Response Surface Method Using Box-Behnken Design for Probabilistic Resource Assessment: A Case Study in Atadei Geothermal Field, Indonesia

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Abstract. Resource assessment in geothermal green-fields will most likely encounter some difficulties due to the limited initial data and directly impact the accuracy of the estimated resources. Proper electricity potential based on resource assessment affects the development scenario in order to determine optimum capacity to be installed. Therefore, this paper applied the response surface method approach using three-level Box-Behnken Design (BBD) to the TOUGH2 numerical model of Atadei geothermal green-field to generate probabilistic resource assessment results. This study aimed to perform the Response Surface Method (RSM) using Box-Behnken design for probabilistic resource assessment in Atadei geothermal green-field. A Box-Behnken design was used to build 27 experiments and investigated four parameters (permeability, porosity, liquid saturation, and feed zone location) at three levels (minimum, most likely, and maximum). The results from multiple model runs were used to create a polynomial function (proxy equation) and then applied to Monte Carlo simulation to generate a probabilistic distribution of the potential power output. This method had been successfully estimated a more robust electricity potential covering the entire range of possible values of important reservoir parameters. The probabilistic electricity potential using Monte Carlo based on Response Surface Method for 30 years production for P10, P50, and P90 are 11.7 MW, 18.2 MW, and 25.6 MW respectively.

1. Introduction
To meet Indonesian geothermal target by 2025, which is 7242 MW, the Indonesian government has committed conducting development in geothermal prospect, including the prospected areas in East Indonesia. One of the prospect areas in Eastern Indonesia, which currently under development is Atadei geothermal prospect area. Atadei is situated in Lembata Regency, East Nusa Tenggara, Indonesia. The location of Atadei geothermal field is shown in Figure 1, and the prospect area is considered as located in a remote area. To reach Atadei from Jakarta would take around two consecutive days and this is counted as one of the challenges found in developing this field. PT. PLN (a state-owned company), since April 2017 has been the concession owner of this field based on SK-permits No. 1894 K/30/MEM/2017.

Nowadays, it is necessary to do probabilistic resource potential assessments that consider the uncertainty of the data. Probabilistic resource assessment is the practice of generating the probability distribution function of a geothermal systems’ resource size or resource potential based on the
uncertainties of the available reservoir information [1]. The most common application of probabilistic resource assessment is carried out with the heat stored method through the Monte Carlo simulation. Probabilistic resource assessment with heat stored method has been carried out by several researchers; [2] in Arjuno-Welirang geothermal field, [3] in Kerinci geothermal field, [4] in Mataloko geothermal field, and [5] in Ulumbu geothermal field. The range of parameter values in these method (heat stored) covers the range of uncertainty for that particular variable [6]. The experimental design based on production is preferred than the heat stored method to provide a better estimate in the resource assessment process [7].

The uncertainties in both subsurface parameters and the development to implement in Atadei geothermal green-field resources can be accommodate using probabilistic assessment with experimental design. Experimental design (ED) is a systematic way of simultaneously testing multiple variables that affect the response. Power capacity calculation with the experimental design using Plackett-Burman which has a fewer combination than others design is enough to represent a valid result in Karaha-Talaga Bodas geothermal field [8]. This study aimed to build a numerical simulation of Atadei geothermal green-field and to perform the response surface method (RSM) based on Box-Behnken design (BBD) for probabilistic resource assessment.

![Atadei geothermal green-field prospect area](image)

**Figure 1.** The location of Atadei geothermal green-field prospect area [9]

2. **Response Surface Method in Reservoir Simulation**

The main objectives of response surface method when using reservoir simulations are the following [1]:

- To systematically design and perform simulation experiments on the reservoir model in order to understand the relationship between uncertain parameters and performance-related responses, and
- To fit a response surface (proxy polynomial) on the simulation experiment result in order to describe the performance-related responses as a polynomial function of the uncertain parameters.
If all parameters are assumed to be measurable, the response surface can be expressed as follows:

\[ Y = f(x_1, x_2, x_3, \ldots, x_k) \]  

where \( Y \) is the answer to the system, and \( x_i \) the parameters of action called factors [10].

This study used a Box-Behnken design with four factors. Box-Behnken design is a class of rotatable or nearly rotatable second-order design based on three-level incomplete factorial design. For three factors, its representation can be seen in Figure 2. The parameters that have high uncertainty in the model are porosity, permeability, liquid saturation, and the location of the feed zone. With four parameters at three levels, a Box-Behnken design will be 27 experiments.

