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Integrating Analytical Hierarchy Process into Play Fairway Analysis to Construct Favorability Model of Lumut Balai Geothermal System, Indonesia

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ABSTRACT

Play Fairway Analysis (PFA) has been broadly applicable in the geothermal resource assessment. Nevertheless, bias and inconsistency may appear during the resource parameter sensitivity evaluation. A proportional factor number should be assigned to these parameters to measure their impact on the favorability model.

This paper promotes the integration of the Analytical Hierarchy Process (AHP) into the PFA approach to eliminate inconsistency in the resource parameter evaluation. Eighteen resource parameters from Lumut Balai geothermal system were evaluated to construct a favorability model in a 3D environment. The result suggests that feedzone and temperature conditions are highly affecting the favorability assessment in this area. AHP obtained a sensitivity factor for feedzone and temperature of 10.6% and 9.3%, respectively. The study demonstrates a compelling outcome and improves certainty in our favorability model.

1. INTRODUCTION

Play Fairway Analysis (PFA) for the resource assessment was adopted from the oil and gas industry to be applied in the geothermal environment. However, the resource parameters in the geothermal system are unique and influence the favorability outcome differently. To measure this influence, we integrate the Analytical Hierarchy Process (AHP) methodology and weigh the significance of the PFA parameters proportionally. In addition, we tested the consistency and dependency between each parameter to avoid biased judgment in the classification procedure. Eighteen parameters were categorized, factorized, and combined to construct the favorability model of the Lumut Balai geothermal system.

Lumut Balai (LMB) geothermal field is located in Muara Enim, South Sumatra province, Indonesia. Operated by Pertamina Geothermal Energy (PGE), The first unit was commissioned in 2015 from Unit-1, generating 55 MW of electricity. Currently, PGE is working on a development project to generate an additional 55 MW of electricity from Unit-2.

2. GEOTHERMAL SYSTEM OVERVIEW

Lumut Balai (LMB) geothermal field is situated in the Bukit Barisan mountain range on Sumatra island, associated with the oblique subduction between the Indo-Australia and the Sunda plate beneath the island. The regional tectonic motion induces a relatively NNE-SSW normal fault, e.g., the Air Gemuha Besar, Air Ringkih, and Ogan Kanan Fault.

LMB geothermal system develops inside the Old-Lumut caldera with a 10 km diameter. The product of quaternary volcanism dominates the surface formation in the area with andesitic, basaltic, to rhyolitic composition. Tertiary sediment product was found as the basement formation of the LMB geothermal system. The rock formations in LMB geothermal fields from older to younger, are; the metasedimentary basement, pre Old-Lumut, pre Lumut caldera, Lumut caldera, and the post Lumut caldera volcanic product (Figure 1).

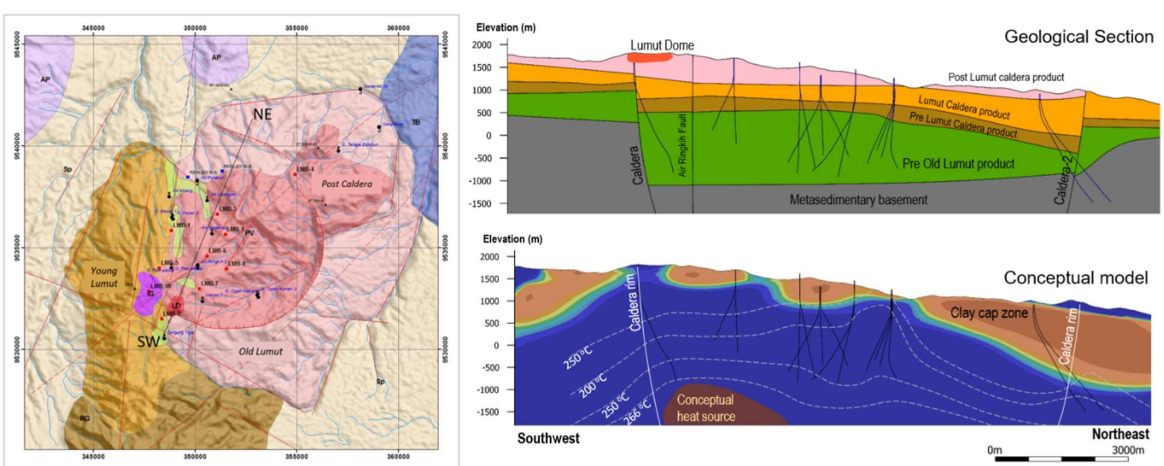

Figure 1: Geological map, subsurface profile and conceptual model of Lumut Balai geothermal system

LMB geothermal system is a water-dominated reservoir with a temperature estimated around 230 to 260°C. Reservoir enthalpy spans between 900 to 1200 kJ/kg, and productive feedzone was discovered at elevation 300 to -1000 from the sea level. The possible heat source was estimated beneath the Lumut dome intrusion located near the southwest part of the caldera rim.

