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Original research article

Application of Fuzzy Multicriteria Group Decision-Making to Prioritize Infectious Waste Incineration Development in Phayao Province Hospitals Lacking Supportive Information

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ABSTRACT

This research proposes a method to prioritize sites for infectious waste incineration development plants using Phayao Province hospitals as a case study. The framework consists of four main process categories as criteria selection: scoring and weighting approach, weighted score aggregation and defuzzification method, and sensitivity analysis. The literature review determined six evaluation criteria as waste volume, space, human resource, administration and management, complaints, and environmental stability. Since most of the criteria are in the spects of spoken word or fuzzy language, the fuzzy additive weighting decision rule is applied. Hence, the scoring and the weighting criteria are collected from interviewing the competitive hospitals' group decision- makers and chief executives. Weight-score aggregation, center-of-area defuzzification and sensitivity analyses were used to convert the overall score of all elements of fuzzy numbers into crisp values and test the effect of criteria on the ranking. Results identified three hospitals that showed high potential as sites for the development of new infectious medical waste incineration plants as Dokkhamtai, Chiangkham, and Phayao Hospitals. The developed framework assisted group decision-making based on the ability of the hospitals to develop a new infectious waste incineration plant. This framework can be applied to prioritize facility development in any province lacking supportive information.

Keywords: Fuzzy multicriteria group decision-making; Infectious waste incineration; Priority for development

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1. Introduction

The cost of managing infectious waste disposal by hospitals in Thailand increases every year because disposable medical supplies are widely used in the healthcare industry. Waste collection has now changed from on-site incineration to off-site outsourcing by private contractors in many hospitals [1]. This situation has resulted from many factors, including damage to incinerators that are more than 10 years old [2, 3], environmental problems and complaints from the surrounding communities [4]. The Ministry of Public Health (MPH) has announced that on- site waste disposal will now be subject to outsourcing management services. Hospital budget allocations for waste disposal have been increasing. Currently, the rate for infectious waste handling is 12 THB/kg [4, 5]. In 2019, the total waste generated by the whole country was 31,330 t [6], leading the government to spend at least 375 million THB (around 12 million USD) on disposal management. The Pollution Control Department reported that infectious waste volume is increasing by about 5.5% per year [4].

To handle the increasing amounts of infectious waste requiring treatment and to reduce costs, hospitals must improve the efficiency of incinerators using new technology [1-3]. A report by the Department of Health (DOH) stated that on-site waste disposal and internal operations must keep the budget under cost on logistics, with no risk of contamination to the surrounding areas. However, on-site disposal plant construction is difficult because of the environmental and social impacts and must consider the different potentials in each hospital. These issues must be studied to evaluate potential ability as results may affect prioritization. Furthermore, outgrowth could lead to hospitals being able to expand external waste treatment services to cover the whole province, similar to Bangkok and Chiang Rai prototypes that have central infectious waste incineration plants (as On-Nuch and Mae Fah Luang University, respectively) [7].

The strategy of decentralized waste disposal at city or province level is popular in many Southeast Asian countries [8-11] or even around the world [12-16]. In addition to evaluating and finding alternative high potential hospitals to improve or construct waste disposal plants, this preliminary study conducted problem- solving based on the individual situation and the potential ability of each hospital. Infectious waste disposal consists of various types, i.e., microwave and steam sterilization. In this study, waste disposal incineration was selected as the study prototype with the lowest installation cost [2, 3] and used and accepted in many countries [8, 9, 11, 12].

Prioritization methods/techniques include Impact Effort Matrix, the RICE scoring model, MoSCow analysis, and the Kano model [17-18], Multicriteria decision analysis (MCDA) has proved suitable and is widely used as a valuable tool for evaluating alternative options. The difficulty and complexity of decision problems can be combined with environmental, social and other factors [19-22]. A literature review on the evaluation criteria [12, 23, 24] revealed scant supporting information. The volume of infectious waste at each hospital is usually recorded and given to outsourcing waste contractors who change by waste weight [6]. Furthermore, criteria for the site choice of an infectious waste incineration plant were mainly based on the possibilities of future social and environmental incidents [12], since both complaints and administration criteria are not numeric variables.

