Multi-Attribute Selection of Coal Center Location:
A Case Study in Thailand

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Abstract. Under Power Development Plan 2015, Thailand has to diversify its heavily gas-fired electricity generation. The main owner of electricity transmission grids is responsible to implement several coal-fired power plants with clean coal technology. To environmentally handle and economically transport unprecedented quantities of sub-bituminous and bituminous coal, a coal center is required. The location of such facility is an important strategic decision and a paramount to the success of the energy plan. As site selection involves many criteria, Fuzzy Analytical Hierarchy Process or Fuzzy-AHP is applied to select the most suitable location among three candidates. Having analyzed relevant criteria and the potential alternatives, the result reveals that engineering and socioeconomic are important criteria and Map Ta Phut is the most suitable site for the coal center.

1. Introduction
The decades of continuously economic growth in Thailand have fueled its GDP and its electricity consumption per capita from 2016 USD and 1454 kWh in 2000 to 6229 USD and 2471 kWh in 2013 according to World Bank. To ensure sustainable economic development and satisfy growing consumption, Thailand Power Development Plan 2015-2036 (PDP2015) is developed. Under this plan, Thailand has committed to diversify its heavily gas-fired electricity generation by increasing other sources of energy, including coal. Despite its controversy, coal has a long history in Thailand and remains the reliable and economical source of electricity.

At the time of writing, coal-fired electricity generation accounts for 21% of total electricity production in Thailand [1]. As the main owner of electricity transmission grids, Electricity Generation Authority of Thailand (EGAT) is recently committed by PDP2015 to implement several power plants with clean coal technology in the southern and central regions, which require approximately ten and seven million tons per annum of coal respectively. To environmentally handle and economically transport unprecedented quantities of sub-bituminous and bituminous coals, a coal center is required. Perhaps, the most important challenge for establishing a coal center is its location since it affects a long-term planning and touches on many aspects. As a result, the goals of this article are to identify important criteria for developing and operating a coal center as well as to select the most suitable location of coal center for the EGAT clean coal projects.

2. Literature Review

2.1. Site Selection

Site selection is considered as one of the most well-known Multi Attribute Decision Making (MADM) problems, which usually refer to problems regarding a discrete number of predetermined alternatives. The main purpose of MADM is to provide the decision makers with the most appropriate alternative according to the levels of preference importance of each criterion. Consequently, certain analyses of criteria importance are performed prior to evaluation of an individual alternative. In high preliminary investment project, where decision makers must prudently choose potential locations [2]; otherwise, localization error could induce bankruptcy [3]. Furthermore, consensus decision is difficult to achieve because of conflicting/competing criteria, hence proper methodologies for site selection should be selected thoroughly.

Among effective techniques applied to MADM problems, Analytical Hierarchy Process (AHP) is outstanding because it can decompose a complex problem into a hierarchical structure, imitating human perception, and can analyze qualitative and quantitative criteria simultaneously. Nonetheless, researchers tend to emphasize more on quantitative than qualitative preferences because of imprecision and uncertainty of qualitative criteria's assessment originated from incomplete information, unobtainable information, and partial ignorance [4]. To enhance precision and certainty in assessments, Fuzzy logic is combined with AHP (Fuzzy-AHP) [5].

2.2. Fuzzy AHP
Fuzzy AHP method was first introduced in van Laarhoven and Pedrycz's work by comparing each fuzzy ratio through triangular membership functions. Buckley substituted triangular membership functions with trapezoidal membership functions, which created a novel version of Fuzzy AHP methods. Chang later proposed the extent analysis method for determining the synthetic extent values of the pairwise comparisons for Fuzzy AHP [6]. However, Wang et al. [7] proved that the extent analysis method may result in a wrong judgment due to a zero weight assigned to useful criteria and attributes; in addition, the weights of criteria or alternatives cannot be derived because this method assigns numerical values, which only represent the priority of a criterion/attribute over the others, to criteria/attributes.

3. Methodology

3.1. Criteria and attributes for coal center site selection
According to Yaron et al. [8], a new approach to bulk unloading in an open sea was proposed. The paper presented site conditions and operating requirements for designing a new terminal. Proper soil condition and geological oceanography were essential for foundation construction. To attain targeted operation performance, physical oceanography was used to determine the specification of facilities. Moreover, environmental concerns were taken into account. Likewise, environmental, health and safety guidelines for port and harbor facilities [9] underlined the importance of minimizing coastal and inland environmental impacts. If any phases of construction or operation undergoing at particular location caused tremendous adverse impacts on environment, a better alternative would be proposed. As a result, a list of criteria and attributes for coal center site selection was developed.