Figure 2. The geometry of Box-Behnken Design. (a) A cube that consists of the central point and the middle point of the edges. (b) A Figure of three interlocking \( 2^2 \) factorial designs and a central point [11].

3. Conceptual Model
The conceptual model was updated by [9] shown in Figure 3. The conceptual model was designed based on comprehensive geoscience reviews and verified by a numerical model approach.
Figure 3. Conceptual model of Atadei geothermal system [after 9].

It appears that hot geothermal fluid is upwelling from the deep part of the Watuwawer caldera. The deep leakage of fracture permeability from Watuwawer Fault and Lewo-Kebingin Fault control the flows of hot fluids-in which it ascends through the given vertical permeability-with some fluids flow laterally to the Southeast until rising to the surface through Mauraja Fault as outflow. In contrary to the initial model, there is a change in determining the depth of the top reservoir as the updated model has followed the interpretation of Magnetotelluric data rather than DC-Resistivity. It stated that in general top of reservoir of Atadei geothermal area is situated around -800 masl. The only exception applied for Watuwawer area in which the reservoir reached the depth of -700 masl.

4. Atadei Numerical Model

4.1. Gridding and Layering

Based on the conceptual model of Figure 4, a numerical model of the Atadei geothermal system was developed. The modeling process was carried out by using a pre- and post-processor of TOUGH2. The grid of the model is rotated at 127° to the East to accommodate the material assignment to be necessary for an arrangement with the alignment of the conceptual model. It is covering a total area of 6.4 km x 5 km or equal to 32 km² and a total thickness of 3.45 km (i.e., from 950 masl to -2500 masl)-which is shown in Figure 13. The horizontal dimension of grid blocks varies from the smallest 100 m x 100 m to 500 m x 500 m, and the smallest grid blocks are used near the reservoir area, wells, and faults to increase the modeling accuracy on that area. The model is divided into 13 layers with some of the top layers following the real topographical condition. The total number of grid blocks is 22,560 by using a rectangular grid. This model used EOS1 for water and water for tracer because of data limitation and to simplify the modeling process.
4.2. Initial and Boundary Condition
The initial condition is needed to input the initial temperature and pressure for each grid-block on the model. At the initial condition, the normal gradient is used for both temperature and pressure. Meanwhile, the top layer is set to constant atmospheric conditions with the pressure is set at $1\times10^5$ Pa and the temperature at 25°C.

4.3. Rock Properties (Assign Material)
During the numerical modeling, determining the permeability structure is the essential step to be iteratively adjusted until the steady state condition was achieved. The iterative process is done by several trial and errors. The permeability structure used in the final modeling is shown in Table 1 and its distribution to the grid model, also shown in Figure 4.

![Material assignment to the model.](image)

**Table 1.** Material properties

| Material | Porosity (%) | $K_{x}$ (mD) | $K_{z}$ (mD) | Color |
|----------|--------------|--------------|--------------|-------|
| ATM      | 99           | 10           | 10           |       |
| GW       | 10           | 0.002        | 0.002        |       |
| CAPR     | 5            | 0.00001      | 0.00001      |       |
| BOUND    | 3            | 0.00005      | 0.00001      |       |
| HEAT     | 10           | 100          | 100          |       |
| RES1     | 8            | 60           | 30           |       |
| RES2     | 7            | 40           | 30           |       |
| RES3     | 7            | 20           | 20           |       |
| RES4     | 7            | 10           | 10           |       |
| RES5     | 9            | 70           | 70           |       |
| RESMT    | 10           | 60           | 30           |       |
| FAULT    | 7            | 30           | 30           |       |
| BASE     | 7            | 3            | 3            |       |
| FAUL1    | 5            | 30           | 20           |       |
| TRNS     | 7            | 0.001        | 0.001        |       |
4.4. Numerical Modeling Result
During the initial state calibration, the computer model was run until natural steady-state conditions were reached. The results were then compared against actual wells temperatures and reservoir temperature estimation obtained from geothermometer. The proper fit between model results and field observation data was obtained by adjusting the permeability structures in an iterative process.

There is only one observation well available to match the model, and it is obtained from AT-1. The dummy wells in Atadei area were also used to match the reservoir temperature by comparing with the temperature estimation obtained from the ammonia geothermometer, considering well AT-1 was not reached the depth of the reservoir. The modeling process was carried out by using a pre- and post-processor of TOUGH2. The temperature distribution at the top of the reservoir is also shown in Figure 5. Figure 6 indicates the temperature matching of AT-01. It shows a good alignment between the actual and the modeled temperature.