Evaluating the alternative site selection possibilities and determining the best choices are likely to become controversial topics in Phayao Province [25]. Therefore, this study implemented concepts and techniques to rank hospitals best suited for the development of new infectious waste incineration plants. The objective focused on evaluating and ranking the hospitals based on the ability for development using multicriteria group decision analysis with fuzzy additive weighting for the study area of Phayao Province. This area was chosen because it has problems similar to other provinces including lacking supportive information, while budget spending has increased annually for private off-site expenses and the area is facing environmental and social difficulties.

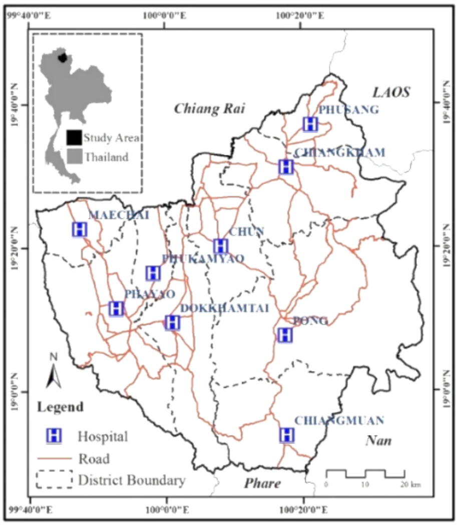

Fig. 1. Location of the study area and hospitals.

Phayao Province is located in the northern part of Thailand and covers 6,335 km^2 [26]. Similar to other provinces, Phayao Province provides medical services following MPH regulations and the World Health Organization (WHO). There are primary healthcare centers or first-level referral units in every sub-district, called Health Promoting Hospitals (HPHs), with secondary care units or mid-level referral hospitals in every district, called District Community Hospitals (DCHs). Moreover, there are general hospitals (GH) or high-level referral hospitals in the capital district [27], as seen in Fig.1. Provincial infectious medical waste administration and management are decentralized at the district level, with a DCH responsible for each district. Infectious waste from HPHs is transported and collected weekly, with large amounts gathered at each DCH. Private disposal contractors transport the waste off-site [28]. In 2019, the infectious medical waste was around 256,364 kg [6], and the three highest waste generators were Phayao, Chiangkham and Dokkhamtai Hospitals (Table 1).

Table 1. Infectious waste volumes of hospitals in Phayao Province [6].

Site	Hospital	Type	Waste volume (kg/year)
1	Phayao Hospital	GH	133,778
2	Chiangkham Hospital	DCH	58,021
3	Dokkhamtai Hospital	DCH	18,766
4	Pong Hospital	DCH	13,279
5	Chun Hospital	DCH	11,805
6	Maechai Hospital	DCH	8,272
7	Chiangmuan Hospital	DCH	4,593
8	Phusang Hospital	DCH	3,993
9	Phukamyao Hospital	DCH	3,857

2. Materials and Methods

The nine hospitals listed in Table 1 were ranked in the order of suitability as a location for a new waste incineration plant. The framework comprised the following: (1) criteria selection and input data, (2) criteria scoring and weighting, (3) weight-score aggregation and defuzzification, and (4) sensitivity analysis.

2.1 Criteria selection and input data

Under the decision situation mentioned earlier, relevant literature [20, 29, 30] was examined to select indicators or evaluation criteria. The linguistic terms/labels of each criterion were assessed based on the decision-makers' opinions and preferences, with consensus [31-33] used to decide the strategy to resolve a conflict case or inconsistency.

After the literature review, apart from *waste volume* (VL), net weight (mass) was considered as a primary important characteristic for hospital site choice [3, 23]. The ability of the infectious waste disposal plant was another main criterion in ranking potential sites. From the literature reviews

[12, 23, 24, 34], five relevant criteria for selecting the new waste incineration development sites were *space* (SP), *human resource* (HR), *administration and management* (AM), *complaints* (CP), and *environmental stability* (ES) as described below.

(1) *Space* is considered a land area of sufficient scale and configuration to accommodate the designated level of the incineration plant.

(2) *Human resource* includes skilled workers capable of operating the incineration plant without additional recruitment announcement.

(3) *Administration and management* are particular characteristics of executives and staff to set policy and plan and solve problems within the organization.

(4) *Complaints* are considered as sensitive echoes from the surrounding community/society.

(5) *Environmental stability* includes air, biological composition, visual landscape and ecological land systems. They were considered to be stable and sustainable changes without incurring unacceptable loss of value.

