i \in \{0, 1\} \quad (22)$$

$$Z_{i,k} \in \{0, 1\} \quad (23)$$

In this paper, the objective function of the MSLP model is to minimize total cost (facility cost, operating cost and transportation cost). Eq. (17) ensures that the demand of each hospital j is fulfilled. Eq. (18) ensures that the service prepared by a site cannot exceed its capacity. Eq. (19) ensures that the sum of the services provided by a site cannot exceed the sum of its capacities and Eq. (20) that the selected municipalities must use only k -size incinerators. Eqs. (21), (22) and (23) are binary. The optimal solution of this model can be solved by LINGO13.

3.3. FAHP-GP model

A new multi-objective facility location problem model which combines the fuzzy analytic hierarchy process and goal programming, namely the FAHP-GP model, is proposed to select new, suitable locations for infectious waste disposal. This proposed model is required to achieve the two main goals, lowest total cost and maximum weight, under the limits of available resources, at the same time. Traditional linear programming is used to solve only one single objective, minimization goal or maximization goal. In order to solve a multi-objective optimization problem, GP was developed in the early 1960s for such complex problems with multiple objectives. Moreover, GP can solve problems with non-homogeneous units of measure [25]. The FAHP provides the priority weights for each element i . The maximum final weight of FAHP is the best alternative for the relevant factors, but the minimum cost of candidate location is the best solution for the total cost factor. Therefore, in order to achieve the above goals simultaneously, the FAHP-GP model can be formulated to solve the problem. The objective can be written as Eq. (24), and Eqs. (17–23, 25) and Eq. (26) are the constraints of this model.

Deviation variables:

d_i^- , d_i^+ are vectors of under achievement and over achievement of target for each objective.

Additional parameters: w_i is the final priority weights of municipality i .

TC is the target for total cost (defined by total cost of the MSLP model).

w_{tc} is the objective's weight of total cost according to experts' opinions.

w_{FAHP} is the objective's weight of FAHP according to experts' opinions.

Objective functions of the FAHP-GP model:

$$min z = w_{tc} d_1^+ + w_{FAHP} d_2^- \quad (24)$$

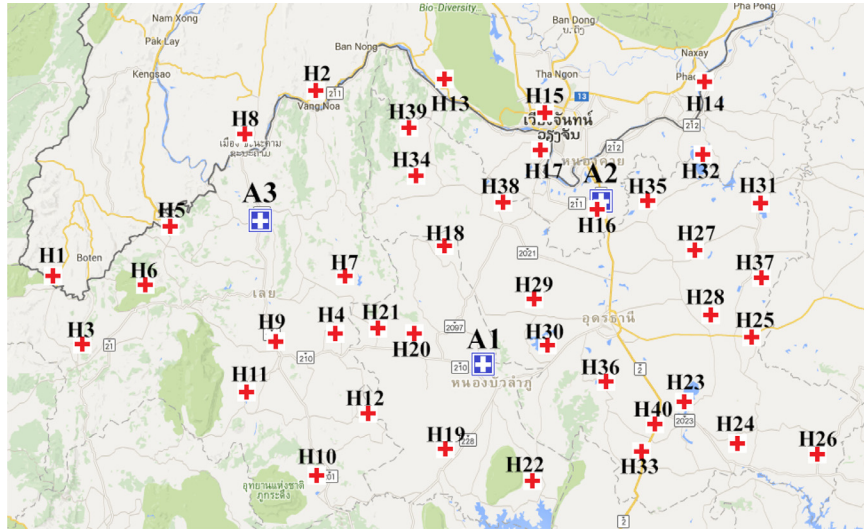


Fig. 3. The transportation network of the candidate locations and hospitals.