![Figure 5. Temperature distribution in the top of the reservoir](image5.png)

![Figure 6. AT-1 Temperature matching](image6.png)
Meanwhile, the distribution of gas saturation in the reservoir which indicated as steam caps is found a relatively further steam formation in Watuwawer and most likely thin steam cap present in Lewo Kebingin as illustrated in Figure 7.

Figure 7. Gas distribution in the model

One of the crucial driver outcomes of the reservoir numerical modeling is the simulation of heat and mass flow within the system, as illustrated in Figure 8. It concludes the whole fluid flow process from the upwelling geothermal heat flow beneath the Watuwawer caldera in which the hot fluids ascend directly through the given vertical fracture permeability later emerge as upflow manifestation in Watuwawer, Lewo Keba and Lewo Kebingin. The residual fluids circulate within permeable zones as the hot fluid with lighter in density ascends until it reaches the impermeable layers where heat losses occur resulting in some cooling fluids descending back to the reservoir and some other flow laterally until it emerges as outflow manifestation in the surface in Mauraja and Lewo Kebingin.
5. Response Surface Method on the Atadei Model

The response surface method (RSM) concept was applied in Atadei reservoir model in order to analyze the dependency from uncertain reservoir parameters to know the amount of production (MW) for 30 years. Furthermore, it also has a purpose to construct polynomial functions (proxy equations) to the reservoir simulation in the probabilistic Monte Carlo simulation. The simulation experiment requires choosing the parameters that will be included in the investigation. The following parameters are deemed sufficient for the current study: porosity, permeability, liquid saturation by changing the relative permeability value, and the location of the feed zone. The sensitivity for each parameter is shown in Table 2.

| Parameter           | Minimum (-1) | Most likely (0) | Maximum (+1) |
|---------------------|--------------|-----------------|--------------|
| Porosity (POR)      | -20%         | Initial Condition | 20%          |
| Permeability (PERM) | -20%         | Initial Condition | 20%          |
| Liquid Saturation (SW) | 0.3      | 0.4             | 0.5          |
| Feed Zone (FZ)      | -600 s/d -800 masl | -800 s/d -1000 masl | -800 s/d -1200 masl |

A three-level of Box-Behnken design, namely minimum, most likely, and maximum with four factors for response surface method was implemented. The required number of runs will be determined based on the Box-Behnken design using software Minitab. The total run for this study is 27 runs for 30 years of production. Table 3 summarised the entire Box-Behnken design with four factors.
Table 3. A three-level of Box-Behnken design with four parameters.

| RunOrder | POR | PERM | SW | FZ |
|----------|-----|------|----|----|
| 1        | 0   | 1    | 0  | -1 |
| 2        | 1   | 0    | 1  | 0  |
| 3        | 0   | 0    | 0  | 0  |
| 4        | 0   | -1   | 1  | 0  |
| 5        | 0   | -1   | 0  | -1 |
| 6        | 0   | 1    | -1 | 0  |
| 7        | 1   | 0    | -1 | 0  |
| 8        | 0   | 0    | 0  | 0  |
| 9        | 0   | 0    | 1  | 1  |
| 10       | 0   | 0    | 0  | 0  |
| 11       | -1  | 0    | -1 | 0  |
| 12       | -1  | 0    | 1  | 0  |
| 13       | 0   | -1   | 0  | 1  |
| 14       | -1  | -1   | 0  | 0  |
| 15       | 1   | 1    | 0  | 0  |
| 16       | -1  | 0    | 0  | -1 |
| 17       | -1  | 0    | 0  | 1  |
| 18       | 0   | 1    | 0  | 1  |
| 19       | 1   | -1   | 0  | 0  |
| 20       | 1   | 0    | 0  | 1  |
| 21       | 0   | 0    | 1  | -1 |
| 22       | 0   | 0    | -1 | 1  |
| 23       | 1   | 0    | 0  | -1 |
| 24       | -1  | 1    | 0  | 0  |
| 25       | 0   | -1   | -1 | 0  |
| 26       | 0   | 0    | -1 | -1 |
| 27       | 0   | 1    | 1  | 0  |

The model parameters then are changed according to the box-behnken design for each combination. The model was run until steady-state conditions to recalibrate the PT well in order to determine whether the model still in natural state conditions or model are not involved in the next process. After reaching natural state conditions, the model then produced for 30 years for each combination.

