A Hybrid Multi-Criteria Analysis Model for Solving the Facility Location–Allocation Problem: A Case Study of Infectious Waste Disposal

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Abstract. Choosing locations for infectious waste disposal (IWD) is one of the most significant issues in hazardous waste management due to the risk imposed on the environment and human life. This risk can be the result of an undesirable location of IWD facilities. In this study a hybrid multi-criteria analysis (Hybrid MCA) model for solving the facility location–allocation (FLA) problem for IWD was developed by combining two objectives: total cost minimization and weight maximization. Based on an actual case of forty-seven hospitals and three candidate municipalities in the northeastern region of Thailand, first, the Fuzzy AHP and Fuzzy TOPSIS techniques were integrated to determine the closeness of the coefficient weights of each candidate municipality. After that, these weights were converted to weighting factors and then these factors were taken into the objective function of the FLA model. The results showed that the Hybrid MCA model can help decision makers to locate disposal centers, hospitals and incinerator size simultaneously. Besides that the model can be extended by incorporating additional selection criteria/objectives. Therefore, it is believed that it can also be useful for addressing other complex problems.

Keywords: *facility location–allocation problem; Fuzzy AHP; Fuzzy TOPSIS; infectious waste disposal; multi-criteria decision making.*

1 Introduction

Infectious waste is produced by hospitals during diagnosis, immunization, surgical procedures and treatment of patients and can transmit infections to hospital staff, attendants, and nearby public [1,2]. Improper infectious waste management leads to environmental pollution that may cause adverse health effects. Choosing suitable locations for the construction of IWD facilities is an important step for minimizing environmental hazards, pollution control and minimizing total cost.

In Thailand, governmental and public concern has arisen over insufficient treatment and disposal systems for infectious waste management. Major

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problems in infectious waste management are often found, such as delayed collection, illegal disposal in appropriate places and illegal dumping because the existing disposal facilities are insufficient to meet existing demand and this situation tends to worsen every year. Although some public hospitals in Thailand have their own incinerators to dispose of their infectious waste, many incinerators inside public hospitals have been shut down because of environmental concerns and protests by local residents. Hence, these hospitals have to rely on the services of outside waste management agencies [3]. However, serious problems are often connected to using the services of outside waste management agencies, such as delayed collection and illegal dumping in inappropriate places.

The Thai government is aware of these problems and has set policies to encourage the establishment of new facilities for IWD in potential areas of municipalities in order to address the abovementioned problems and increase the efficiency of infectious waste management. These facilities must be able to provide services to neighboring hospitals and at the same time reduce cost and social and environmental problems. Therefore, building new, suitable, disposal facilities is an issue that is particularly important to consider.

Community hospitals are often confronted with the aforementioned problems. Moreover, the existing IWD facilities are insufficient to cope with existing demand. Consequently, building new disposal facilities more effectively is an issue that it is particularly important to consider. At present, local government municipalities in Thailand are legally responsible for infectious waste disposal. Therefore, potential locations from existing municipalities must be selected for building new, suitable, disposal facilities. Choosing new suitable sites in this FLA problem is a complex problem that is difficult to tackle using existing techniques separately, because minimization of costs is as important as maximization of satisfaction level regarding relevant factors, such as social and environmental factors. All perspectives must be considered simultaneously in designing the location network.

Referring to the literature reviewed, the FLA problem for IWD is a multi-criteria decision making (MCDM) problem because there are several factors/criteria that must be considered together, including both tangible and intangible factors such as costs, social responsibility and environmental awareness. Choosing locations considering these special problems is a difficult process, because it requires combining several criteria and it also depends on various regulations. Therefore, one of the most important difficulties in addressing such complex problems is to select a suitable method for simultaneously evaluating complicated criteria. Traditionally, FLA models are single-objective linear programming (LP) models that minimize/maximize tangible factors but cannot simultaneously consider intangible factors in the objective. Hence, a traditional FLA model is needed: minimum total cost and maximum satisfaction of stakeholders. Undoubtedly, an LP model can be used to solve the first objective (minimum total cost), while the second objective could be addressed by a MADM tool. In order to combine the multiple objectives of the FLA model to a single-objective FLA model, a novel integrated MCDM method [4] was used here because the combined method is simple but flexible and effective.

Fuzzy AHP is a well-known method for solving MADM problems. There are several reasons why this method was selected as a suitable tool in this study. It is a widely used MADM method [5] and one of its most important advantages is that it is based on pair-wise comparison and evaluates the inconsistency index. Another distinguishing feature of Fuzzy AHP is that it is a powerful tool for solving MADM problems that are difficult to interpret [6-10]. However, ranking in both AHP and Fuzzy AHP is rather imprecise.

