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Determination of the Red Mud Industrial Cluster Sites in Indonesia Based on Sustainability Aspect and Waste Management Analysis through PROMETHEE

Hendrik [1,2], Yin Yuan [1,3,*], Akhmad Fauzi [4], Widiatmaka [2], Dyah Tjahyandari Suryaningtyas [5], Florentinus Firdiyono [6] and Yang Yao [1,3,*]

1 State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China; hendrik_lee@apps.ipb.ac.id
2 Natural Resources and Environmental Management Science Study Program, Graduate School, IPB University, Kampus IPB, Baranangsiang, Bogor 16143, Indonesia; widiatmaka@ipb.ac.id
3 State Environmental Protection Key Laboratory of Ecological Industry, Chinese Research Academy of Environmental Sciences, Beijing 100012, China
4 Regional and Rural Development Planning Science Study Program, Faculty of Economics and Management, IPB University, Bogor 16680, Indonesia; fauziakhmad@gmail.com
5 Research Center for Mine Reclamation, IPB University, Kampus IPB, Baranangsiang, Bogor 16144, Indonesia; reklatam_ipb@apps.ipb.ac.id
6 Research Centre for Metallurgy, National Research and Innovation Agency, Kawasan Puspiptek, Gedung 474, Tangerang Selatan 15314, Indonesia; flor001@brin.go.id
* Correspondence: yuanyin@craes.org.cn (Y.Y.); yaoyang@craes.org.cn (Y.Y.); Tel.: +86-10-84914256 (Yin Yuan)

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Abstract: Red mud storage is associated with an increased risk of dam failure and there is an urgent need to address the environmental problem caused by the very fine particle size (average 4.9 µm) of red mud with high alkalinity (pH = 10–12.5) in the alumina industry. The specific objective of this study was to investigate the use of red mud based on the "simulation" integrating the sustainability aspect through the PROMETHEE method. The data source is from a field survey with experts conducted at the research location from the province of West Kalimantan, Indonesia. The results of the study using the PROMETHEE ranking parameter showed that the best optimal industrial cluster sites were Ketapang, followed by Belitung Island, Mempawah, and Teluk Batang, with scores of 0.4167, 0.0476, 0.0, and −0.463, respectively. However, using economic input and environmental output, the efficient frontier showed that Ketapang, Teluk Batang, and Pulau Belitung are efficient sites. Considerably more work will need to be carried out to determine the strategic partner in the increasing significant added value in the red mud industrial cluster sites.

Keywords: waste management; environmental protection; mineral resources; sustainable development; cleaner production; eco-industry parks; ecological industry; circular economy; green development

1. Introduction

Since it was reported by the World Commission on Economic and Development (WCED) in 1987, sustainable development has been attracting a lot of interest from across the country. In the literature, this term tends to be used to refer to "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The past decade has seen a growing global demand for bauxite (representing rare earth elements) and its production. However, the issue of utilization and storage of generated residues (red mud) has received considerable critical concern. Consequently, management of several waste streams from metallurgical plants can be a challenging and contentious operation [1,2]. For every ton of alumina produced, about 0.8–1.5 tons of red mud are produced [3]. "Depending on the quality of the raw material processed, 1–2.5 tons of red mud are generated per ton of alumina produced", according to other authors [4]. According to the Central Statistics Bureau (BPS), when alumina production reached 1.17 million tons in 2020, about 1.75 million tons of red mud were produced. It has been previously observed that red mud contains 60 ppm scandium, a valuable rare earth element [5]. Previous research comparing all processing systems for scandium production from red mud has found that red mud pilot plants must have a very long working life because their recovery processes are characterized by very high capital costs (USD 1.5–60 billion) [6].

The Pedersen process can be seen as one of the most powerful alternative methods for recovering alumina from bauxite in a more sustainable manner than the well-known Bayer process. This process technology, which is being adopted by the Greek Pilot Plant, does not produce bauxite residue (red mud), which has many problems regarding disposal and environmental risks. Red mud is a major environmental problem and there has been a debate in the urban community over this red mud disposal lake [7]. Red mud was classified as either a hazardous mirror entry (MH) or a harmless mirror entry (MNH) by the European Parliament and Council commission in 2014 [8]. A mirror entry is defined in the waste classification technical guidelines as two or more related entries, one of which is hazardous and the other not. Red mud is classified as MH or hazardous waste (code number 01-03-10 *) when it contains substances that exceed a certain limit, such as explosive, oxidizing, flammable, irritant, aspiration and/or acute toxicity, carcinogenic, corrosive, and acute release of toxic gases. It is classified as MNH waste or non-hazardous waste (code number 01-03-09) if it does not contain any of the previously mentioned hazardous substances. Storage in dams especially may pose a disaster risk such as the case of the red mud reservoir failure in Hungary in 2010. As a result, this research is of international significance because red mud has not only raised public awareness, questioning the alumina industry's sustainability and environmental footprint more than ever before, but it has also been identified as a potential resource of by-products that can be valorized and converted into valuable raw materials.

In the history of the development of alumina pilot plants, technologies for recycling red mud have been thought of as a key factor to prevent red mud environmental risk accumulation in dumps [9]. The adoption of new technology, such as the Greece Pilot Plant, has recently played an essential role in addressing the issue of red mud recovery [10,11]. Thus, sustainable assessment of pilot plant sites for red mud industrial cluster is fundamental to the red mud recovery process, especially after the completion of 11 alumina refinery pilot plants in West Kalimantan of Indonesia in 2024, which will produce approximately 17.55 million tons of red mud.