In this study, six criteria are determined as significant criteria, namely socioeconomic (SOC), infrastructure (INF), engineering (ENG), transportation (TRA), environment (ENV), and cost (COS). SOC refers to social perspectives and acknowledgement of the new project and is divided into acceptance of the local community (AOL), approval of the government (AOG), and security of the area (SOA). INF is defined as availability of basic infrastructure at each candidate site, which results in the difficulty levels of construction processes, and is broken down into electricity availability (ELA) and water supply network (WSN). ENG, technical suitability in terms of construction processes and operation conditions required, is characterized by ability to expand capacity (AEC), coastal morphology (COM), meteorology (MET), physical oceanography (POC), and terrain (TER). TRA refers to inland and maritime accessibility as well as modes of transportation from the potential sites to end users and its attributes are proximity to customers (PTC), land routes (LAR), maritime routes and transportation options (MAR), and railways (RAI). ENV concentrates on the degree of environmental changes that might affect a local community and irreversible environmental conditions. Abiotic

resources (ABR), biotic resources (BIR), human use value (HUV), and quality of life (QOL) are sub-criteria of ENV. COS is the investments including land, dredging, environmental protection, equipment, and constructing costs. The last criterion consists of construction cost (COC) and damage cost (DMC).

3.2. Evaluation of weights
Buckley's method is utilized as it is comfortable to apply to fuzzy logic and guarantees a unique solution to the reciprocal comparison matrix [10]. The proposed approach is developed with respect to the AHP framework [11]. The analysis steps of such approach are discussed in this subsection.

3.2.1. Construction of the hierarchical structure. To decompose the problem, goal of the problem is firstly defined. Based on the goal, significant criteria are determined. Each criterion is characterized by several essential attributes, which are further used in evaluation of three potential alternatives. The relationship of the four components of hierarchical structure, namely goal, criteria, attributes, and alternatives, are demonstrated as levels and sub-levels shown in figure 1.

3.2.2. Pairwise Comparison. All criteria are compared against all others through the linguistic variables in table 1, which are translated into triangular fuzzy number consisting of lower-bound, most-likely, upper-bound or (l,m,u). Triangular fuzzy numbers is x-y coordinate of (l,m,u) on x-axis and membership function $\mu(x)$ on y-axis. Similarly, all attributes corresponding to their criterion are compared with each other as well as all alternatives are compared with the others pertaining to each attribute. The interval between l and u presents the level of uncertainty; the wider the interval (l-u), the more uncertainty. Fuzzy comparison matrix (**A**) represents fuzzy relative importance of each pair of criteria i and criteria j where elements of matrix are $a_{ij} = (l_{ij}, m_{ij}, u_{ij})$ and $a_{ji} = (a_{ij})^{-1} = (u_{ij}^{-1}, m_{ij}^{-1}, l_{ij}^{-1})$ as depicted in table 4.

Table 1. Definition of linguistic variables for fuzzy importance scale.

Linguistic Variable		Triangular Fuzzy Numbers (l,m,u)
Not important	(NI)	3/8,3/7,1/2
Very less Important	(VLI)	3/7,1/2,3/5
Less Important	(LI)	1/2,3/5,3/4
Slightly less Important	(SLI)	3/5,3/4,1
Equally Important	(EI)	1,1,4/3
Slightly more Important	(SMI)	1,4/3,5/3
More Important	(MI)	4/3,5/3,2
Very Important	(VI)	5/3,2,7/3
Very strongly important	(VSI)	2,7/3,8/3

3.2.3. Consistency tests for fuzzy weights. According to Buckley [12], if the crisp value of triangular fuzzy number matrix comparison is consistent, the fuzzy comparison matrix is consistent as well. In order to verify the acceptance of the judgment, the consistency evaluations of "most-likely" value are performed. A Consistency Index (CI) examines the consistency of the pairwise comparison matrix through CI = $(\lambda_{max}$-$n) / (n$-1$)$, where n is the number of criteria, attributes, or alternatives and λ_{max} is the eigenvalue of the comparison matrix. A Consistent Ratio (CR) or CI/RI measures the judgement consistency, where Consistency Random Index (RI) are generated by numerous simulations of pairwise matrix comparison demonstrated in table 2. Therefore, CR represents the errors caused by decision makers and should be less than 10% of RI or CR<0.1 [13].