A distinguishing feature of Fuzzy TOPSIS is that it is easy to understand and it can be used to rank the alternatives effectively [11]. Although there are many tools for solving MADM problems, Fuzzy AHP and Fuzzy TOPSIS are often recommended for this task [5,12,13]. In this case, the integration of Fuzzy AHP and Fuzzy TOPSIS is reasonable. Consequently, this article presents a new hybrid FLA model for infectious waste disposal in order to use the advantages of both methods while overcoming their weaknesses. Using this Hybrid MCA model is expected to enhance the confidence of decision makers in choosing suitable locations for infectious waste disposal by considering cost and environmental factors under available resource limitations.

The rest of this paper is organized as follows. Section 2, Section 3 and Section 4 discuss related literature, the proposed method and its application, respectively. Finally, Section 5 contains the conclusion.

2 Literature Review

The theory of location problems (LP) has been studied for many decades, but it is generally accepted that Alfred Weber's book *Theory of the Location of Industries* from 1909 is the historic origin of location science [14]. Location determination is often considered the most important strategic decision leading to the success of an organization. The process of choosing a facility location area can be divided into three branches: the facility location problem, the facility allocation problem, and the facility location–allocation (FLA) problem. The FLA problem consists of how to locate a set of new facilities such that the costs of transportation from facilities to customers is minimized and simultaneously how to select the optimal number of facilities to be placed in an area of interest in order to satisfy customer demand [15]. The concept of the FLA problem was initially proposed by Cooper [16]. Since then the FLA problem has received attention from many researchers [17-19] and has been considered in a number of various ways (heuristic and exact techniques). Many FLA problems have been studied, such as two-echelon inventory allocation and distribution center location analysis [20]; hierarchical maximal-coverage location–allocation: a case of generalized search-and-rescue [21]; a location–allocation heuristic for the capacitated multi-facility Weber problem with probabilistic customer locations [22]; and multi-source facility location–allocation and inventory problem [23].

Unfortunately, some special FLA problems, such as selecting disposal sites for hazardous waste, choosing sites for nuclear power plants and location selection for waste disposal, cannot be addressed using a cost-based model alone. These problems are multi-criteria decision making (MCDM) problems because there are several criteria and various regulations that must be considered together. Although FLA theory has a long history in single-objective problems, since the origin of MCDM theory in management sciences, the MCDM theory and location theory have been integrated for application in real-world complex problems of location selection in many ways [24-26].

FLA problems can be divided into single-objective/criterion FLA problems and multi-criteria/objective FLA problems. Although there are many tools to address multi-objective optimization problems, a Fuzzy AHP-based integer linear programming model for solving the multi-criteria transshipment problem has been proposed by He, *et al.* [4]. This model provides several novel insights into how to combine the multiple objectives of a transshipment model to a single-objective transshipment model by using a novel integrated MCDM method. The combination method is simple but flexible and effective.

MCDM problems are divided into multi-objective decision making (MODM) and multi-attribute decision making (MADM) problems. The MODM problem is a multi-objective problem that is often solved by optimization techniques, whereas the MADM problem is often difficult to interpret, with a limited number of predetermined alternatives and a single objective. Although there are many tools to address MADM problems, such as Analytic Network Process (ANP) [27], Analytic Hierarchy Process (AHP) [28] and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [29], these traditional MADM tools do not reflect the style of human thinking. Moreover, it is difficult to apply an exact value to express the decision maker’s opinion in a comparison of alternatives and traditional tools are often criticized because they use an unbalanced scale of judgments. Later, the fuzzy set theory of Zadeh [30] has been integrated with traditional MADM tools in order to overcome this weak point. These contemporary tools have often been used to replace traditional MADM tools to solve complex problems [31-33].

As mentioned above, Fuzzy AHP and Fuzzy TOPSIS are often recommended to solve this type of problems [5,12,13]. Fuzzy AHP has the following advantages: (1) the consistency of the evaluation procedure can be measured; (2) it is applicable for quantitative and qualitative factors; (3) it can easily be calculated by most managers [6-9,34,35]. However, Fuzzy AHP also has disadvantages: (1) consistency is difficult to achieve when there are too many criteria and alternatives; (2) the ranking of the Fuzzy AHP method is rather imprecise.

Fuzzy TOPSIS has the following advantages: (1) it can measure the distance between alternative solutions and the ideal solution; (2) it can obtain the result that is closest to the ideal solution; (3) it is easy to use and understandable [11]. Hence, a combination of the advantages of each technique (Fuzzy AHP and Fuzzy TOPSIS) can overcome their weaknesses to solve the above issues, which is potentially capable of solving MADM problems.

Because of the weaknesses of MADM tools that cannot handle the limitations of existing resources, a group of researchers [36-39] have proposed using combined MADM tools and mathematical models to solve complex problems that require allocating resources simultaneously. An optimization model is a powerful tool to solve location selection problems according to [40] and [41]. Furthermore, the combined Fuzzy AHP–Fuzzy TOPSIS method is a powerful, flexible and potentially capable technique for solving MADM problems according to [10] and [11]. Hence, the combined fuzzy AHP–fuzzy TOPSIS method with an optimization model is expected to be more beneficial than using either method individually. One of the main advantages of this hybrid method is that it is able to simultaneously evaluate the effects of relevant factors in realistic situations.