Constraints:

$$\sum_{i=1}^m \sum_{k=1}^K f_k Z_{i,k} / TC + \sum_{i=1}^m \sum_{k=1}^K o_k Z_{i,k} / TC + \sum_{i=1}^m \sum_{j=1}^K c_{ij} X_{ij} / TC + d_1^- - d_1^+ = 1 \tag{25}$$

$$\sum_{i=1}^m w_i Y_i + d_2^- - d_2^+ = 1 \tag{26}$$

The objective is the minimization of unwanted deviations, d_i^- , d_i^+ ; these deviations are deviation variables of under achievement and over achievement of targets for each objective. In these data, each objective has different units; therefore this paper has to normalize all units to 1. Like the MSLP model, the optimal solution of the FAHP-GP model can be solved by LINGO13.

4. Application of the proposed methodology

The methodology proposed in Section 3 was used to identify suitable locations (disposal centers) for IWD in sub-Northeastern Thailand, Nong Bua Lam Phu, Nong Khai, Loei and Udon Thani. Decision makers evaluated three candidate municipalities, namely Nong Bua Lam Phu (A1 or NLTM), Nong Khai (A2 or NKTM), and Loei (A3 or LTM), whereas Udon Thani is not a candidate municipality due to several limitations such as the suitable distance between the candidate area and communities, and the population density. New, suitable locations were selected from three candidate municipalities to serve forty community hospitals, namely H1, H2, ..., H40 (see details in Fig 3), given the resource restrictions and preferences. The steps of calculation are shown in Sections 4.1–4.3.

4.1. Calculate the final priority weights of each candidate alternative using FAHP

This section presents the steps to determine the priority weights of elements at each level. Firstly, a three-level hierarchical structure was constructed by consulting four decision makers, who have worked in the field for more than fifteen years, and stakeholders (see Fig. 4). In the hierarchy, level 1 was the objective, the new suitable location for infectious waste disposal, and level 2 was the relevant criteria. There were three criteria: infrastructure (C_1), geological (C_2) and environmental & social (C_3). Secondly, fuzzy

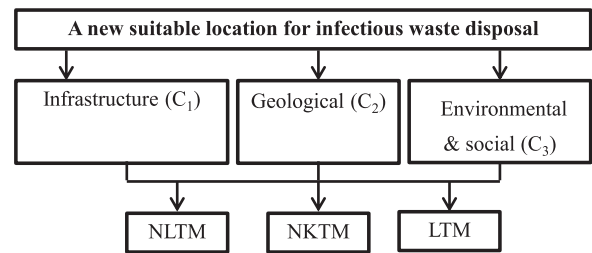


Fig. 4. A hierarchy for selecting locations for infectious waste disposal.

pair-wise comparison matrices were constructed from the four decision makers, using the 9 - point scale of FAHP, as shown in Table 3. Third, the fuzzy pair-wise comparison matrices of the decision makers were aggregated into a FAHP combined matrix (\tilde{C}) using Eq. (7), and the priority weights of level 1 were calculated using Eqs. (8)–(10), shown in Table 4. Finally, the local priority weights of level 2 and the final priority weights of level 3 were computed, as shown in Table 5 and Table 6 respectively.

4.2. Compute the optimal solution for infectious waste disposal with the MSLP model

To obtain the optimal solution for the lowest total cost, the MSLP model was used to solve the problem. The demand and real distance matrix of three candidate locations and forty hospitals are shown in Table 7 as d_j and dt_{ij} . The value of u is 4.3 baht/km. In Table 8, f_k ($k=1$ and $k=2$) are 1893 and 3485 baht per day, and o_k are 9870 and 18,644 baht per day respectively. The values of s_k are 400 and 800 kg per day. After that, LINGO13 was used, and the optimal solution is shown in Table 9.

4.3. Compute the suitable locations for infectious waste disposal using FAHP-GP model

After calculating the FAHP and MSLP model in Sections 4.1 and 4.2 respectively, in order to minimize the unwanted deviations d_1^+ , d_2^- in Eq. (23), we set $w_{TC} = 0.5$ and $w_{FAHP} = 0.5$ according to experts' opinions. The minimum total cost based on the MSLP model was substituted into Eq. (24) as the target of total cost (TC) in the FAHP-GP model. Similarly, the final priority weights (w_i) were substituted into Eq. (25), and the target of FAHP was equal to

Table 3
Comparison matrix of criteria with respect to goal from the four decision makers.