Table 2. Consistency Random Index (RI) for n = 1, 2,…, 9 [11]

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

3.2.4 Calculation of the fuzzy weights. To obtain fuzzy weights, the calculations of geometric mean are performed for all criteria using equation (2), an example on lower-bound geometric mean of the *i*th criterion (l_i). Geometric mean of m_i and u_i can also be calculated likewise.

$$l_i = \left[\prod_{j=1}^{J} l_{ij} \right]^{1/J} \text{ and } L = \sum_{i=1}^{I} l_i \tag{2}$$

Where l_{ij} is the lower-bound of the *i*th criterion compared with the *j*th criterion and *L* is the total of lower-bound geometric mean. The fuzzy weight of *i*th criterion ($\mathbf{W}_i$) is defined as equation (3).

$$\mathbf{W}_i = \left(l_i \cdot U^{-1}, m_i \cdot M^{-1}, u_i \cdot L^{-1} \right) \quad \forall i \tag{3}$$

3.2.5 Defuzzification. This study selects the center of gravity approach to compute the crisp number of fuzzy weights from all experts because of its simplicity and efficiency. Consequently, the local weight of each criterion is calculated by equation (4) and equation (5) in accordance with Pan's proposed technique [14].

$$\mu_i(x) = \max \left\{ \min \left[\left(\mu_i(x) \right)_{1\text{th expert}}, \left(\mu_i(x) \right)_{2\text{th expert}}, ..., \left(\mu_i(x) \right)_{n\text{th expert}} \right] \right\} \tag{4}$$

Where $\mu_i(x)$ is the membership function of the *i*th criterion and $(\mu_i(x))_{n\text{th expert}}$ is $\mathbf{W}_i$ from the first to the *n*th expert's evaluation regarding the *i*th criterion.

$$x_i^* = \int \frac{\mu_i(x) \cdot x dx}{\mu_i(x) dx} \tag{5}$$

Where x_i^* is the local weight of the *i*th criterion. Repeating equation (2) through (5) for all criteria, attributes, and alternatives yields the local weights of all criteria, attributes, and alternatives. The global weight of the *k*th attribute (AG_k) can be computed by equation (6)

$$AG_k = x_i^* \cdot A_{ik} \quad \forall i \forall k \tag{6}$$

Wherer A_{ik} is the local weight of *k*th attribute subordinate to *i*th criterion. Similarly, the final weights of each alternative (D_m) are computed by equation (7)

$$D_m = \sum_{m=1}^{M} AG_k \cdot D_{km} \quad \forall k \tag{7}$$

Where D_{km} is the overall weight of *m*th alternative pertaining to *k*th attribute.

3.2.6 Sensitivity analysis. Prior to the conclusion of the final results, the α - cut concept is conducted to justify the degrees of uncertainty pertaining to the experts' judgments. The triangular fuzzy numbers in table 1 can be denoted in Eq. (8) for SMI, MI, VI, and VSI. The others are the inverses of those variables, except the equally important variable, whose value is (1,1,1).

$$a_{ij}(\alpha) = \left(l + \frac{1}{3}\alpha, m, u - \frac{1}{3}\alpha \right)_{ij} \tag{8}$$

4. Case Study

This study takes the approaching clean coal power plant projects in the central region of Thailand with coal demand of seven million tons per annum as the clients of the coal center. Map Ta Phut, Si Racha, and Tab Sakae are screened and selected as the potential alternatives. Group decision-makers consisting of five experts who have technical expertise and extensive experiences are formed. To further simplify the problem, the hierarchical structure in figure 1 is created, which considers the ultimate goal of this study– selecting the most appropriate site for a coal center – as the highest level and chosen criteria and attributes as sub-levels of the structure. Based on the hierarchical structure, experts' evaluations are employed to calculate weights of criteria, attributes, and alternatives. Pairwise comparisons are made through linguistic variables depicting in table 2. For example, SOC vs. INF is interpreted as the significance level of SOC compared to INF. Pairwise comparisons of criteria in table 3 exemplify the conversion of linguistic variables to triangular fuzzy numbers of the first expert's assessment in table 4.

Table 3. Pairwise comparisons of criteria.