3 Proposed Method

This paper presents a new hybrid MCA model combining three techniques for solving the FLA problem of infectious waste disposal. First, the combined Fuzzy AHP–Fuzzy TOPSIS method as a method for evaluating the weights of each candidate location is presented and then the combined Fuzzy AHP–Fuzzy TOPSIS–FLA model, called the Hybrid MCA model, is presented as an extension for considering additional criteria in the FLA problem. Details of the conceptual framework are shown in Figure 1.

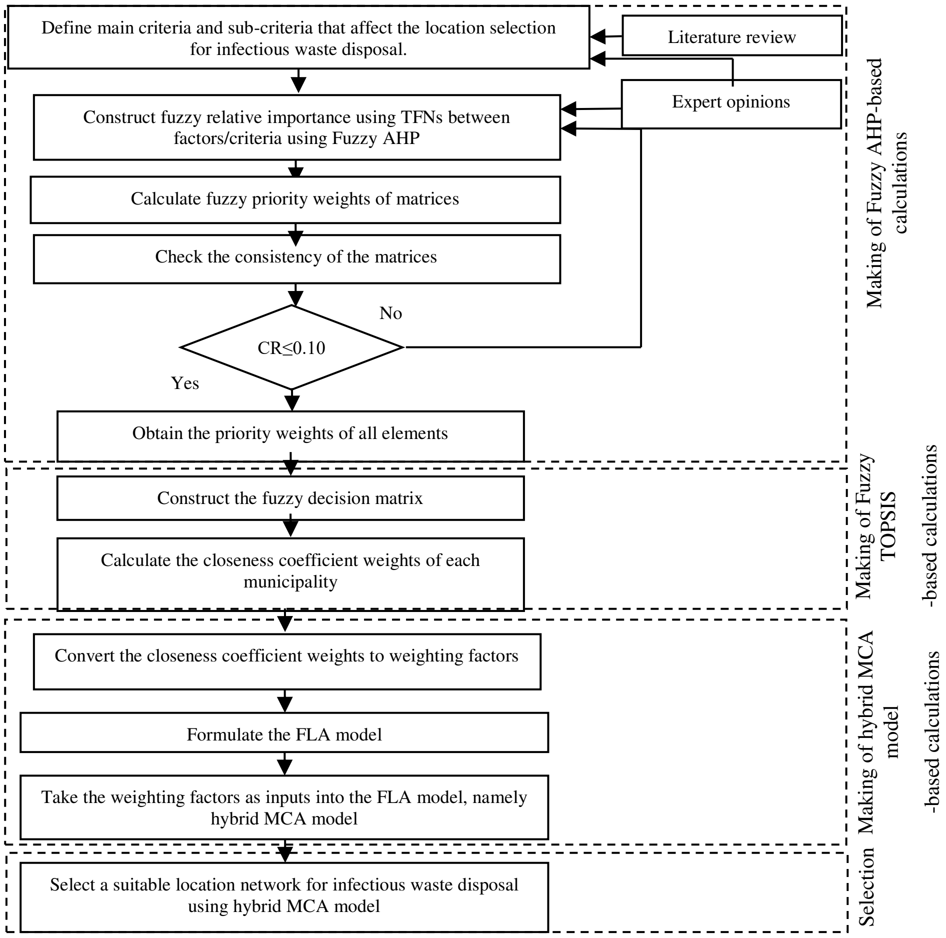

Figure 1 The conceptual frame work of the proposed method.

3.1 Fuzzy Set Theory

Fuzzy set theory was first introduced by Zadeh [30] to deal with problems involving uncertainty and vagueness. Applications of fuzzy set theory can be found in fields such as computer science, engineering, operation research, control theory and management sciences, etc. In this paper, the triangular fuzzy number for pair-wise comparison is illustrated as a triplet (*a, b, c*), as shown in Figure 2.

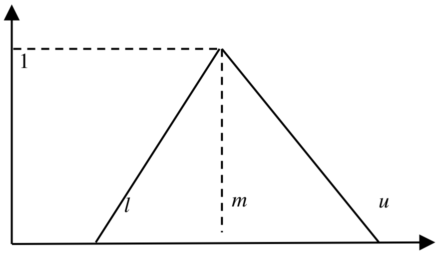

Figure 2 Membership function of a triangular fuzzy number.

where *l, m* and *u* are the least possible value, mode value and highest possible value for each criterion, and $\mu(x)$ is a membership function defined by Eq. (1):

$$\mu(x) = \begin{cases} (x-l)/(m-l) & ,l \le x \le m \\ (u-x)/(u-m) & ,m \le x \le u \\ 0 & ,otherwise \end{cases} \tag{1}$$

3.2 Fuzzy AHP

AHP, introduced by Saaty [42,43], is a useful and practical tool that provides the ability to incorporate both qualitative and quantitative criteria in the decision making process. However, it is generally criticized because of the use of a discrete scale of 1-9 that cannot handle the uncertainty and ambiguity present in deciding the priorities of different attributes [44].