Various and quantitative criteria are essential to pilot plant investors in long-term planning. As reported by the previous authors [12], the success or failure of pilot plant site decisions depends on the following factors: availability of raw material, location nearness to the market, transport facilities, availability of labor, availability of water, disposal of waste, local community consideration, suitability of climate, and availability of land. However, previous studies have not dealt with severe problems of urban red mud waste management in West Kalimantan Province as they involved many complex, contradictory, and multidimensional factors [13]. For these reasons, multicriteria decision-making is considered a systemic approach to solve the severe problems.

Many researchers in several multicriteria decision making (MCDM) applications have investigated the location selection of urban waste management systems in various types of pilot plants [14,15]. Izadikhah and Saen [16] proposed a data envelopment analysis (DEA) method with geographic information system (GIS) to determine the best location for constructing agro-industry in seven urban centers in Markazi province, Iran. Ramya and Devadas [17] used the GIS-analytical hierarchy process (AHP), a technique for order preference by similarity to ideal solution (TOPSIS)-based method to solve suitable urban development in Uttarakhand State, India. Kaya et al. [18] found the best site selection of waste electrical and electronic equipment recycling pilot plant, implementing Pythagorean fuzzy measure to determine the criteria weight to reflect the preferences of experts to rank alternative locations at the urban centers on the European part of Istanbul, Turkey. Ghoseiri and Lessan [19] evaluated urban municipal solid waste disposal site selection using fuzzy multicriteria AHP and the ELimination Et Choix Traduisant la Realit'e (ELECTRE)-based method in Arak, Iran.

Mousavi et al. [20] explained the pilot plant location decision using an integrated Delphi–AHP–PROMETHEE methodology. Wu et al. [21] considered various factors, such as economic, environmental, social, and technological factors, to determine the appropriate characteristics for the selection of the pilot plant site. There is no exact method of analysis or assurance for determining the best location. However, recent advances in PROMETHEE methods have facilitated the investigation of the optimization of pilot plant site selection [22–24]. Batubara et al. [25] demonstrated how PROMETHEE could help regulators to develop policies aimed at the development of sustainable petroleum resources.

The specific objectives of this study were to examine alternative uses of red mud (the Pedersen process) through quick assessment by comparing several suitable locations. This paper attempts to address several suitable locations by selecting optimal red mud pilot plant sites based on various weight criteria and a finite set of alternative sites. By applying the PROMETHEE method to solve this severe multicriteria problems [26–29], this study will then solve the severe problems with multiple criteria, multiple weights for decision-making under multidimension criteria, and multiple choices.

2. Materials and Methods

2.1. Study Area

The study area was chosen in a mining town in West Kalimantan Province, Indonesia, owing to its relatively large bauxite areas, as shown in Figure 1. The alternative red mud pilot plant site was representative of port and alumina refinery pilot plant sites [30].

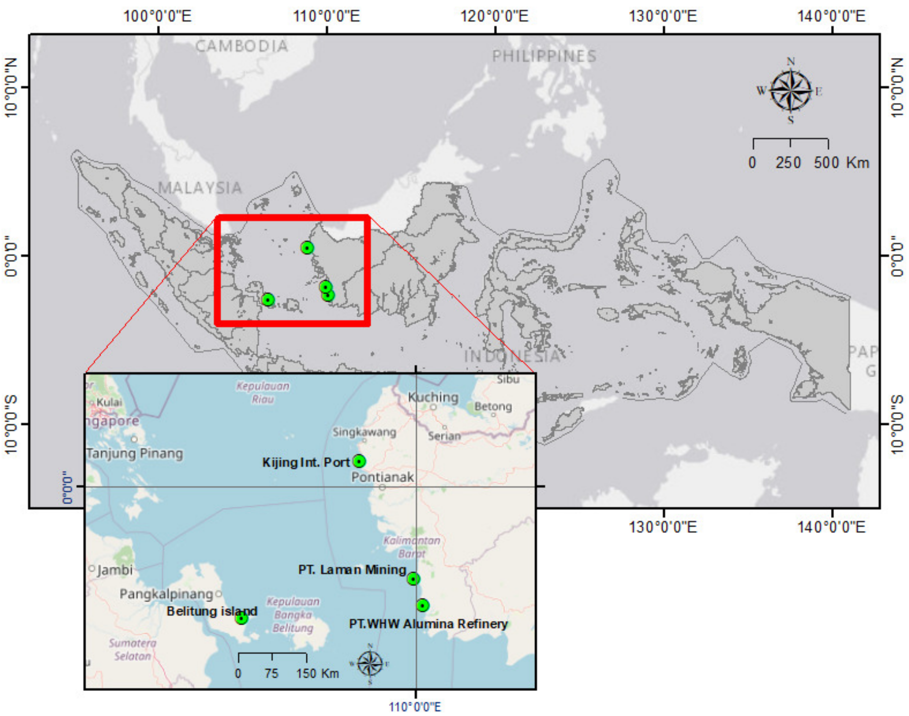


Figure 1. Location of the alumina refinery development plan.