The criteria and attributes classification were based on the decision-makers' opinions for screening possible linguistic terms (attributes) of the criteria (Table 2). The first criterion, *waste volume*, was derived from the report of [6], while the remaining five were collected from interviews with nine decision-makers as the chief executives of the competing hospitals. The construction cost criterion was ignored and removed because the specs of an incineration plant are the same in any hospital.

Table 2. The criteria and their attributes.

Criterion	Attributes		
VL		kg/year	
SP	Limited	Adequate	Expansive
HR	Limited	Moderate	Exceptional
AM	Low	Moderate	Exceptional
CP	Numerous		Few
ES	Sensitive	Acceptable	Stable

2.2 Criteria scoring and weighting

2.2.1 Scoring of waste volume

The characteristic of *waste volume* is ratio-scale. From the interviews, the lower limit was recommended for satisfactory development with the fuzzy number of 1. Alternative site choices with lower waste volume could also be accepted with lower preference and assigned as fuzzy numbers between 0 and 1. This process of the standardization of scores was necessary for score aggregation, commensurable with the other criteria.

2.2.2 Scoring of criteria for site choice of an infectious waste incineration plant

Criteria with two classes were represented by fuzzy numbers as (0.4, 0.6, 0.6, 0.8) and (0.6, 0.8, 0.8, 1.0). For criteria with three linguistic classes, their sets of fuzzy numbers were "low" = (0, 0, 0.2, 0.4), "medium" = (0.2, 0.5, 0.5, 0.8), and "high" = (0.6, 0.8, 1, 1), corresponding to previous studies [20, 35, 36]. Criteria attributes can be many classes: medium and high for two classes, and low, medium, and high for three classes. Each class was represented by four elements of a trapezoidal/triangle as *a*, *b*, *c* and *d*, as seen in Fig.2.

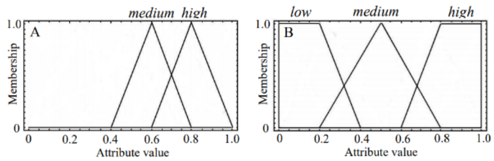

Fig. 2. The fuzzy number of each criterion with two (a) and three (b) linguistic classes [20, 35].

2.2.3 Criteria weighting

The multiple pairwise comparison method (or Dunn's method) was selected for criteria weighting [37] due to having group decision-makers. This method analyzed all possible pairwise means. This case study had six evaluation criteria, with 15 possible pairwise comparisons, as seen in the interview example (Table 3). Conceptually, some decision-makers who preferred a given criterion to another recognized the degree of importance. The assumption of individual decision-makers was to cooperate as a team (or have homogeneity within a group) [20]. This method provides preferences for all criteria by the ratio of *rank/range*. The *rank* of a certain criterion was determined from the summation of the total decision-makers. The *range* was determined from *nk* - *k*, where *n* is the number of criteria, and *k* is the number of decision-makers. The ratio of *rank/range* was later normalized to between 0 and 1.

Table 3. Examples of interviews and answers derived from a decision-maker for weight estimation.

Pair wise	X	Y	Opinion X>Y	Opinion Equally	Opinion X<Y
1	VL	SP			✓
2	VL	HR			✓
3	VL	AM			✓
4	VL	CP			✓
5	VL	ES			✓
6	SP	HR			✓
7	SP	AM			✓
8	SP	CP	✓		
9	SP	ES	✓		
10	HR	AM			✓
11	HR	CP	✓		
12	HR	ES	✓		
13	AM	CP	✓		
14	AM	ES	✓		
15	CP	ES	✓		

2.3 Weight-score aggregation and defuzzification

2.3.1 Weight-score aggregation

Weight-score aggregation was achieved using the Fuzzy Additive Weighting (FAW) decision rule [38]. This is similar to the conventional Simple Additive Weighting method. Theoretically, the total score of each alternative is calculated by the summation of multiplying the weights and scores (attributes) of the criteria. Two strong assumptions were made as to the linearity and additivity of criteria attributes. The former assumed that the relationship between attributes was linear, while the latter concluded that there was no interaction effect between criteria attributes [20]. Lastly, the highest score was the best alternative when the total score was obtained and defuzzified. The FAW decision rule can be written as

$$F_i = \sum w_j x_{ij}, \qquad (2.1)$$

where F_i is the overall score of each trapezoidal fuzzy number (i.e., *a*, *b*, *c,* and *d*) obtained by multiplying the score and weight, x_{ij} is the score of the *i*th alternative concerning the *j*th attribute through membership functions (*a*, *b*, *c* and *d*), and w_j is the normalized weight of each attribute.