Fuzzy AHP has been widely used to solve MADM problems in many fields. In this paper, the priority weights of each element will be calculated with the same method as used by Wichapa in [7].

3.3 Fuzzy TOPSIS

3.3.1 Constructing the Fuzzy Decision Matrix

Given *m* alternatives, *n* sub-criteria, a typical fuzzy multi-criteria group decision making problem can be expressed in matrix format as in Eq. (2):

$$D = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \end{array} \tag{2}$$

where $A_1, A_2, \ldots, A_m$ are the alternatives to be chosen, $C_1, C_2, \ldots, C_n$ denote the evaluation sub-criteria, $\tilde{x}_{ij}$ represents the fuzzy rating of alternative A_i with respect to criterion C_j. In this study, the fuzzy rating of each alternative i with respect to the each criterion j is determined by adding the weights per location multiplied by weights of the corresponding sub-criteria.

3.3.2 Normalizing the Fuzzy Decision Matrix

This step transforms various attribute dimensions into non-dimensional attributes, which allows comparison across criteria. If $\tilde{R}$ denotes the normalized fuzzy decision matrix, then it gets Eq. (3).

$$\tilde{R} = \left[\tilde{r}_{ij}\right] \quad i = 1,2,\ldots,m; j = 1,2,\ldots,n \tag{3}$$

where $\tilde{r}_{ij}$ defined in Eqs. (4) and (5):

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right) \; and \;\; c_j^* = \max(c_{ij}) \;\; (for\, benefit\, criteria) \tag{4}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right) \; and \; a_j^- = \min(a_{ij}) (for\, \cos t\, criteria) \tag{5}$$

3.3.3 Constructing the Weighted Normalized Decision Matrix

The weighted normalized decision matrix $\tilde{V}$ is defined in Eq. (6) as:

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{mxn} \tag{6}$$

$$\tilde{v}_{ij} = \tilde{w}_j \otimes \tilde{r}_{ij} \tag{7}$$

where $\tilde{w}_j$ in Eq. (7) represents the fuzzy weights of criteria from using the Fuzzy AHP technique.

3.3.4 Determining the Fuzzy Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS)

Because the positive triangular fuzzy numbers are included in interval [0, 1], the fuzzy ideal solution (*FPIS*, A^+) and fuzzy negative ideal solution (*FNIS*, A^-) can be defined in Eq. (8) as:

$$A^+ = \left(\tilde{v}_1^+, \tilde{v}_2^+, \ldots, \tilde{v}_n^+\right), \;\; A^- = \left(\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^-\right) \tag{8}$$

where $\tilde{v}_j^+ = (1,1,1)$ and $\tilde{v}_j^- = (0,0,0),\ j = 1,2,3,...,n$

The distances d_i^+ and d_i^- of each alternative from *FPIS* and *FNIS* can be derived respectively as in Eq. (9):

$$d_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^+), \qquad d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-) \tag{9}$$

If $\tilde{x} = (a_1, b_1, c_1)$, $\tilde{y} = (a_2, b_2, c_2)$ are two TFNs, then the distance between two TFNs can be calculated as:

$$d(\tilde{x}, \tilde{y}) = \sqrt{\frac{1}{3}[(a_1\text{-}a_2)^2 + (b_1\text{-}b_1)^2 + (\mathrm{c}_1\text{-}\mathrm{c}_2)^2]} \tag{10}$$

3.3.5 Defining the Ranking of the Alternatives According to ccw_i

Once the closeness coefficient weight (ccw_i) is determined, the ranking order of all alternatives can be obtained, allowing decision makers to select the most feasible alternative. The ccw_i of each alternative is calculated as:

$$ccw_i = \frac{d_i^-}{\left(d_i^+ + d_i^-\right)} \tag{11}$$

Obviously, a large value of index ccw_i indicates that the alternative is closest to *FPIS* and farthest from *FNIS*, in which case this alternative will get a high ranking order.

3.4 FLA Model for Infectious Waste Disposal

The FLA model for IWD is formulated to choose multi-size incinerators and multiple municipalities. The details of the mathematical model are shown below.

Indices:

i is the index of hospitals, i = 1, 2,...,I, (I = 47), j is the index of municipalities, j = 1, 2,...,J, (J=3) and k is the index of incinerators, k = 1, 2,…,K, (K=2).

Parameters:

f_k is the facility cost (baht/day), o_k is the operating cost (baht/day), u is the unit transportation cost (baht/km), dt_{ij} is the actual distance between municipality j and hospital i, s_k is the size of each incinerator k, di is the demand of hospital i (kg/day), AD is the maximum allowable distance, and P is the number of opened locations to located.