2.2. Source of Research Data

Bathymetric data from National Research and Innovation Agency and map were used in this study and are described as follows:

1. The map (Figure 1) showed the difficulty in locating a deepwater port in the Sukadana Bay area because New Panamax ships need 16 m of draft.

2. The Sadai industrial estate (Figure 1) is relatively attractive. It appears to be integrated with Pangkalbalam ports.
3. Regional government scheme promotes Teluk Batang as an alumina pilot plant site, but a forestry permit is required. Karimata Island, a 141 km bauxite haul from Teluk Batang, is unacceptable because of a strongly protected nature reserve (Figure 1).
4. Antam and several alumina refinery pilot plants use the PT Pelindo II Mempawah port to export alumina from the port and import bauxite (Figure 1).
5. Ketapang industrial estate is integrated with a 7 km jetty to the deepwater anchorage. The site is located near Rahadi Oesman airport and International Supadio airport.

2.3. Research Stage

The research material is primarily obtained from the in-depth interview with $n = 5$. Purposive sampling methods were chosen because the experts have extensive experience and were represented from academician, bauxite mining industry, mining community, and local government. Aggregation multi-expert is given by the geometric mean formula, as shown in Equation (1):

$$GM = \sqrt[n]{x_1 x_2 x_3 x_n} \tag{1}$$

where n is the number of expert(s) of which the rating of the quantitative value of each expert will be multiplied and x_1, x_2, x_3, x_n is the rating of quantitative value from the undesirable ($x = 1$) to excellent ($x = 10$). Another rating qualitative value is the five-point Likert scale, which is secondary data obtained from the Central Statistics Bureau (BPS).

This analysis of red mud pilot plant site selection was based on the conceptual framework proposed by J.P. Brans et al. [31]. The following stage of this research process was used to determine the red mud pilot plant sites (Figure 2). The stage of this research process has four separable basic steps. Firstly, the choice of data area where people, materials, money, machinery, and equipment are collected to establish a pilot plant location. Secondly, the decision on the location of the pilot plant is critical because, once the pilot plant is in place, the organization must weigh the benefits and drawbacks of the initial decision. Thirdly, the investors must consider a variety of factors when deciding where to locate their pilot plant sites, including the availability of labor, materials, money, machinery, and equipment. At the same time, pilot plant location decisions should consider facility expansion and development, proximity to markets, transportation facilities, fuel and electricity availability, water and sewerage availability, and so on. This level of analysis and study can help to maximize the chances of finding the right location. Fourthly, pilot plant site selection decisions necessitate a careful consideration of several factors. These are classified as primary and secondary factors; both can have an impact on the business in the long run [32]. Market and red mud utilization, Sc, wool, pig iron, energy, and infrastructure are all important factors. The socioeconomic environment is a secondary factor. For instance, the sustainability of the climate has a significant impact on alumina industries. Factory locations in these industries are not suitable for extremely humid or dry conditions. The climate can affect labor efficiency and productivity. When deciding where to locate a factory, it is critical to understand existing local government policies such as licensing policies, state-sponsored training, government subsidies, government benefits for locating units in industrial cluster areas, and so on. Disposal of waste is a major problem, particularly for industries such as the alumina industry. Thus, the selected plant location should have a provision for the disposal of brown mud waste. The evaluation of the decision matrix was carried out using PROMETHEE software.

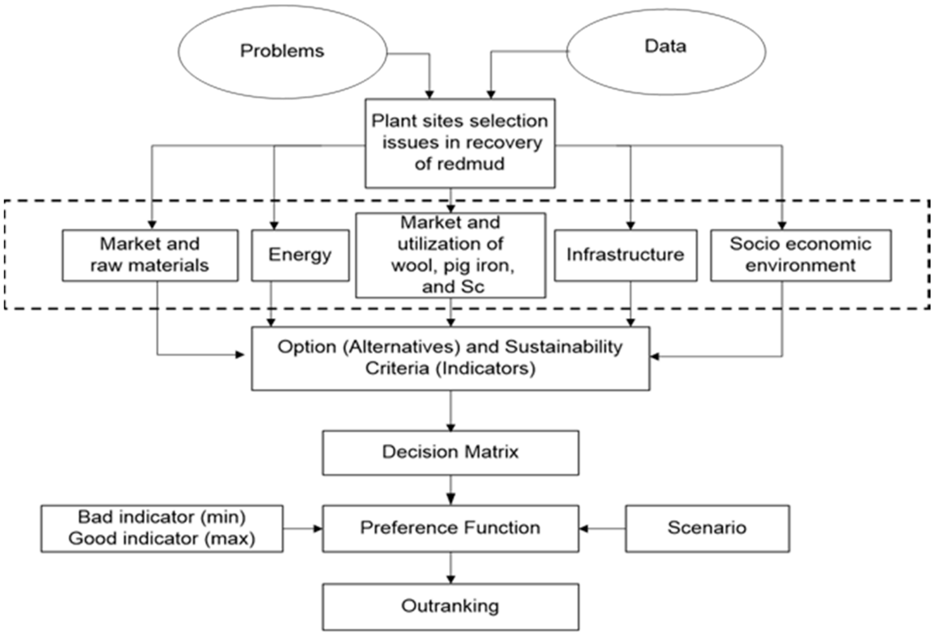


Figure 2. Technology roadmap of research.