2.3.2 Defuzzification

The center-of-area defuzzification [39, 40] was applied to convert the overall score of all the elements into a single numeric value (x^*). This represents the degree of development priority of each alternative. The center of the area of any fuzzy number ($\tilde{c}$) can be defined by

$$x^* = \frac{\int \mu_{\tilde{c}}(x)\,dx}{\int \mu_{\tilde{c}}\,dx}. \qquad (2.2)$$

The alternative hospital site choices were subsequently ranked based on the defuzzified values. Choices with a higher value exhibited a higher potential for success.

2.4 Sensitivity analyses

The process of map removal sensitivity analysis [41, 42] corresponding with the One-At-a-Time (OAT) method [43] was adopted in this study. This removes one criterion at a time to test the effect of that criterion on the overall score. The analysis identified which of the criteria could be removed with the least impact on the score [44]. Criteria that affected the total score when they were removed were considered very important. The sensitivity measure was calculated by the formula [41]:

$$S = \left[\frac{\left| \frac{V}{N} - \frac{\dot{V}}{n} \right|}{V} \right] \times 100, \qquad (2.3)$$

where S is the sensitivity measurement expressed in terms of the variation index, V and $\dot{V}$ are the unperturbed and the perturbed overall scores, respectively, and N and n are the numbers of criteria used to compute V and $\dot{V}$ [41] as the alternative-based or site-based analysis. An alternative with a very high or very low score of a removed criterion affected the variation index (S). According to [42], the variation index in terms of the normalized mean difference of each criterion removal indicated which criterion was less effective at a certain site. Any criterion with low normalized value had less effect.

3. Results and Discussion

3.1 Criteria selection and input data

The goal was to determine prioritization rankings for the nine hospitals sites. After examining the relevant literature, the evaluation criteria were split into two groups as *waste volume* (VL) and criteria required for the development of an infectious waste incineration plant including *space* (SP), *human resource* (HR), *administration and management* (AM), *complaints* (CP), and *environmental stability* (ES). The criteria and their attributes are listed in Table 2. Supportive information and input data for this framework were mostly sourced from the opinions of the decision-makers, except for *waste volume* which was recorded by [6].

3.2 Criteria scoring and weighting

3.2.1 Waste volume score

Data compiled from interviews with chief executives of the nine competitive hospitals indicated that the preferred mean of the infectious medical waste incineration plant waste volume was 15,000 kg per year. Therefore, the waste volumes of each alternative site (listed in Table 1) were converted to a standardized (fuzzy) score. The graph in Fig. 3. shows the conversion process.

3.2.2 Infectious waste incineration plant scoring criteria

The opinions of the informants were collected as linguistic terms and converted to trapezoidal fuzzy numbers represented by a score of each element (i.e., *a*, *b*, *c*, and *d*). Scores of informants for the same criterion were averaged as the criterion score of each potential alternative site, with results shown in the form of trapezoidal fuzzy numbers (Table 4).

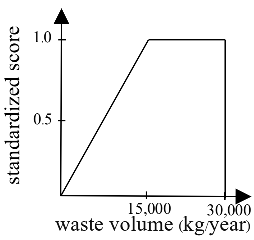

Fig. 3. Standardized *waste volume* score.

3.2.3 Criteria weighting

The process and results of the weight determination are shown in Table 5. The step 1 calculation with the nine decision-makers showed that four thought that the weight of VL was more than SP, while five had a different opinion. The *space* weight was assigned with the highest value at 0.23, while the weights of *complaints* and *waste volume* were high (0.22 and 0.21) and not much different from *space*. *Environmental stability* and *human resource* were assigned as moderately important, while the weight of *administration and management* was the lowest.

3.3 Weight-score aggregation and defuzzification

Criteria scores and weights were multiplied and aggregated according to the

FAW decision rule. The aggregation results in the form of trapezoidal fuzzy numbers were defuzzified using the center-of-area method. The alternative sites were then ranked according to these defuzzified values, as shown in Table 6. Higher values indicated higher priority for the development of an alternative hospital site.

Table 4. Criterion scores of each potential alternative site.