Decision variables:

X_{ijk} is a binary decision variable; $X_{ijk} = 1$ if the customer i is served by municipality j and incinerator k only, otherwise $X_{ijk} = 0$.

$Y_{j,k}$ is a non-negative integer decision variable; $Y_{j,k} = 1$ if municipality j is opened by using incinerator k , otherwise $Y_{j,k} = 0$.

Objective function:

$$Min \ z_1 = \sum_{j=1}^{J}\sum_{k=1}^{K} f_k \cdot Y_{jk} + \sum_{j=1}^{J}\sum_{k=1}^{K} o_k \cdot Y_{jk} + \sum_{i}^{I}\sum_{j}^{J}\sum_{k}^{K} u \cdot dt_{ij} \cdot X_{ijk} \tag{12}$$

Subject to:

$$\sum_{j=1}^{J}\sum_{k=1}^{K} X_{ijk} = 1 \qquad \forall i \tag{13}$$

$$\sum_{k=1}^{K} Y_{jk} \le 1 \qquad \forall j \tag{14}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K} Y_{jk} = P \tag{15}$$

$$X_{ijk} \le Y_{jk} \qquad \forall i, j, k \tag{16}$$

$$\sum_{i=1}^{I}\sum_{k=1}^{K} d_i \cdot X_{ijk} \le \sum_{k=1}^{K} s_k \cdot Y_{jk} \qquad \forall j \tag{17}$$

$$dt_{ij} \cdot X_{ijk} \le AD \qquad \forall i, j, k \tag{18}$$

$$X_{ijk} \in \{0,1\} \tag{19}$$

$$Y_{jk} \in \{0,1\} \tag{20}$$

The objective function given by Eq. (12) will attempt to minimize the total cost. Eq. (13) ensures that the demand of each hospital i is fulfilled. Eq. (14) ensures that the sum for incinerator k at each municipality j cannot exceed 1. Eq.(15) requires exactly p facilities to be located.

Eq. (16) expresses that hospital i can be served by opened location j only. Eq. (17) expresses that the service prepared by a site cannot exceed its capacity. Eq. (18) expresses that each travel distance from point i to point j cannot exceed the maximum acceptable distance. Eqs. (19) and (20) are binary constraints.

3.5 Hybrid MCA Model for Infectious Waste Disposal

The Hybrid MCA model was formulated for addressing the infectious waste disposal problem in a case study. Initially, the weights of candidate locations in each municipality (w_j) will be converted to weighting factors (ω_j) using Eq. (21) [4].

$$\omega_j = \frac{\sum_{j=1}^{n} w_j - w_j}{\sum_{j=1}^{n} w_j \cdot (n-1)} \tag{21}$$

After that, ω_j is taken into Eq. (12). Finally, the following new hybrid objective function can be written:

$$Min\ \ Z = \sum_{j=1}^{J}\sum_{k=1}^{K} f_k \cdot \omega_j \cdot Y_{jk} + \sum_{j=1}^{J}\sum_{k=1}^{K} o_k \cdot \omega_j \cdot Y_{jk} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k}^{K} u \cdot \omega_j \cdot dt_{ij} \cdot X_{ijk} \tag{22}$$

The objective function of the Hybrid MCA model is shown in Eq. (22) and the system constraints are shown in Eqs. (13-20). Finally, the optimal solution of the Hybrid MCA model can be solved using LINGO 13.

4 Application

Based on Section 3, the Fuzzy AHP and Fuzzy TOPSIS and FLA models were hybridized to identify suitable locations for IWD in sub-northeastern Thailand. In this case study, there were forty-seven hospitals, namely H1, H2, ... H47, and three municipalities, including Nong Bua Lam Phu Town municipality (A_1 or NLTM), Nong Khai Town municipality (A_2 or NKTM), and Loei Town municipality (A_3 or LTM).

The candidate municipalities were extracted from legislation, regulation and expertise judgments from experts. Therefore, the suitable municipalities for IWD were selected from three candidate municipalities to serve the forty-seven community hospitals (see details in Figure 3). Details of the calculation are shown in Subsections 4.1, 4.2 and 4.3.