2.4. Technique Analysis and Criteria Determination

The PROMETHEE method can evaluate a reasonable pilot plant site, giving best results to generate a profit for the business in the long run. The pilot plant site was chosen for their primary factors, such as relative proximity to the raw materials (red mud) and proximity to the pig iron, wools, and scandium market. Secondary factors are also considered important in affecting the pilot plant location.

J.P. Brans et al. [31] first proposed PROMETHEE as "a multicriteria decision technique". Different authors have measured the pilot plant site in different ways [33,34]. According to J.P. Brans and Mareschal [35], the following PROMETHEE implementation steps are used:

Stage 1: Make at least two alternatives using at least two objects (four alternative red mud pilot plant sites are involved in this site selection).

Stage 2: Conduct a prior literature review to identify several criteria that must be met before planning a decision. In this study, 13 criteria were used to solve a red mud pilot plant site selection problem. Table 1 presents the criteria used in this study. This study employs the appropriate portfolio formation criteria by government reports [36].

Stage 3: Determine the criterion dominance when each criterion has the same weight value or differs from other criteria. There are four predominant criteria:

a. If π (a, b) = 0, there is no difference between a and b or no preferences for a over b.
b. If π (a, b) ~ 0, the weak preference of a is better than b's.
c. If π (a, b) ~ 1, the strong preference of a is superior to b.
d. π (a, b) = 1 indicates that the absolute preference of a is superior to b.

As the nature of the research is to integrate the available criteria, each criterion's weight is the same or equal among other criteria. The appropriate weighting of portfolio formation is assigned unequally in this study using government reports (see Table 1).

Table 1. Criteria for pilot plant location.

Criteria	Min/Max	Type *	Preference Function	Weight *
Proximity to raw materials (PRM)	Max	Qualitativee	Level	3
Proximity to pig iron, wools, and scandium market (PPWSM)	Max	Qualitative	Level	4
Transport facilities (TF)	Max	Qualitative	Level	2
Communication, construction, and maintenance facilities (CCMF)	Max	Qualitative	Level	2
Skilled and unskilled labor (SUL)	Max	Qualitative	Level	2
Labor rate (LR)	Max	Qualitative	Level	1
Waste disposal (WD)	Max	Qualitative	Level	2
State-sponsored training (SST)	Max	Qualitative	Level	1
Water supply (WS)	Max	Qualitative	Level	2
Energy cost (EC)	Min	Qualitative	Usual	4
Building cost index (BCI)	Max	Qualitative	Level	2
General climate (GC)	Max	Qualitative	Level	1
Seismic zone (SZ)	Min	Qualitative	Usual	2

* Weight: degree of importance (4 = most important, 1 = least). * Rating type: quantitative: 10 to 1 (10 = excellent, 1 = undesirable), qualitative: five-point Likert scale (very low, low, average, high, very high).

Stage 4: There are six different forms of preference for each criterion: usual, quasi, linear, level, linear quasi, and gaussian. If the criteria are qualitative and have a minimum scale of 3 or 5, the preference of usual can be chosen. Furthermore, if a quantitative criterion with an indifferent threshold is provided, the preference of quasi can be chosen. Additionally, if quantitative criteria are given, even if the deviation is small, it must be considered for the selection of linear preference. Moreover, if qualitative criteria with a large number of rating levels (e.g., 10 scales) are used, the preferred level is chosen. Yet, if quantitative criteria are expected to yield the desired Q indifference threshold, linear quasi is preferred. When the model is more complex, the latter Gaussian to determine the threshold between P and Q is selected. In general, the following types of preferences are preferred: usual, level, and linear. However, the preference function assistant is provided by the software. It can suggest that the user determines the preference as well. This study employs the usual preference on each parameter to determine the optimum red mud pilot plant site for urban sustainability in West Kalimantan Province (Table 1), because the criteria are qualitative and have a minimum scale of 5. Equation (2) shows the formula used for usual preferences:

$$p(d) = \begin{cases} 0, & -q \leq d \leq q \\ 1, & if\ d < -q\ or\ d\ > q \end{cases} \tag{2}$$

If a = b or f(a) = f(b), this form of preference asserts that there is no difference between options a and b; hence, the preference value is 0. The criterion value that is higher than one option will outperform low criterion value alternatives.

Stage 5: As a starting point for ranking, compute the net flow value. The PROMETHEE method employs three net flows: entering flow, leaving flow, and net flow value. The two central values used to rank alternatives are the entering flow, as shown in Equation (3), and leaving flow, as shown in Equation (4). The following is the equation for entering flow:

Entering flow:

$$\Phi+ = \frac{1}{n-1} \sum a\ \in A\ \varphi\ (a, x) \tag{3}$$

Leaving flow:

$$\Phi- = \frac{1}{n-1} \sum a\ \in A\ \varphi\ (a, x) \tag{4}$$

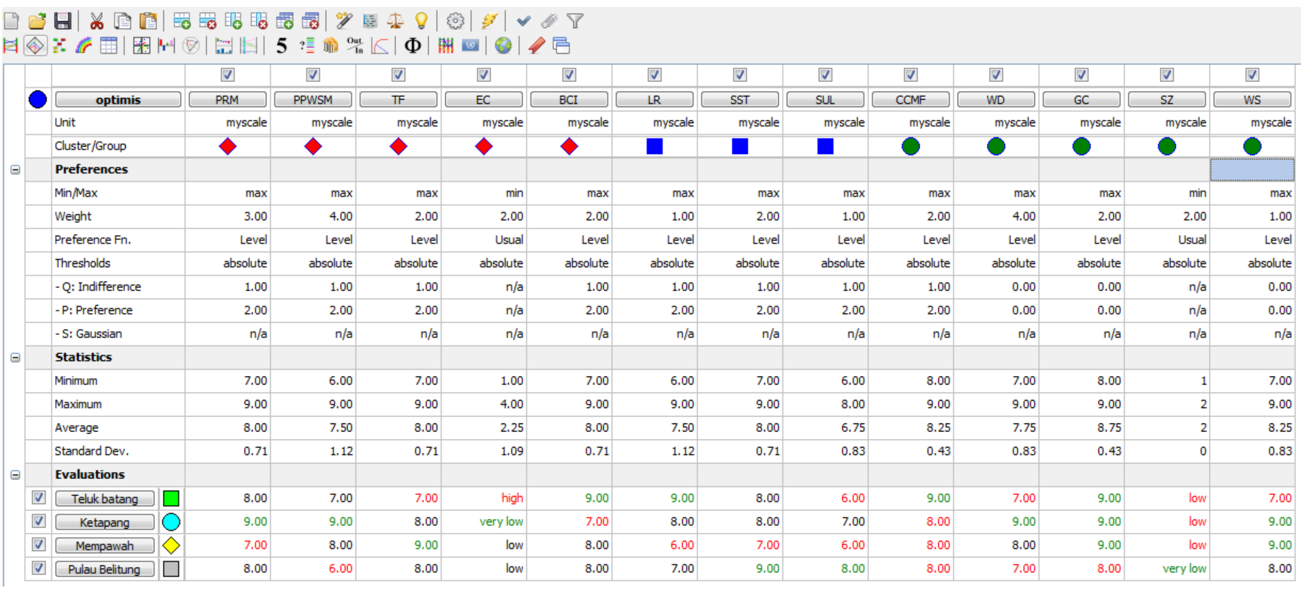
Net flow:

$$\Phi^{+}(a) - \Phi^{-}(a) = \Phi\,(a) \quad (5)$$

where (a) is the net flow, as shown in Equation (5). It is used to make the final decision to rank red mud pilot plant sites in the urban mining industry in West Kalimantan Province, Indonesia, based on the various scenarios.

3. Results

Figure 3 shows the evaluation matrix obtained from the experts' judgment of red mud pilot plant site analysis. In this matrix, each criterion is grouped into economic, social, and environmental groups. Economic groups shown in red include the proximity to raw materials (PRM); proximity to pig iron, wools, and scandium market (PPWSM); transport facilities (TF); energy cost (EC); and building cost index (BCI) criteria. Social groups shown in blue include labor rate (LR), skilled and unskilled labor (SUL), and state-sponsored training (SST). Environmental groups shown in green include communication, construction, and maintenance facilities (CCMF); waste disposal (WD), general climate (GC), seismic zone (SZ), and water supply (WS). Four locations were chosen as alternatives, including Teluk Batang, Ketapang Industrial Estate, Mempawah, and the Sadai industrial estate (Pulau Belitung). The visual PROMETHEE (VP) software was used in this study. In this software, the user can specify the alternatives, the number of criteria, the unit for each criterion, the type of criterion (beneficial or non-beneficial), and the type of preference function. In this study, a usual preference function is chosen. The corresponding threshold (indifference and difference) values for all criteria were assumed to be constant using the VP program's assistant menu. The weight is the same if all criteria are considered equally important. The weight of each criterion, on the one hand, was determined by their primary and secondary factors. Primary factors are regarded as more important than secondary factors. The weight of each criterion has been determined by a previous government report [36]. The software, on the other hand, provides an analysis of sensitivity as shown by the stability interval. It will indicate whether or not the criteria are sensitive to changes in ranking. A previous study [25] showed that the sustainability criteria have various weights that can be adjusted appropriately by decision-makers. For example, the economy criteria are more important to pilot plant site selection than the environmental criteria. Additionally, the value from the experts' judgment was used to run the PROMETHEE program with a single scenario.