Goal	C1	C2	C3
C1	(1.00, 1.00, 1.00), (1.00, 1.00, 1.00) (1.00, 1.00, 1.00), (1.00, 1.00, 1.00)	(0.25, 0.33, 0.50), (0.17, 0.20, 0.25), (1.00, 1.00, 1.00), (2.00, 3.00, 4.00)	(0.11, 0.11, 0.13), (0.11, 0.11, 0.13), (0.13, 0.14, 0.17), (0.13, 0.14, 0.17)
C2	(2.00, 3.00, 4.00), (4.00, 5.00, 6.00), (1.00, 1.00, 1.00), (0.25, 0.33, 0.50)	(1.00, 1.00, 1.00), (1.00, 1.00, 1.00), (1.00, 1.00, 1.00), (1.00, 1.00, 1.00)	(0.13, 0.14, 0.17), (0.13, 0.14, 0.17), (0.13, 0.14, 0.17), (0.13, 0.14, 0.17)
C3	(8.00, 9.00, 9.00), (8.00, 9.00, 9.00), (6.00, 7.00, 8.00), (6.00, 7.00, 8.00)	(6.00, 7.00, 8.00), (6.00, 7.00, 8.00), (6.00, 7.00, 8.00), (6.00, 7.00, 8.00)	(1.00, 1.00, 1.00), (1.00, 1.00, 1.00), (1.00, 1.00, 1.00), (1.00, 1.00, 1.00)

Table 4
Combined comparison matrix of criteria with respect to goal.

Goal	C1	C2	C3	wc(i)	CR						
C1	1.00	1.00	1.00	0.54	0.67	0.84	0.13	0.14	0.16	0.10	0.03
C2	1.19	1.50	1.86	1.00	1.00	1.00	0.13	0.16	0.18	0.13	
C3	6.16	7.17	7.97	5.42	6.44	7.44	1.00	1.00	1.00	0.77	

Table 5
Combined comparison matrix of each location i with respect to criterion j.

C1	A1	A2	A3	wl(i,1)	CR						
A1	1.00	1.00	1.00	0.50	0.58	0.71	0.59	0.76	1.00	0.25	0.05
A2	1.41	1.73	2.00	1.00	1.00	1.00	0.71	0.76	0.84	0.36	
A3	1.00	1.32	1.68	1.19	1.32	1.41	1.00	1.00	1.00	0.39	
C2	A1	A2	A3	wl(i,2)							
A1	1.00	1.00	1.00	1.00	1.00	1.00	0.84	1.00	1.19	0.33	0.03
A2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.32	1.68	0.36	
A3	0.84	1.00	1.19	0.59	0.76	1.00	1.00	1.00	1.00	0.31	
C3	A1	A2	A3	wl(i,3)							
A1	1.00	1.00	1.00	2.00	3.00	4.00	2.38	3.41	4.43	0.61	0.06
A2	0.25	0.33	0.50	1.00	1.00	1.00	0.71	0.76	0.84	0.18	
A3	0.23	0.29	0.42	1.19	1.32	1.41	1.00	1.00	1.00	0.21	

Table 6
All priority weights for each level.

wc(i)	CR	wl(i,j)	CR	w(i)	
wc(1)=	0.10	0.03	wl(1,1)= 0.25, wl(2,1)= 0.36, wl(3,1)= 0.29	0.05	0.54
wc(2)=	0.13	0.03	wl(1,2)= 0.33, wl(2,2)= 0.36, wl(3,2)= 0.31	0.03	0.22
wc(3)=	0.77	0.06	wl(1,3)= 0.61, wl(2,3)= 0.18, wl(3,3)= 0.21	0.06	0.24

1. Like the MSLP model, Eqs. (17)–(23) were the same constraints for this model. After that, LINGO13 was used, and the optimal solution was compared with FAHP-only and MSLP models, as shown in Table 10.