3. METHOD

Eighteen 3D index models were constructed from the geoscience surveys and borehole parameters. The extent of the caldera architecture and the thermal manifestation distribution constrains the boundary of the block model. The vertical boundary was set to 3800 m thickness to accommodate the surface topography and ± 300 m buffer from the borehole trajectory.

The index models were categorized based on specified conditions into six types representing their favorability from zero to five. Adapting from Poux and O'Brien (2020), five is assigned to the most favorable cell, and zero attributes to the least encouraging area (Figure 2).

NO n=18	INDEX MODEL (IM)	CATEGORY					
		0	1	2	3	4	5
	Structure Group:						
1	Distance to Calderas IM	>300	250-300	200-250	150-200	100-150	< 100
2	Distance to Caldera_2 IM	>300	250-300	200-250	150-200	100-150	< 100
3	Distance to Fault Air Gemuha Besar IM	>300	250-300	200-250	150-200	100-150	< 100
4	Distance to Fault Air Ringkih IM	>300	250-300	200-250	150-200	100-150	< 100
5	Distance to Fault Air Udangan IM	>300	250-300	200-250	150-200	100-150	< 100
6	Distance to Fault Ogan Kanan IM	>300	250-300	200-250	150-200	100-150	< 100
7	Distance to Fault Intersections IM	>300	250-300	200-250	150-200	100-150	< 100
8	Distance to Well Traces IM	otherwise	<150	150-200	200-250	250-300	>300
	Remarks: Interference risk	*Ignored*	*High*				*Low*
9	Elevation IM	otherwise	2500-3000	< 1000	2000-2500	1500-2000	1000-1500
	Remarks	*high risk and costly*	*no feedzones*	*Top feedzones*	*bottom FZ*	*bottom of major FZ*	*Top of major FZ*
10	Lithology IM	otherwise	Metasediment	Post Lumut Caldera	Lumut Caldera	Pre Lumut Caldera	Pre Old Lumut
	Remarks	*Ignored*	*High risk depth*	*Shallow lava*	*High MeB zone*	*Tof of epidote zone*	*Proven feedzones*
11	Temperature IM	otherwise	>200	200 to 225	225 to 250	250 to 275	>275
12	Detailed Alteration IM	otherwise	Chl-SQ-Epi	Chl-SQ-Epi-Adu	Chl-SQ-Epi-Act	Act-Wai	Chl-SQ-Epi-Gar-Act
	Remarks	*Ignored*	*all epi zone*	*epi-adu*	*high temp zone*	*high T and k zone*	*Potassic zone*
13	Feedzone (FZ) IM		otherwise				Major
	Remarks		*low permeability*				*measured feedzones*
14	Claycap IM	otherwise	20-18	18-16	16-14	<14	>20
	Remarks: LMB clay value <18 ohm.m	*Ignored*					
15	MeB IM	otherwise	>32	24 to 32	12 to 24	6 to 12	<6
	Remarks	*Ignored*	*reactive clay*	*argillic zone*	*transition zone*	*top of reservoir zone*	*reservoir zone*
16	Density anomaly IM	otherwise	<0	0 to 2.45	2.45 to 2.5	2.5 to 2.6	>2.6
	Remarks: heat source impression	*Ignored*					
17	Data certainty from borehole distance IM	otherwise	<1000	1000 to 1200	1200 to 1400	1400 to 1500	>1500
	Remarks	*Ignored*	*extrapolation*				*high certainty data*
18	Distance to fumaroles IM	otherwise	>500	300 to 500	200 to 300	100 to 200	<100

Figure 2: Categorization of eighteen (18) resource parameter index models based on its favorability index

The influence of a single index model on the favorability assessment was weighted by multiplication with a unique factorization number. The factorization number measures the sensitivity of the parameter to the favorability model proportionally. Factorization numbers were generated by comparing the importance of each parameter into a pairwise comparison matrix using the AHP to provide a benchmark for consistency. The intensity of importance was quantified from a qualitative judgment within a spectrum of zero to nine suggested by Saaty (1987) as presented in Figure 3. If the two compared elements are equally important, it is rated as one (1). The greater *intensity of importance* indicates a more significant influence magnitude and if a parameter is less important than another, we assign it as a fractional number (1 / *intensity of importance*).