optimis	PRM	PPWSM	TF	EC	BCI	LR	SST	SUL	CCMF	WD	GC	SZ	WS
Unit	myscale	myscale	myscale	myscale	myscale	myscale	myscale	myscale	myscale	myscale	myscale	myscale	myscale
Cluster/Group													
Preferences													
Min/Max	max	max	max	min	max	max	max	max	max	max	max	min	max
Weight	3.00	4.00	2.00	2.00	2.00	1.00	2.00	1.00	2.00	4.00	2.00	2.00	1.00
Preference Fn.	Level	Level	Level	Usual	Level	Level	Level	Level	Level	Level	Level	Usual	Level
Thresholds	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute
- Q: Indifference	1.00	1.00	1.00	n/a	1.00	1.00	1.00	1.00	1.00	0.00	0.00	n/a	0.00
- P: Preference	2.00	2.00	2.00	n/a	2.00	2.00	2.00	2.00	2.00	0.00	0.00	n/a	0.00
- S: Gaussian	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Statistics													
Minimum	7.00	6.00	7.00	1.00	7.00	6.00	7.00	6.00	8.00	7.00	8.00	1	7.00
Maximum	9.00	9.00	9.00	4.00	9.00	9.00	9.00	8.00	9.00	9.00	9.00	2	9.00
Average	8.00	7.50	8.00	2.25	8.00	7.50	8.00	6.75	8.25	7.75	8.75	2	8.25
Standard Dev.	0.71	1.12	0.71	1.09	0.71	1.12	0.71	0.83	0.43	0.83	0.43	0	0.83
Evaluations													
Teluk batang	8.00	7.00	7.00	high	9.00	9.00	8.00	6.00	9.00	7.00	9.00	low	7.00
Ketapang	9.00	9.00	8.00	very low	7.00	8.00	8.00	7.00	8.00	9.00	9.00	low	9.00
Mempawah	7.00	8.00	9.00	low	8.00	6.00	7.00	6.00	8.00	8.00	9.00	low	9.00
Pulau Belitung	8.00	6.00	8.00	low	8.00	7.00	9.00	8.00	8.00	7.00	8.00	very low	8.00

Figure 3. Red mud pilot plant site selection using visual PROMETHEE (VP) (see online version for colours).

Although maximization is usually preferred, seismic zones are minimized because of their site risk. Figure 4a shows the ranking results and net flow obtained from four pilot plant site selections. Figure 4b shows the distribution of Phi+ and Phi− from four alternative pilot plants.

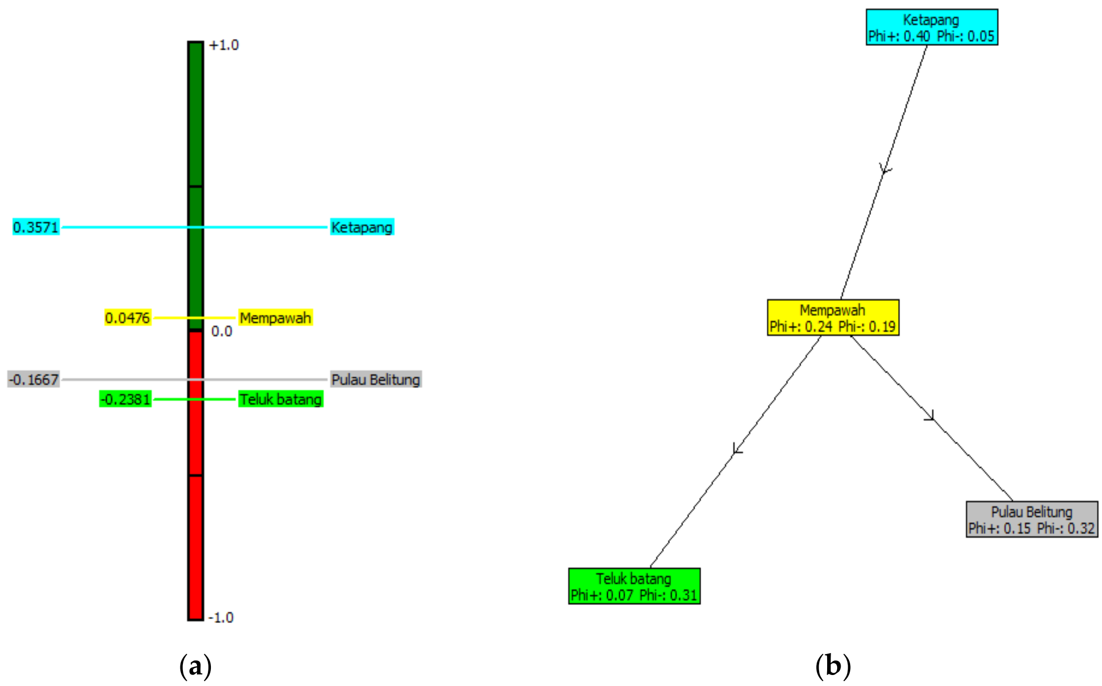


Figure 4. (**a**) Ranking PROMETHEE; (**b**) net flow from four pilot plant site selections.

In addition to ranking PROMETHEE, the results of the contribution from each criterion to the scores obtained for each alternative through the PROMETHEE rainbow can be compared, as shown in Figure 5.