As seen in Table 10, based on the FAHP method, the results show that A1 and A3, namely Nongbua Lamphu Town Municipality and Loei Town Municipality, were the selected locations. The final priority weights of A1 and A3 are 0.54 and 0.24, respectively, and the total cost is 40,242.25 baht/day. Next, based on the MSLP model, A1 and A2, namely Nongbua Lamphu Town Municipality and Nong Khai Town Municipality, were selected by consideration of the minimum total cost, about 37,913 baht/day. The final priority weights of A1 and A2 are equal to 0.54 and 0.22, respectively. Finally, the FAHP-GP model was formulated to solve this problem because this model can be considered as multi-objective at the same time. Like the MSLP model, the results show that the suitable candidate municipalities were A1 and A2. It can decrease the total cost by selection of FAHP-only by about 2329 baht/day. Although the weight of A2 was slightly lower than the weight of A3 (selected by

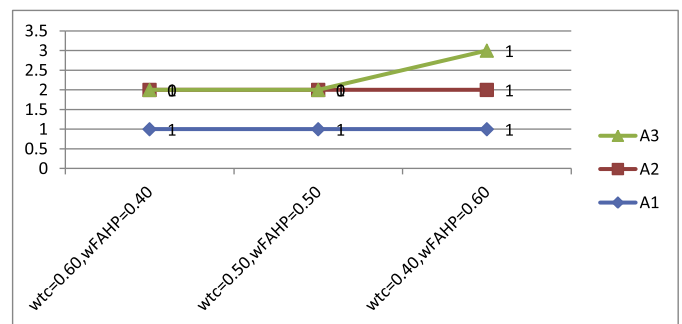


Fig. 5. Sensitivity analysis of locations for different values of w_{tc} , w_{FAHP} .

FAHP-only, A1 and A3), by about 0.02, the total cost objective was achieved using the new proposed model. Therefore, this model can lead to the selection of new suitable locations for infectious waste disposal by considering both tangible factors and intangible factors simultaneously. Moreover, the proposed model is realistic and feasible, since it considers resource limitations that need to be solved in the location selection problem.

The sensitivity analysis of the FAHP-GP model was also performed for different levels of objective weights. The sensitivity analysis is conducted to evaluate the influence of objective weights on the MOFLP. The results are summarized in Table 11 and Figs. 5–7. It can be seen that by increasing w_{tc} and decreasing w_{FAHP} at the same time, the total cost goal has a decreasing trend (minimum total cost). On the other hand, it can also be seen that by decreasing w_{tc} and increasing w_{FAHP} at the same time, the number of locations and total cost have an increasing trend. Finally, the solutions from the sensitivity analysis for different values of objec-

Table 7
Resource data for the MSLP model.