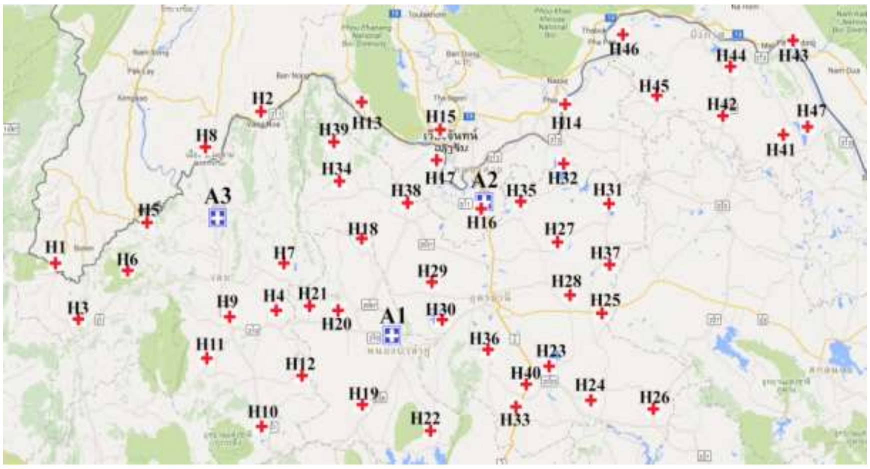

Figure 3 Transportation network of the candidate municipalities and hospitals.

4.1.1 Estimating the Weights of Municipalities Using Combined Fuzzy AHP and Fuzzy TOPSIS

This section presents the evaluation to determine the ccw_i of each candidate municipality. First, a multi-level hierarchical structure is constructed by consulting six decision makers, who have worked in the field for more than fifteen years, and stakeholders. In the hierarchy (see Figure 4), level 0 is the end-goal, finding suitable municipalities for infectious waste disposal, and level 1 contains three main criteria: infrastructure (C_1), geological (C_2) and environmental and social (C_3). Level 2 has ten sub-criteria: public utilities (SC_{11}), traffic (SC_{12}), area size (SC_{21}), features of area (SC_{22}), flooding in the past (SC_{23}), density of population (SC_{24}), municipal administrators (SC_{31}), ability of municipalities (SC_{32}), distance from communities (SC_{33}), and distance from public water resources (SC_{34}). Level 3 contains three candidate municipalities, A_1 = NLTM, A_2 = NKTM and A_3 = LTM.

Then, fuzzy comparison matrices are constructed from the judgment of the six decision makers who have worked in the field for more than fifteen years using the 9 scales of Fuzzy AHP [7]. The priority weights are evaluated, as shown in Table 1. Finally, Fuzzy TOPSIS is used to rank the alternative municipalities. The results and final ranking of alternative municipalities are shown in Table 2.

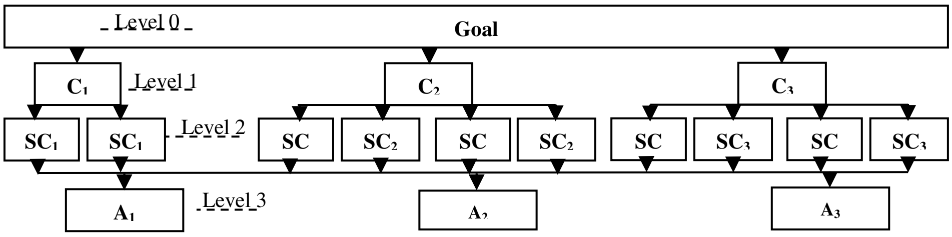

Figure 4 Multi-level hierarchy for selecting locations for infectious waste disposal.

Table 1 Combined comparison matrix of main criteria with respect to goal.

comparison matrix	C1	C2	C3	w_{ci}	*CR*
C1	(1, 1, 1)	(0.52, 0.64, 0.79)	(0.12, 0.13, 0.15)	0.10	0.03
C2	(1.26, 1.57, 1.91)	(1, 1, 1)	(0.13, 0.15, 0.18)	0.13	
C3	(6.48, 7.50, 8.09)	(5.61, 6.62, 7.63)	(1, 1, 1)	0.77	

Table 2 Final evaluation and ranking of alternative locations.

	di^{+}	di^{-}	ccw_i
A_1 (NLTM)	2.45	0.71	0.22
A_2 (NKTM)	2.70	0.29	0.10
A_3 (LTM)	2.67	0.32	0.11

4.2 Compute Suitable Locations Using FLA

The FLA model described above was applied to identify a suitable network for IWD. The network that incurs the lowest total cost was regarded as the optimal solution. The data for the analysis were collected as follows. The demand and actual distance matrix of three candidate municipalities and forty-seven hospitals are shown in Table 3 as d_i, dt_{ij}. The values of u and AD were 4.3 baht/km and 480 km respectively. The values of f_k (k = 1 and k = 2) were 1,893 and 3,485 baht per day, and values of o_k were 9,870 and 18,644 baht per day respectively. The values of s_k were about 500 and 1,000 kg per day. After that, LINGO13 was used; the solutions are shown in Table 4.

As can be seen in Table 4, NLTM and NKTM were the selected municipalities. The size of the selected incinerators is 500 kg/day and the lowest total cost is 43,028 baht/day.

Table 3 Necessary data for analysis for the FLA model.