Pairwise criteria Reference			Result 1st Expert	2nd Expert	3rd Expert	4th Expert	5th Expert
SOC	vs.	INF	MI	MI	VI	VI	MI
SOC	vs.	ENG	SLI	LI	SLI	EI	LI
SOC	vs.	TRA	EI	SLI	EI	MI	SLI
SOC	vs.	ENV	MI	MI	MI	MI	EI
SOC	vs.	COS	VI	VI	VSI	VSI	MI
INF	vs.	ENG	NI	NI	NI	VLI	NI
INF	vs.	TRA	VLI	VLI	LI	LI	VLI
INF	vs.	ENV	EI	EI	EI	SLI	SLI
INF	vs.	COS	MI	MI	MI	EI	EI
ENG	vs.	TRA	MI	EI	MI	MI	MI
ENG	vs.	ENV	VI	MI	VI	VI	VI
ENG	vs.	COS	VSI	VSI	VSI	VSI	VSI
TRA	vs.	ENV	MI	MI	MI	MI	MI
TRA	vs.	COS	VI	VSI	VI	MI	VI
ENV	vs.	COS	MI	MI	MI	MI	MI

Table 4. Pairwise comparisons of criteria.

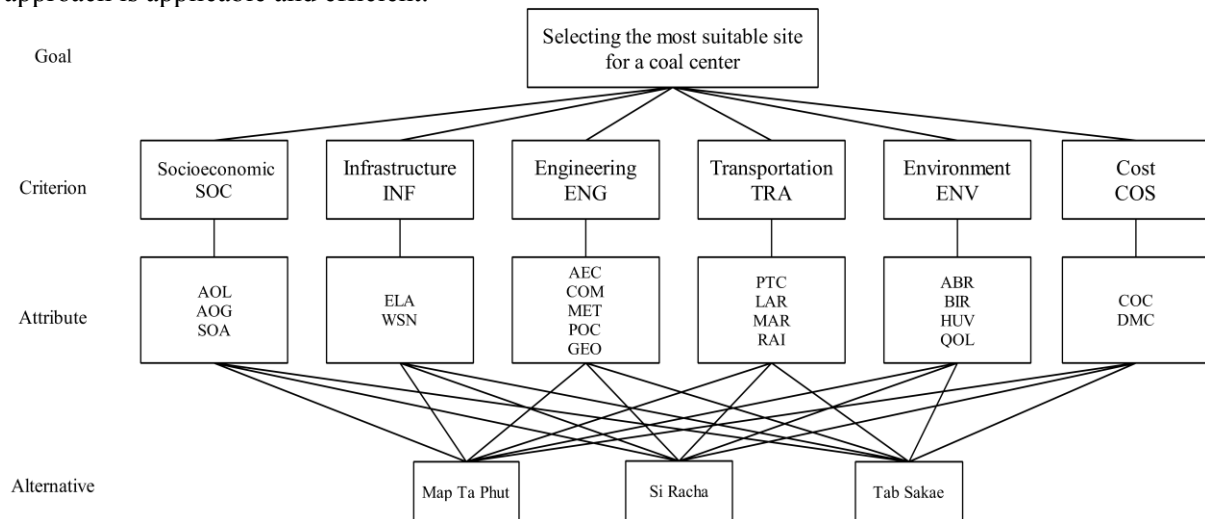|	SOC	INF	ENG	TRA	ENV	COS
SOC	(1,1,1)	(2,7/3,8/3)	(3/5,3/4,1)	(1,1,4/3)	(4/3,5/3,2)	(2,7/3,8/3)
INF	(3/8,3/7,1/2)	(1,1,1)	(3/8,3/7,1/2)	(3/8,3/7,1/2)	(3/8,3/7,1/2)	(1,1,4/3)
ENG	(1,4/3,5/3)	(2,7/3,8/3)	(1,1,1)	(4/3,5/3,2)	(5/3,2,7/3)	(2,7/3,8/3)
TRA	(1,1,4/3)	(2,7/3,8/3)	(1/2,3/5,3/4)	(1,1,1)	(1/2,3/5,3/4)	(5/3,2,7/3)
ENV	(1/2,3/5,3/4)	(2,7/3,8/3)	(3/7,1/2,3/5)	(4/3,5/3,2)	(1,1,1)	(2,7/3,8/3)
COS	(3/8,3/7,1/2)	(1,1,4/3)	(3/8,3/7,1/2)	(3/7,1/2,3/5)	(3/8,3/7,1/2)	(1,1,1)
					Consistency Ratio 0.02	