ID.	Hospital name	NLTM (A1)	NKTM (A2)	LTM (A3)	Amount of infectious waste (kg/day)
H1	Nahaeo	190.00	275.00	128.00	11.50
H2	Pakchom	187.00	162.00	71.00	25.50
H3	Dansai	168.00	253.00	106.00	50.00
H4	Erawan	55.70	140.00	61.90	17.00
H5	Tha Li	156.00	240.00	122.00	21.00
H6	Phurua	132.00	216.00	69.30	8.00
H7	Na Duang	65.00	150.00	52.30	13.00
H8	Chiang Khan	148.00	202.00	31.20	15.00
H9	Wang Saphung	78.40	163.00	44.30	30.00
H10	Phu Kradung	94.40	168.00	96.40	15.50
H11	Phu Luang	102.00	187.00	70.00	16.00
H12	Pha Khao	78.60	148.00	98.50	15.00
H13	Sangkhom	142.00	99.00	134.00	16.00
H14	Phon Phisai	154.00	75.40	264.00	31.00
H15	Si Chiang Mai	103.00	60.20	173.00	15.00
H16	Sakhrui	89.60	6.00	200.00	7.00
H17	Tha Bo	102.00	44.00	192.00	31.00
H18	Suwannakhuha	53.00	102.00	145.00	19.00
H19	Si Bun Rueang	40.70	114.00	154.00	36.50
H20	Na Klang	26.80	111.00	90.70	31.00
H21	Na Wang	43.90	125.00	76.40	13.00
H22	Non Sang	55.60	129.00	169.00	15.00
H23	Kumphawapi	95.70	82.00	209.00	11.50
H24	Si That	120.00	106.00	233.00	25.00
H25	Chai Wan	109.00	89.50	222.00	50.00
H26	Wang Sam Mo	147.00	134.00	261.00	17.00
H27	Phibun Rak	94.00	47.50	207.00	21.00
H28	Nong Han	90.20	70.80	204.00	8.50
H29	Kut Chap	52.10	81.80	166.00	13.00
H30	Nong Wua So	27.00	61.70	140.00	15.50
H31	Ban Dung	138.00	71.50	251.00	30.00
H32	Sang Khom	124.00	49.00	237.00	15.50
H33	Non Sa-at	107.00	93.30	220.00	16.00
H34	Nam Som	80.90	95.70	83.90	15.00
H35	Phen	96.10	21.20	209.00	16.50
H36	Nong Saeng	81.60	81.20	195.00	31.00
H37	Thung Fon	121.00	101.00	231.00	15.00
H38	Ban Phue	95.70	82.00	209.00	7.00
H39	Na Yung	120.00	106.00	233.00	31.00
H40	Huai Koeng	109.00	89.50	222.00	6.00
	Total	4074.00	4633.30	6281.90	795.50

Table 8
Expense details.

Expense details (baht/day)	Incinerator size (kg/day)	
	400	800
1. Facility cost		
1.1 Incinerator	274	548
1.2 Landfill	68.5	137
1.3 Storage	986	1973
1.4 Infectious waste tank	246.5	493
1.5 Cleaning system	16.5	33
1.6 Emergency generator	301	301
Total facility cost (baht/day)		
2. Operating cost per day	1893	3485
2.1 Labor cost	7289.5	14,579
2.2 Maintenance costs (6% of incinerator)	164.5	329
2.3 Cost of air pollution measurement	1096	1096
2.4 Cost of IWD (3.3 Baht/kg)	1320	2640
Total operating cost (baht/day)	9870	18,644

Table 9
Optimal solution of MSLP model.

Opened location	Size of location (kg/day)	Hospitals
NBTM or A1	400	H1, H3, H4, H5, H6, H7, H8, H9, H10, H11, H12, H18, H19, H20, H21, H22, H23, H26, H29, H30, H34
NKTM or A2	400	H2, H13, H14, H15, H16, H17, H24, H25, H27, H28, H31, H32, H33, H35, H36, H37, H38, H39, H40
Objective value	37,913.37 baht/day	

tive weights were offered to the six decision makers. The decision makers confirmed that these locations (A1 and A2) are appropriate as new locations for IWD, and they believed that our work can provide essential support for decision makers in the assessment of IWD problems, in this case study and other areas of Thailand.

Table 10
Comparison of FAHP, MSLP and FAHP-GP models.

Location (L(i))	Final priority weights (W _i)	FAHP	MSLP model	FAHP-GP model
A1 (NBTM)	0.54	Selected	Selected	Selected
A2 (NKTM)	0.22	Not selected	Selected	Selected
A3 (LTM)	0.24	Selected	Not selected	Not selected
	Total cost (Baht/day)	40,242.25	37,913.37	37,913.37

Table 11
Sensitivity analysis for different values of objective weights.