ID	Hospital name	NLTM (km)	NKTM (km)	LTM (km)	Amount of infectious waste (kg/day)
H1	Nahaeo	190.00	275.00	128.00	11.5
H2	Pakchom	187.00	162.00	71.00	25.5
H3	Dansai	168.00	253.00	106.00	50.0
H4	Erawan	55.70	140.00	61.90	17.0
H5	Tha Li	156.00	240.00	122.00	21.0
H6	Phurua	132.00	216.00	69.30	8.0
H7	Na Duang	65.00	150.00	52.30	13.0
H8	Chiang Khan	148.00	202.00	31.20	15.0
H9	Wang Saphung	78.40	163.00	44.30	30.0
H10	Phu Kradung	94.40	168.00	96.40	15.5
H11	Phu Luang	102.00	187.00	70.00	16.0
H12	Pha Khao	78.60	148.00	98.50	15.0
H13	Sangkhom	142.00	99.00	134.00	16.0
H14	Phon Phisai	154.00	75.40	264.00	31.0
H15	Si Chiang Mai	103.00	60.20	173.00	15.0
H16	Sakhrai	89.60	6.00	200.00	7.0
H17	Tha Bo	102.00	44.00	192.00	31.0
H18	Suwannakhuha	53.00	102.00	145.00	19.0
H19	Si Bun Rueang	40.70	114.00	154.00	26.5
H20	Na Klang	26.80	111.00	90.70	21.0
H21	Na Wang	43.90	125.00	76.40	13.0
H22	Non Sang	55.60	129.00	169.00	15.0
H23	Kumphawapi	95.70	82.00	209.00	11.5
H24	Si That	120.00	106.00	233.00	25.0
H25	Chai Wan	109.00	89.50	222.00	50.0
H26	Wang Sam Mo	147.00	134.00	261.00	27.0
H27	Phibun Rak	94.00	47.50	207.00	31.0
H28	Nong Han	90.20	70.80	204.00	8.5
H29	Kut Chap	52.10	81.80	166.00	13.0
H30	Nong Wua So	27.00	61.70	140.00	15.5
H31	Ban Dung	138.00	71.50	251.00	30.0
H32	Sang Khom	124.00	49.00	237.00	15.5
H33	Non Sa-at	107.00	93.30	220.00	16.0
H34	Nam Som	80.90	95.70	83.90	15.0
H35	Phen	96.10	21.20	209.00	16.5
H36	Nong Saeng	81.60	81.20	195.00	31.0
H37	Thung Fon	121.00	101.00	231.00	15.0
H38	Ban Phue	95.70	82.00	209.00	7.0
H39	Na Yung	120.00	106.00	233.00	31.0
H40	Huai Koeng	109.00	89.50	222.00	6.0
H41	Seka	215.0	196.0	328.0	86.0
H42	Phon Charoen	213.0	157.0	326.0	18.5
H43	Bung Kla	285.0	206.0	395.0	7.0
H44	Si Wilai	236.0	189.0	349.0	20.0
H45	So Phisai	200.0	121.0	310.0	32.3
H46	Pak Khat	197.0	118.0	307.0	15.3
H47	Seka	215.0	196.0	328.0	15.3
	Total	**5635.0**	**5816.3**	**8624.9**	**991**

Table 4 Optimal solution of the FLA model.

Number of predefined locations (*P*)	**Total weight**	**Total cost (baht/day)**	**Name of opened locations**	**Size of opened incinerators** (kg/day)	**Total demand** (kg)
p=1	0.22	46,360	NLTM	1,000	990
p=2	0.32	**43,028**	NLTM and NKTM	500, 500	494, 497
p=3	0.43	52,550	NLTM, NKTM and LTM	500, 500, 500	322, 478, 190

4.3 Computing Suitable Locations Using Hybrid MCA Model

After obtaining the weights of each location (w_j), these weights were converted to weighting factors (ω_j) using Eq. (21), as shown in Table 5.

Table 5 Weighting factors for taking into the FLA model.

Location	**Weight of each location (w_j)**	**Weighting factor (ω_j)**
NLTM	0.22	0.244
NKTM	0.10	0.384
LTM	0.11	0.372

As can be seen in Table 5, a lower weighting factor means a better location. These weighting factors were integrated into the FLA model, as shown in Equation (22). After that, LINGO13 was used to solve the hybrid MCA model, i.e. Equation (22) and Equations (13-20), and the optimal solution was compared with hybrid MADM-only optimization models, as shown in Table 6.

Table 6 Comparison of Fuzzy AHP–Fuzzy TOPSIS, FLA and Hybrid MCA models.

Location	**Closeness coefficient**	**Fuzzy AHP-Fuzzy**	**FLA model**	**Hybrid**
NLTM	0.22	**Selected**	**Selected**	**Selected**
NKTM	0.10	Not selected	**Selected**	**Selected**
LTM	0.11	**Selected**	Not selected	Not selected
Total cost (baht/day)		**66,165**	**43,028***	**43,028***

The optimal solutions from the analysis and comparison of the combined Fuzzy AHP–Fuzzy TOPSIS technique as shown in Table 6, the FLA model and the Hybrid MCA model were offered to the six decision makers. The decision makers selected the lowest total cost (43,028 baht/day) as the optimal solution; the details of the optimal solution are shown in Table 7.