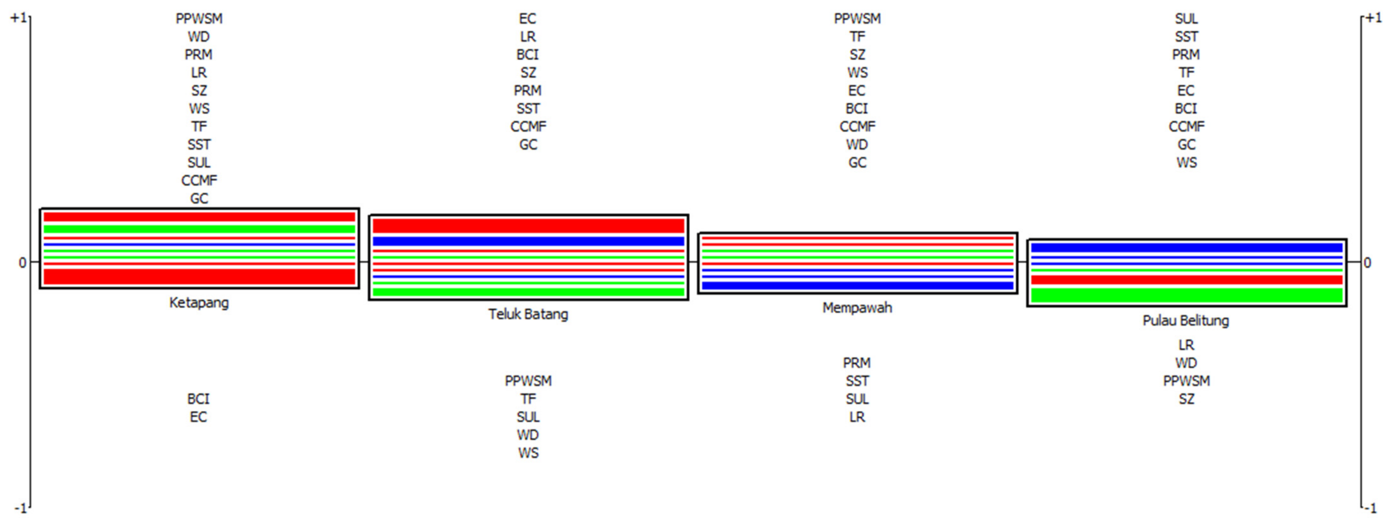


Figure 5. PROMETHEE rainbow for four pilot plant site selections.

Figure 6 shows GAAI plane, which explains the descriptive component of the PROMETHEE ranking. The GAAI shows thirteen criteria (proximity to pig iron wools and Sc, proximity to raw material, transport facilities (communication, construction, and maintenance facilities), labor rate, building cost index, seismic zone, general climate, waste disposal, water supply, state-sponsored training, seismic zone, and energy costs) represented by lines and four evaluated rural areas at locations in Indonesia (Teluk Batang, Ketapang, Mempawah, and Pulau Belitung) represented by squares.

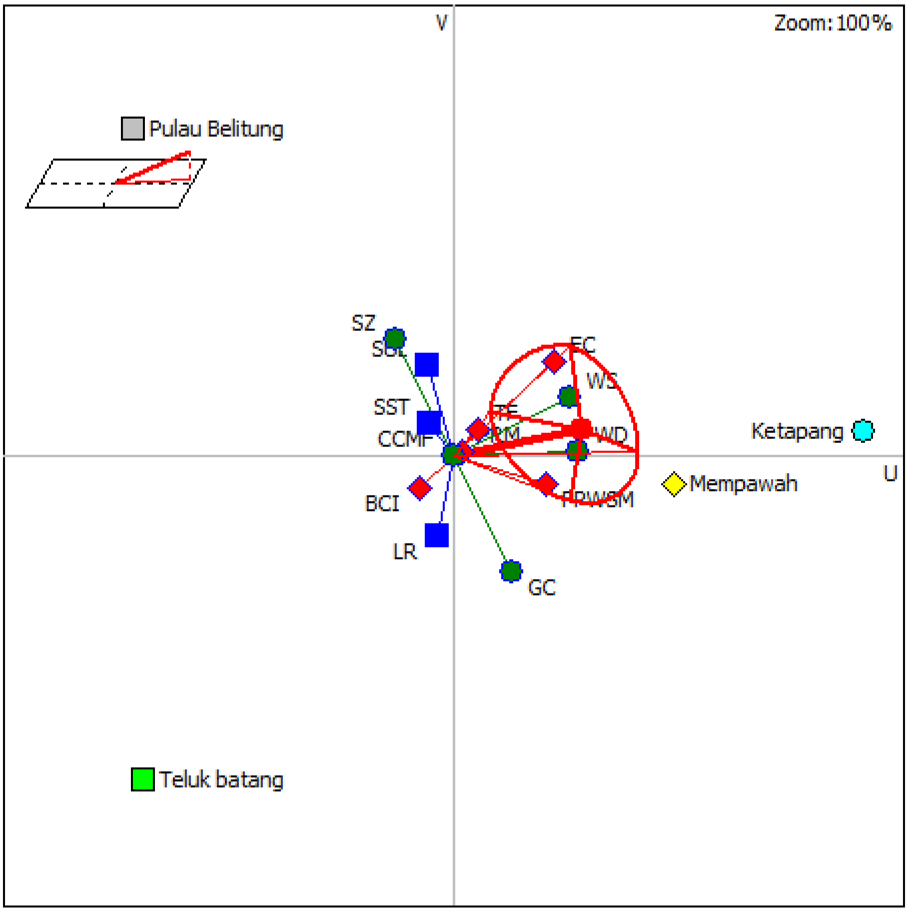


Figure 6. Alternatives and criteria in the GAIA plane.

Figure 7 shows PROMETHEE V, which explains the multicriteria decision analysis under constraints. The constraint is related to budget and contributes positively to its net flow score.

Actions		Net Flow	Optimal	Compare
		Total:	0.3571	0.3571
Teluk batang		-0.2381	no	no
Ketapang		0.3571	yes	yes
Mempawah		0.0476	no	no
Pulau Belitung		-0.1667	no	no

Constraints	Optimal			Compare		
	LHS		RHS	LHS		RHS
Minimum	1.00	>=	1.00	1.00	>=	1.00
Maximum	1.00	<=	4.00	1.00	<=	4.00
Budget	35000000.0	<=	60000000.0	35000000.0	<=	60000000.0

Figure 7. Net flow obtained from PROMETHEE V.