5. Result and Discussions

The results of analyses of criteria importance indicate that engineering is the most important criteria and socioeconomic, transportation, environment, infrastructure, and cost are ranked respectively. Engineering is considered important most as facility design depends highly on the suitability of an area for construction and operation. Specification and Number of facilities– berth, breakwater, jetty, dredging, stockyard area, and heavy equipment – vary considerably with COM, POC, and TER and have a large effect on cost. Since the presence of the coal center is a tool to advance the prosperity and growth of the nation, acknowledgement and well-being of the local community must not be overpassed. Consequently, socioeconomic is ranked in second. The third ranking is transportation. PTC is the highest attribute importance because the closer end users, the lower delivery cost and delivery time. Additionally, marine transportation is the best transportation mode due to capacity and cost per transshipment. The weight of environment is only a little lower than transportation's because of modern construction techniques, the state-of-the-art facilities, and preventive measures, which have abilities to lessen the adverse environmental impacts significantly. The second lowest and lowest ranks are infrastructure and cost since transmission grid and water supply usually exist although the improvement is required and the coal center construction should not be limited by budget.

In terms of criteria weights, attribute weights and alternative weights, the alternative ranking is Map Ta Phut, Si Racha, and Tab Sakae presented in table 5. Map Ta Phut has the remarkable advantages on engineering and socioeconomic because it is situated in an industrial area with permission granted by the government. Its location is distant from the local community area and is

well-equipped with proper engineering conditions for construction and operations the coal center. However, it has a constraint on limited expandability. On the other hand, Si Racha is selected as the contingency alternative due to its high ability to expand capacity even though there is a tradeoff between expandability and conditions for construction and operations.

To justify the reliability of the results, the α-cut of one is employed. The result shows that the most appropriate alternative is still unchanged, Map Ta Phut (0.385), Si Racha (0.330), and Tab Sakae (0.285). The experts also ensure the rationality and correctness of the results. This strengthens that the approach is applicable and efficient.

Figure 1. Hierarchical structure for coal center site selection.

Table 5. The results of the alternatives.

Criterion		Attribute			Alternative			Final weight		
	Local weight		Local weight	Global weight	Map Ta Phut	Si Racha	Tab Sakae	Map Ta Phut	Si Racha	Tab Sakae
SOC	0.22	AOL	0.40	0.08	0.44	0.28	0.30	0.037	0.024	0.025
		AOG	0.34	0.07	0.47	0.28	0.26	0.034	0.020	0.019
		SOA	0.27	0.06	0.40	0.29	0.32	0.023	0.016	0.018
INF	0.09	ELA	0.60	0.05	0.40	0.20	0.40	0.022	0.011	0.022
		WSN	0.40	0.04	0.33	0.33	0.33	0.012	0.012	0.012
ENG	0.26	AEC	0.16	0.04	0.10	0.30	0.60	0.004	0.012	0.024
		COM	0.25	0.06	0.53	0.33	0.14	0.033	0.021	0.009
		MET	0.18	0.05	0.33	0.33	0.33	0.015	0.015	0.015
		POC	0.24	0.06	0.50	0.25	0.25	0.030	0.015	0.015
		TER	0.19	0.05	0.41	0.29	0.31	0.019	0.014	0.015
TRA	0.19	PTC	0.34	0.06	0.30	0.60	0.10	0.019	0.039	0.006
		LAR	0.19	0.04	0.37	0.42	0.21	0.013	0.015	0.008
		MAR	0.28	0.05	0.36	0.41	0.23	0.019	0.022	0.012
		RAI	0.21	0.04	0.42	0.15	0.43	0.017	0.006	0.017
ENV	0.18	ABR	0.28	0.05	0.42	0.28	0.30	0.021	0.014	0.015
		BIR	0.19	0.03	0.44	0.31	0.25	0.015	0.011	0.009
		HUV	0.33	0.06	0.36	0.34	0.32	0.021	0.020	0.019
		QOL	0.23	0.04	0.36	0.30	0.36	0.015	0.012	0.015
COS	0.10	COC	0.50	0.05	0.50	0.30	0.20	0.024	0.015	0.010
		DMC	0.50	0.05	0.45	0.27	0.28	0.022	0.013	0.014
							Total	0.415	0.326	0.297

6. Conclusion

Precise and accurate selection of the most appropriate site literally generate the success of the coal center. This paper proposes the Fuzzy-AHP approach to resolve the difficulty of dealing with

qualitative and quantitative concurrently and to attain the result with certainty. Based on criteria importance computed by Fuzzy-AHP, high suitability of construction and operational conditions with low adverse effects on the local community are the main reason that justify Map Ta Phut as the most appropriate site for the coal center.

Acknowledgments

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