	$w_{tc}=0.60,$ $w_{FAHP}=0.40$	$w_{tc}=0.50,$ $w_{FAHP}=0.50$	$w_{tc}=0.40,$ $w_{FAHP}=0.60$
A1	Selected (s(1)=400)	Selected (s(1)=400)	Selected (s(1)=400)
A2	Selected (s(1)=400)	Selected (s(1)=400)	Selected (s(1)=400)
A3	Not selected	Not selected	Selected (s(1)=400)
Total cost (Baht/day)	37,913.37	37,913.37	47,381.89
Total priority weights	0.76	0.76	1.00

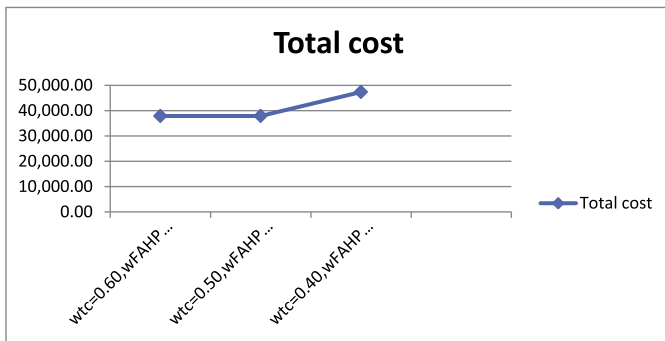


Fig. 6. Sensitivity analysis of total cost for different values of w_{tc} , w_{FAHP} .

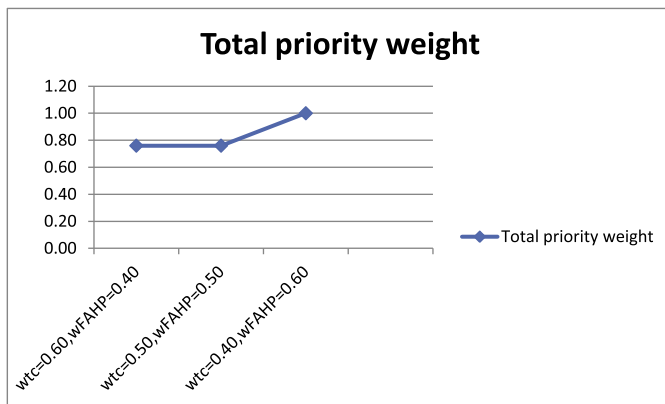


Fig. 7. Sensitivity analysis of total priority weight for different values of w_{tc} , w_{FAHP} .

5. Conclusion

This paper presents a new approach for choosing a suitable new location for infectious waste disposal. From several previous studies, a gap was found in the research because researchers solve the facility location problem for minimum cost or minimum distance using only quantitative objectives, without qualitative objectives. To solve this problem, the authors present a model to solve multi-objective problems with both quantitative and qualitative objectives. This model was tested with a case study, for forty hospitals and three candidate facilities, in sub-Northeastern Thailand. Firstly, the FAHP was used to define the priority weights of each element in a three level hierarchy. Secondly, the MSLP model was formulated to identify the size of incinerators and the optimal locations, and the optimal solution (minimum total cost) of the model was solved by LINGO13. Next, the FAHP-GP model (multi-objective model) was formulated to solve this complex problem; the priority weights of FAHP and the optimal solution of the MSLP model were included in the model. Finally, the optimal solution was computed by LINGO to select suitable locations for infectious waste disposal. The results show that A1 (NBTM) and A2 (NKTM) are the suitable locations. Even though for one selected location (A2), the final pri-

ority weight of A2 is slightly lower than the selection by FAHP, by about 0.02, the minimum total cost and suitable final priority weight was achieved using the FAHP-GP model. The major advantages of the proposed model are that it can guide the selection of a new suitable location under the multi criteria facility location problem, with quantitative and qualitative factors, and these factors are considered simultaneously. Therefore, it is believed that this approach should be more valuable and applicable than stand-alone optimization techniques and the stand-alone FAHP methodology.

The contribution of this research lies in the development of a new approach that is flexible and applicable by decision makers, to select suitable locations for infectious waste disposal under quantitative and qualitative criteria. This model is simple but powerful, and is a flexible model for decision makers to limit costs and environmental impact. The results from this model show that the model can guide the selection of the lowest cost location and effectively minimize the environmental impact. The advantage of this research is that decision makers can select the optimal location network and give significant weights as needed.

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