However, in practice, waste collection can be operated once a week but incineration should be operated every day. In order to improve/confirm the solutions of the Hybrid MCA model, a comparison analysis was done with variation of the number of days for waste collection. The results are summarized in Table 8. The practical model for collecting and disposing of infectious waste is similar to the EOQ model shown in Figure 5.

Table 7 Optimal solutions of hybrid MCA model.

Opened locations	NLTM	NKTM
Size of incinerators (kg/day)	500	500
Weights	0.22	0.10
Hospitals	H1, H3, H4, H5, H6, H7, H8, H9, H10, H11, H12, H18,H19, H20, H21, H22, H29, H30, H34, H36, H38, H41	H2, H13, H14, H15, H16, H17, H23, H24, H25, H26, H27, H28, H31, H32, H33, H35, H37, H39, H40,H42, H43, H44, H45, H46, H47
Demand (kg)	494	497
Total cost (baht/day)	**43,028**	

Table 8 Comparison for different numbers of days for waste collection.

Details of costs and weights of selected location	Number's days		
	Once a day (**1 day**)		Once a week (**7 days**)
Total cost	**43,028**		179,134 baht/week or 25,590 baht/day
Selected location (weight)	NLTM (0.22)	NKTM (0.10)	NLTM (0.22)
Demand	494	497	6,937 kg/week (991kg/day)
Size of incinerators	500	500	1,000 kg/day (7,000 kg/week)

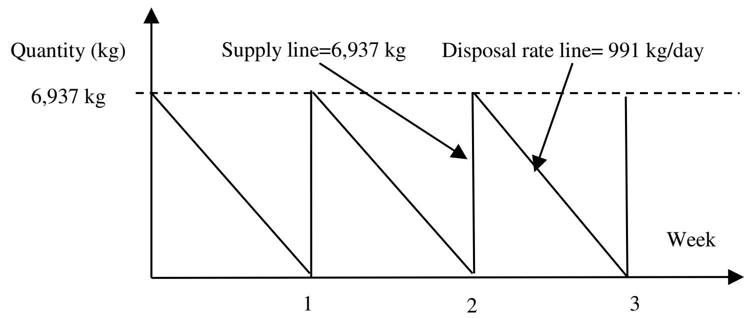

Figure 5 Practical model for collecting and disposing of infectious waste.

As can be seen in Table 8, increasing the number of days for waste collection to 7 days, the total cost of the Hybrid MCA model had a decreasing trend, with total cost = 179,134 baht/week or 25,590 baht/day. This can reduce total cost by 2% and the selected location is also the ideal location (only one undesirable location with a maximum weight). These solutions should be reconsidered and compared with the previous optimal solutions. Thus, the solutions from the analysis in Table 8 and Figure 5 were offered to the six decision makers. As a result, the decision makers reconsidered and chose the new lowest total cost

(25,590 baht/day) with the ideal location weight (0.22) as the new optimal solution instead of the previous optimal solution.

As can be seen in Tables (6-8) and Figure 5, the solutions can provide suitable municipalities and a practical model for IWD with lowest total cost and maximum location weight. Moreover, the decision makers believed that our work can provide essential support for decision makers in the assessment of IWD problems in this case study and in other areas of Thailand. The proposed methodology can also be applied to other complex problems.

5 Conclusions

As presented in this paper, the FLA problem for IWD is a special case involving several factors, including factors that are difficult to interpret and cost factors that require simultaneous allocation of resources. Hence, it is difficult to choose suitable locations in such cases by using stand-alone techniques. To deal with this problem, in this paper a new hybrid MCA model was presented, which hybridizes Fuzzy AHP, Fuzzy TOPSIS and an optimization model for solving the FLA problem. The proposed model was tested with a case study of forty-seven community hospitals and three candidate municipalities in sub-northeastern Thailand. First, the FLA model for IWD was formulated to determine the problem statement for the case study. Next, the FLA model was converted to the Hybrid MCA model and, finally, LINGO13 was used. The results showed that NLTM is a suitable location with lowest total cost (25,590 baht/day) and ideal location weight (0.22). The major advantages of the proposed methodology are that it can guide selection of new suitable municipalities by considering relevant factors simultaneously. In addition, the Hybrid MCA model is a powerful and flexible model for decision makers to limit costs and environmental impacts.

For future research, a limitation of this study was that only one FLA problem case was studied. Considering the generalization of the research findings and the complexity of the location network, more case studies across a broader range of other sectors are necessary to further enhance the validity of the research output. Finally, since the size of problems that can be solved optimally is limited, meta-heuristics can be combined with the MADM techniques for solving large problems.

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