Site	Criteria																				
	VL	SP				HR				AM				CP				ES			
		a	*b*	*c*	*d*	*a*	*b*	*c*	*d*	*a*	*b*	*c*	*d*	*a*	*b*	*c*	*d*	*a*	*b*	*c*	*d*
1	1.00	0.08	0.20	0.32	0.56	0.60	0.80	1.00	1.00	0.60	0.80	1.00	1.00	0.40	0.60	0.60	0.80	0.08	0.20	0.32	0.56
2	1.00	0.08	0.20	0.32	0.56	0.60	0.80	1.00	1.00	0.60	0.80	1.00	1.00	0.48	0.68	0.76	0.88	0.08	0.20	0.32	0.56
3	1.00	0.20	0.50	0.50	0.80	0.20	0.50	0.50	0.80	0.12	0.30	0.38	0.64	0.60	0.80	1.00	1.00	0.32	0.59	0.65	0.86
4	0.89	0.20	0.50	0.50	0.80	0.06	0.15	0.29	0.52	0.12	0.30	0.38	0.64	0.40	0.60	0.60	0.80	0.14	0.35	0.41	0.68
5	0.79	0.20	0.50	0.50	0.80	0.06	0.15	0.29	0.52	0.06	0.15	0.29	0.52	0.60	0.80	1.00	1.00	0.14	0.35	0.41	0.68
6	0.55	0.20	0.50	0.50	0.80	0.06	0.15	0.29	0.52	0.00	0.00	0.20	0.40	0.60	0.80	1.00	1.00	0.20	0.50	0.50	0.80
7	0.31	0.60	0.80	1.00	1.00	0.00	0.00	0.20	0.40	0.00	0.00	0.20	0.40	0.60	0.80	1.00	1.00	0.20	0.50	0.50	0.80
8	0.27	0.60	0.80	1.00	1.00	0.00	0.00	0.20	0.40	0.00	0.00	0.20	0.40	0.60	0.80	1.00	1.00	0.20	0.50	0.50	0.80
9	0.26	0.60	0.80	1.00	1.00	0.00	0.00	0.20	0.40	0.00	0.00	0.20	0.40	0.60	0.80	1.00	1.00	0.60	0.80	1.00	1.00

Table 5. Weight determination using the multiple comparison method.

Step 1 Results of pairwise comparisons of the six evaluation criteria by 9 decision-makers

Criterion	VL	SP	HR	AM	CP	ES
VL	-	5	2	1	5	4
SP	4	-	2	1	4	3
HR	7	7	-	3	6	6
AM	8	8	6	-	7	6
CP	4	5	3	2	-	1
ES	5	6	3	3	8	-
Rank	28	31	16	10	30	20

Step 2 Assessing weights by multiple comparisons.

Criterion	Rank	Rank/Range	Weight
VL	28	0.62	0.21
SP	31	0.69	0.23
HR	16	0.36	0.12
AM	10	0.22	0.07
CP	30	0.67	0.22
ES	20	0.44	0.15
Total		3.00	1.00

Interestingly, this ranking did not correspond to the ranking evaluated solely based on *waste volume*, even though *waste volume* had a high weight value. Actual volumes of the alternative hospital sites were considered based on the waste volume ranking, and converted to a standard score or equal to 1 when over 15,000 kg per year, and incorporated with the other criteria. This caused the scoring of *waste volume* of the alternative sites to become similar to 1; however, their actual scores differed and this led to differences in ranking.

Table 6. Potential alternative sites and their overall scores of each element of the trapezoidal fuzzy number, defuzzified scores, and rankings.

Site	Overall score of each element of the trapezoidal fuzzy number				Defuzzified score	Rank
	a	*b*	*c*	*d*		
1	0.442	0.570	0.654	0.789	0.614	3
2	0.460	0.588	0.689	0.806	0.636	2
3	0.468	0.671	0.729	0.884	0.688	1
4	0.357	0.524	0.556	0.755	0.548	7
5	0.376	0.537	0.617	0.770	0.575	5
6	0.331	0.500	0.575	0.730	0.534	9
7	0.364	0.499	0.627	0.710	0.550	6
8	0.356	0.491	0.619	0.702	0.542	8
9	0.414	0.534	0.692	0.730	0.592	4

3.4 Sensitivity analyses

The sensitivity analysis results are presented in Table 7. The general view of all alternatives expressed that *complaints* affected the overall score, with the mean variation index value highest at 2.55%. Results of the mean variation indices (*S*) *environmental stability* (1.08%), *space* (1.76%), *human resource* (1.83%), *waste volume* (2.25%), and *administration and management* (2.49%). These results also indicated that each alternative site criterion expressed the most effectiveness in the overall score. For example, *complaints* about alternative hospital site number 6 had the highest effect, while alternative site number 1 had the lowest. Therefore, criteria scores with high variation at each alternative site should be examined carefully in aspects of attribute estimation and assessment. For example, *complaint*s strongly affected alternative sites 6, 8, 7, 5 and 9, while *waste volume* had a high effect on alternative sites 1, 4, 2, 3 and 5.