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgement slightly favour one over the other.
5	Much more important	Experience and judgement strongly favour one over the other.
7	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice.
9	Absolutely more important.	The evidence favouring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed

Figure 3: The fundamental scale in comparison hierarchy by Saaty (1987) in quantification of the resource parameter influence and significance level

A non-bias factorization number is obtained when the AHP analysis achieves an acceptable consistency ratio for the eighteen parameters (Figure 4). Finally, a 3D favorability block model was produced by combining and calculating the factorized index models using geothermal 3D modeling software.

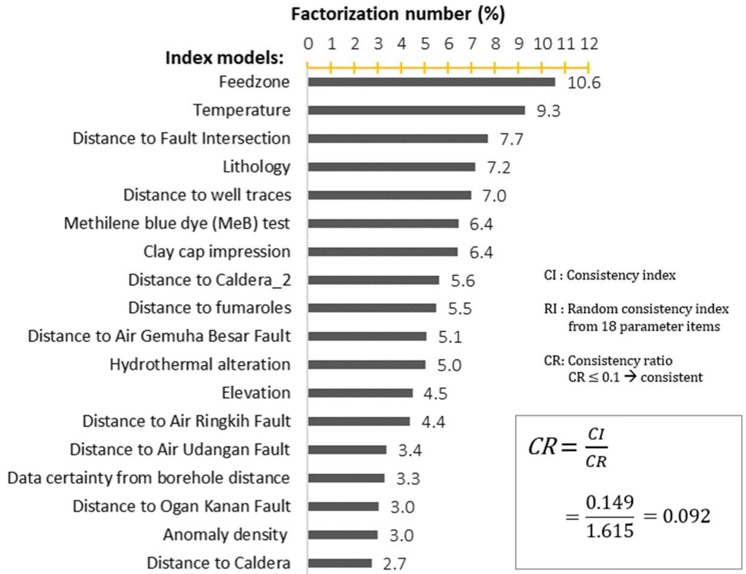

Figure 4: Factorization number for the parameters used in Lumut Balai favorability model assessment

4. RESULT

The normalized pairwise matrix is visualized in Figure 5a, to observe the trend of the importance hierarchy. Feedzone and temperature are the two most significant parameters controlling the favorability assessment in LMB. AHP analysis suggests a greater factorization number for feedzone and temperature, followed by the fault intersection, lithology, and the distance from well traces, ranging from 7.0 to 10.6% (Figure 4).

The significance of the caldera and fault features were exclusively compared based on their impact on productivity and certainty level in the AHP matrix. The spider chart of the structure group indicates the more significant influence of Caldera_2, Air Ringkih Fault, and Air Gemuha Fault compared to the Caldera and Air Udangan Fault (Figure 5b).