Figure 8 shows a concave frontier because of combining input and output maximization. The ratio of the input/output variables is represented by the X and Y axes. Each unit is plotted against this ratio, and a border is drawn to encircle the result.

Figure 8. Efficient frontier using the social aspect (input) and environmental aspect (output).

4. Discussion

In the PROMETHEE method, the decision-makers solve severe multicriteria problems. The first stage is transforming the primary and secondary factors (sustainability criteria) into the decision matrix using the knowledge of experts corresponding to quantitative and qualitative numbers (Figure 3). As shown in Figure 4a, the top half of the scale (green) corresponds to positive net outranking scores, whereas the bottom half (red) corresponds to negative net outranking scores. From the data, it is apparent that the best pilot plant site is Ketapang, which tops the ranking list. Other sites are considered higher risk. Among them, Mempawah has a value of 0.0476, followed by Pulau Belitung with a value of −0.1667. Teluk Batang is the worst site with a value of −0.2381, because it is far from the alumina pilot plant and the deepwater port to transport pig iron, wool, and scandium.

Figure 5 compares the criterion to the labels in ascending order based on entering flow value (Φ+) and leaving flow (Φ−) values. For example, the following criteria contribute positively for the Ketapang option: proximity to pig iron wools and Sc, proximity to raw material, transport facilities (communication, construction, and maintenance facilities), labor rate, building cost index, seismic zone, general climate, waste disposal, and water supply. Meanwhile, Ketapang's negative contribution is related to state-sponsored training, seismic zone, and energy costs. Ketapang is obviously very close to the industrialized red mud discharge from PT WHW and Laman mining. Thus, a follow-up study with a greater emphasis on the risk of a group of radioactive metal contamination in the red mud site is recommended. Elevli and Ozturk [37] found that the ranking results clearly showed that the most contaminated locations are wastewater discharge points and small ports. This study also showed that the PROMETHEE method is very helpful to analyse environmental problems.

Regarding the geometrical analysis for the interactive aid (GAIA) plane from the software, as illustrated in Figure 6, Phi (δ) was 92%, which is greater than 80%, indicating that this information is fairly rich [35]. This means that the data provided by the GAIA plane are reliable and aid in understanding the structure of a multicriteria problem. Phi is related to the score of net flow represented by a red point. When the human brain is included in the origin of the GAIA plane and the weights are changed, the PROMETHEE decision axis indicates that the location of Ketapang is superior to others, followed by the locations of Mempawah and Pulau Belitung. The locations of Pulau Belitung and Mempawah are distinguished by their proximity to alumina pilot plant sites and the deepwater port, whereas the location of Teluk Batang is distinguished by its excellent building cost index and labor rate. In other words, a large area of red mud storage in the locations of Pulau Belitung and Mempawah is required for the long working life of the pilot plant. Red mud resources are close to all locations except Teluk Batang.

To analyze the scandium recovery process under financial constraints for the waste treatment process, the VP program allows the addition of new criteria at the same time on PROMETHEE V. For example, the result of the budget constraints as a decision factor is the Ketapang site, as shown in Figure 7. If the available budget is assumed to be USD 60 billion, the Ketapang location is chosen because it tops the ranking list, followed by Mempawah, Pulau Belitung, and Teluk Batang. However, additional studies that consider the value of stakeholders' views regarding various weightings will be required to develop a complete picture of optimal alternative pilot plant site selection models [37–39].

Another attractive feature of VP is the ratio of the input/output variables represented by the X and Y axes (Figure 8). Each unit is plotted against this ratio, and a border is drawn to encircle the result. Ketapang, and Pulau Belitung are located at an efficient site when the economy is considered as an input and the environment is considered as an output. The worst locations are Teluk Batang and Mempawah. In the future, it may be possible to use a combination of frontier efficient ranking because the frontier efficient could lead to more reasonable efficient unit, while in classic DEA models, some inputs/outputs may be characterized by very low or high weight values [40,41].

5. Conclusions

This study aimed to determine red mud pilot plant site decisions that consider various factors for the best location. The following general observations were obtained using the PROMETHEE method:

1. PROMETHEE shows that the best pilot plant site is Ketapang.
2. Ranking PROMETHEE, PROMETHEE Rainbow, PROMETHEE GAIA, and PROMETHEE V emerge as reliable predictors for determining red mud pilot plant sites.

The findings of this study acknowledged the importance of experts' values in environmental problem management and waste management. However, the procedure for assigning weights to criteria that accurately reflected the investor's decision criteria was particularly difficult for them. This study lays the groundwork for future research into finding a consensus among stakeholders concerned with managing waste streams from alumina pilot plants. Other secondary factors that were not addressed in this study were whether government incentive policy could be meaningfully incorporated into the decision-making process and the availability of finance, because the pilot plant location should be closer to the areas to easily obtain working capital and other financial needs. Therefore, more studies are required to include other factors that influence pilot plant site selection, such as social risk, regency government competition, and other financial constraints. Furthermore, weighting criteria from stakeholder perspectives must be considered for more complex tradeoffs in future research.

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