Table 7. Variation indices of the sensitivity assessment.

Site	Parameter Removal					
	VL	SP	HR	AM	CP	ES
1	3.51	1.16	0.01	1.39	0.97	1.92
2	3.27	1.23	0.12	1.46	1.51	1.96
3	2.77	0.01	1.59	2.60	2.10	0.70
4	3.45	0.86	2.22	2.41	1.48	1.17
5	2.42	0.67	2.27	2.71	3.17	1.27
6	1.00	0.97	2.19	2.94	3.67	0.52
7	1.00	3.77	2.68	2.95	3.46	0.61
8	1.27	3.88	2.67	2.95	3.57	0.57
9	1.51	3.27	2.73	2.98	2.98	0.97
Mean	2.25*	1.76	1.83	2.49*	2.55*	1.08
Min	1.00	0.01	0.01	1.39	0.97	0.52
Max	3.51	3.88	2.73	2.98	3.67	1.96
S.D.	1.06	1.46	1.06	0.63	1.04	0.56

Note: * = High variation

3.5 Discussion

This study solved the problem of where best to develop infectious waste incineration plants, similar to the objectives of [2, 3, 24] using a different approach. This study employed Multi- Attribute Decision Making (MADM), while other studies [2, 3, 24] used Multi-Objective Decision Making (MODM). This approach was suitable for evaluating and ranking the alternative sites [35, 38, 45, 46]. The MADM approach is best suited for a finite number of alternatives [45] that are explicitly known at the beginning of the solution process [46], with the performance of each alternative represented by multicriteria.

MCDA is a traditional simple technique [47], while the MODM approach is suitable for an infinite number of alternative sites, and can be determined by solving a mathematical model [20]. However, for further studies, a combination of the MADM and MODM approaches [48] and hybrid techniques [22] should be considered and compared with the traditional framework.

The evaluation criteria for this research were collected from related literature reviews, corresponding with [34, 40, 45, 46] under the limitation of supportive information, leading to decision- making. Fuzzy attribute data of each hospital derived from informants were supplemented with available explicit and objective information on waste volume as only one criterion. This framework can be applied in any province facing a similar lack of supportive information. In further studies, simulation information derived from the Geographic Information System (GIS) and Remote Sensing should be used, especially for analyzing the density of the surrounding residential areas, road networks, and logistic costs [49]. Moreover, weighting criteria and applying single-parameter sensitivity analyses [41, 44] could be measured and considered for checking weight values and consistency between theoretical and effective weight values [50]. This may help to add or remove evaluation criteria.

4. Conclusion

The objective of this study was to rank nine potential sites based on two main criteria as waste volume and ability of the infectious waste incineration plant. Waste volume of the alternative sites was derived from the DOH inventory. The criteria and assessment scores were collected and adapted from previous studies and assembled after interviews with the chief executives of the competing hospitals. The fuzzy set membership was applied to convert linguistic to numeric rating scales. The multiple comparison method for weighting criteria showed that *space* had the highest weight, while *complaint*s, *waste volume*, *environmental stability*, *human resource*, and *administration and management* had high to low weights. The FAW was used to aggregate the weight- score of each alternative hospital site. These scores expressed the development ranking of each potential site. Results within Phayao

Province revealed high potential sites as Dokkhamtai, Chiangkham, and Phayao Hospitals. This methodology supports group decision-making and can be applied to prioritize development needs in any province lacking supportive information.

The parameter removal sensitivity analyses based on the average variation index also showed that *environmental stability* had the lowest sensitivity, while *complaints*, *administration and management*, *waste volume*, *human resource,* and *space* recorded high to low sensitivity. The sensitivity analysis also determined which criterion provided the most effective alternative. The six criteria mentioned above impacted the ranking of potential sites. However, criteria scores should always be acquired cautiously since they depend on the estimation and assessment of the informants.

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