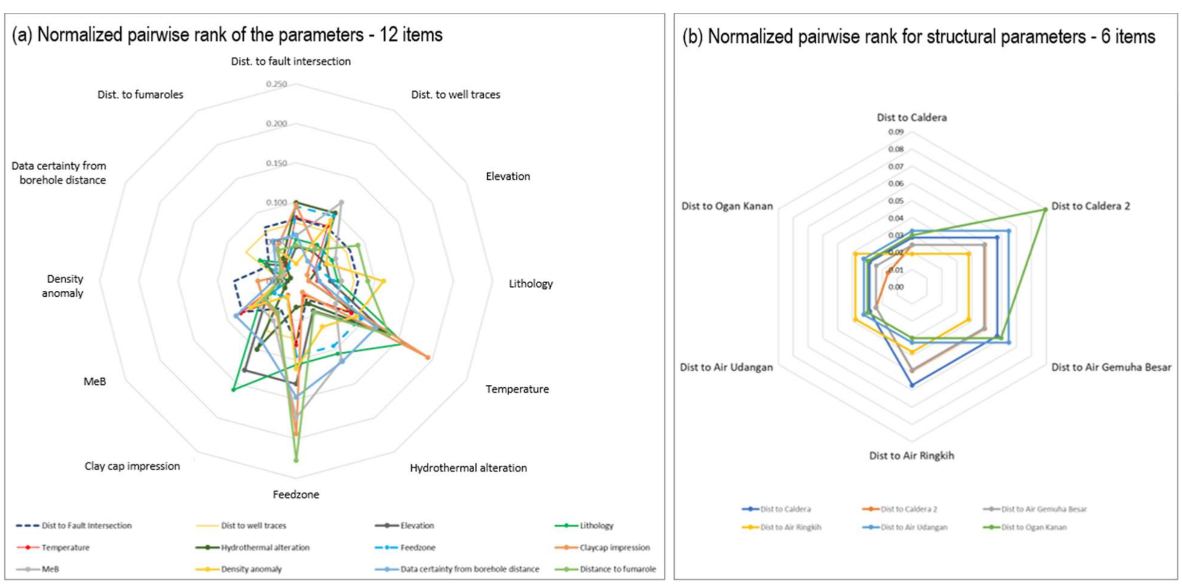

Figure 5: Spider chart depicts the influence hierarchy between the resource parameter are dominated by feedzone and temperature (a). In the structure group, the most influential faults are Caldera_2, Air Gemuha Besar, and Air Ringkih

Figure 2 summarizes the assessment of eighteen parameter index models into six categories. The structure group favorability is categorized based on extrapolating the radius of prominent fault location. The favorable radius is buffered to < 300 m from the structure. A similar manner is applied for the fault intersections, well traces, data certainty from boreholes and fumaroles site, with specified distance variables for different objectives.

Lithology is categorized based on the characteristic of rock formation. The reservoir rock associated with feedzone and high-temperature hydrothermal alteration has a greater favorability score than the others. The lowest point is assigned to the hazardous formation that could lead to an operational problem such as formation collapse. The distribution of secondary minerals classifies the hydrothermal alteration layers. Chlorite, secondary quartz, epidote, adularia, actinolite, wairakite, and garnet are associated with temperature formation > 200℃ discovered in LMB.

The prolific evidence of feedzone and the cost-effective drilling depth influence the elevation rating. The feedzone index model is categorized into two types. The favorable cell with a score of five (5) is given to the discovered feedzone layer by the logging record, and the other area without a feedzone layer is unfavorable (1).

The methylene blue dye (MeB) test and temperature are graded based on the value indicating a high-temperature reservoir zone. The lowest MeB (< 6%) pinpoints the favorable reservoir zone in LMB combined with a temperature of > 275℃.

The magnetotelluric (MT) and gravity measurements are two essential geophysical surveys enclose the extensive area of LMB. The MT model distinguishes the clay cap impression in LMB within the resistivity of 18 to 20 Ω.m. Accordingly, the lowest favorable rank is bounded to this resistivity interval. The anomaly density model derived from the gravity measurement identifies an apparent high-density anomaly within the value ≥ 2.6 gr/cm3. The high-density anomaly implies a dense rock body associated with a possible heat source of the LMB geothermal system.

The favorability block model was produced with a cell size of 200 × 200 × 200 m³. The favorability index attains from the model spans from 0.872 to 3.434% (Figure 6a). This model also points out that the sweet spot for the drill targets in LMB is located within the area with a favorability value greater than 2.40%, or around 4% of the total volume (Figure 5b).

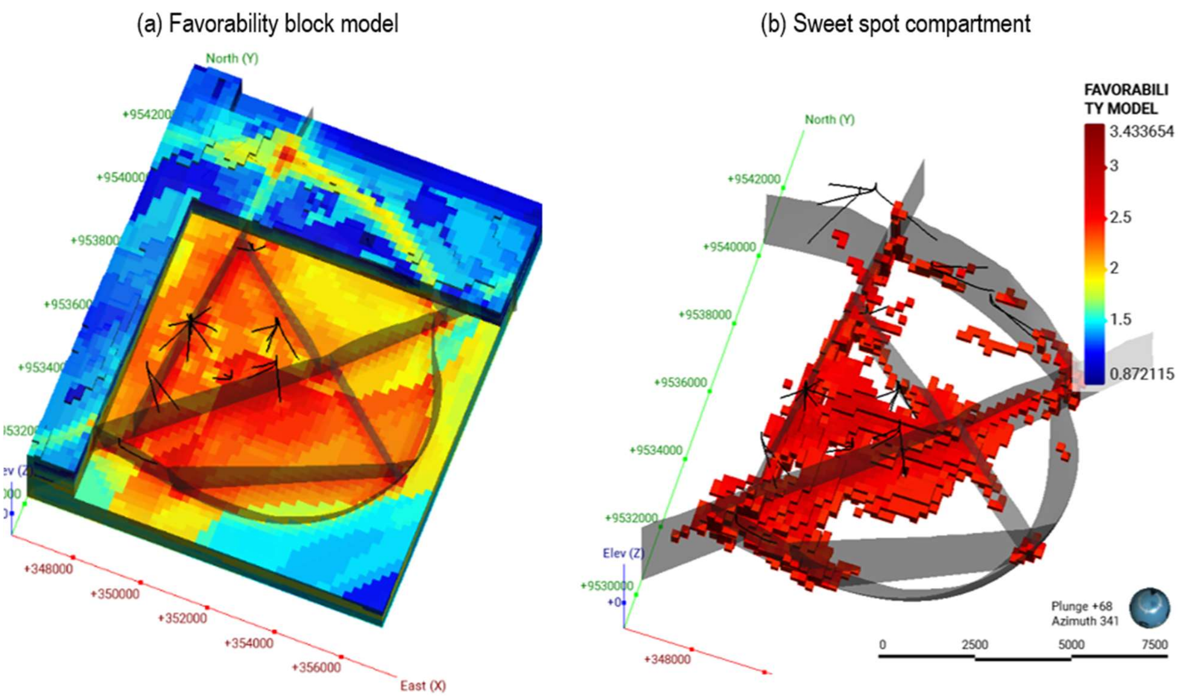

Figure 5: The 3D favorability block model (a) and the preferable block volume that considered as the best drilling target in the Lumut Balai geothermal field with the current modeling factors (b)

4. DISCUSSIONS

PFA assessment of the LMB geothermal system demonstrates the significant influence of the feedzone and temperature parameters. Feedzone and temperature contribution to the favorability model is 10.6 and 9.3%, respectively. The fault intersection has a higher impact than the individual structures. Moreover, if we compare the structure group within itself, the Air Gemuha Besar Fault and Caldera_2 have a notable impact up to 5.1 and 5.2%. The Air Ringkih Fault is likely to be the next preferable target with a 4.4% significance. Despite utilizing a different approach, this result has positive relevancy with the previous LMB fault grading assessment exercised by Nurseto et al. (2020).

PFA in this study has optimized many datasets to build the favorability model. However, the microearthquake (MEq) event data were not included due to its narrow clustered recording area. The thermal manifestations only plot the fumaroles assuming that it discharges from the adjacent source beneath the surface. The hot spring discharge could emerge some kilometers away from the source, increasing uncertainty in the data and distorting the result in our favorability model.

The study demonstrates that the availability and lateral distribution of the dataset affects the favorability model. The favorable zone tends to occupy the block areas with a higher density and frequency of datasets. These block areas are consistently associated with clustered wells and structures.

The LMB favorability block model has a maximum favorability index of 3.434%, indicating that it has no single cell volume containing all the best-graded parameters. The classification procedure was performed for the structural attributes responsible for creating this index value. We classified and factorized the sensitivity of the faults and caldera in this model as a single parameter object. It is done by considering that every fault is unique and has a different level of certainty and productivity. Furthermore, it is not possible in this extensive model to have a cell that collectively accommodates all the regional scale faults in a single block volume as small as 8×10^6 m^3.

Overall, the favorability model points out that the most probable area in the LMB field is situated beneath the Lumut Dome. This result matches the conceptual model of the LMB geothermal system (Figure 1). Positive relevancy between the model and conceptual model should indicate an adequate quality, suggesting that the model is reliable and reasonably assessed.

5. CONCLUSION

The Play Fairway Analysis (PFA) is applicable in the geothermal analysis resource assessment. However, deciding the importance level of the resource parameters is challenging. This situation was solved by integrating the Analysis Hierarchy Process (AHP) into the PFA during the assessment. AHP provides a more accountable procedure for weighing the resource parameters' sensitivity to the favorability model. In addition, AHP allows the comparative decision-making process to be more measurable in consistency and dependency.

Due to different tectonic and geological settings, every geothermal system has a unique character. Thus, the impact of parameters applied in the PFA for each geothermal system will be different from one to another. In this case, temperature and feedzone are responsible the most for the favorability estimation in Lumut Balai geothermal system.

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