The reservoir simulation was run equally distributing using well on deliverability method with PI $1.0E-12 \text{m}^3$ and WHP 10 bar. The total production into 143 wells with targeting the steam zone, two-phase zone, and brine zone with temperature more than $200^\circ\text{C}$ in the reservoir, as illustrated in Figure 9.
To calculate the electric potential in MW, the following equation was used [1] [6]:

\[ M_{W_e} = \frac{\sum_{m=1}^{L} m \times \Delta t}{L \times SSC} \]  

(2)

Where MWe is the power capacity in MW, \( m \) is the produced steam vs time by considering a separation pressure and then calculate the steam rate at the wellhead using total rate and production enthalpy (kg/s), \( \Delta t \) is the delta time at the simulation (years), \( L \) is the project time (years), and SSC is the specific steam consumption (kg/s/MW).

The results of Atadei probabilistic resource assessment for 30 years of steam production with 2 kg/s/MW of SSC is shown in Table 4.

| RunOrder | MWe | RunOrder | MWe | RunOrder | MWe |
|----------|-----|----------|-----|----------|-----|
| 1        | 8   | 10       | 19  | 19       | 18  |
| 2        | 19  | 11       | 19  | 20       | 34  |
| 3        | 19  | 12       | 19  | 21       | 9   |
| 4        | 18  | 13       | 29  | 22       | 34  |
| 5        | 8   | 14       | 17  | 23       | 8   |
| 6        | 21  | 15       | 21  | 24       | 21  |
| 7        | 20  | 16       | 8   | 25       | 18  |
| 8        | 19  | 17       | 32  | 26       | 7   |
| 9        | 32  | 18       | 36  | 27       | 21  |

Based on a fitted line plot and surface plot carried out on the Box-Behnken designed results, the only location of feed zone (FZ) among the parameters tested have a significant effect on the 30 years power capacity of the Atadei geothermal green-field. Fitted line plot and the surface plot shows that porosity and liquid saturation have a steady effect on the 30-year power capacity. These results are shown in Figure 10 and Figure 11.
Figure 10. Fitted line plot of Box-Behnken design results

Figure 11. Surface plots of Box-Behnken design results
The Atadei numerical simulation is approximated by the regression equation to generate the power capacity (MW). The regression equation of power capacity as a function of four independent parameters are the results in this study. The three-level proxy model using -1, 0, and +1 parameters to generate the power capacity responses for Atadei model shown in Equation 3.

\[ MW_{e} = 19.000 + 0.3333 \times POR + 1.6667 \times PERM - 0.0833 \times SW + 12.4167 \times FZ + 0.125 \times POR^2 + 0.125 \times PERM^2 + 0.250 \times SW^2 + 1.250 \times FZ^2 - 0.250 \times POR \times PERM - 0.250 \times POR \times SW + 0.500 \times POR \times SW + 0.000 \times PERM \times SW + 1.750 \times PERM \times FZ - 1.000 \times SW \times FZ \]  

Equation 3 then tested for validity to determine the alignment of the regression equation with the model results from the reservoir simulation. Figure 12 shows the comparison between the second-order regression equation of box-Behnken design and the model results. Figure 12 shows a good alignment between the regression results and the model results. This can be seen from the standard error of the regression (S), which has a value of 0.27 MWe. Furthermore, the second-order regression indicates a high R-square ($R^2$) value of 99.72%.

6. Monte Carlo Simulation for Probabilistic Distribution of Power Capacity

Monte Carlo simulation with 60,000 random number was carried out on the proxy model, using the probability distributions of the individual parameter as described in Table 1. The result is a probability distribution function of the power capacity covering the full range of possible outcomes. The proxy model was then applied to calculate the range of possible values for P10, P50, and P90 of MWe. The cumulative distribution for 30 years of steam production of the power capacity shown in Figure 13. The P10, P50, and P90 are 11.7 MW, 18.2 MW, and 25.6 MW, respectively.
Figure 13. Monte Carlo simulation results with histogram and cumulative distribution functions.

7. Conclusion
   1. The model of Atadei geothermal green-field with 6.4 km x 5 km area has been successfully developed, and it showed a good match with actual AT-1 well and conceptual model.
   2. The numerical simulation with response surface method based on Box-Behnken design has been successfully applied to Atadei geothermal green-field.
   3. The second-order regression equation based on Box-Behnken Design shows good alignment with the results of the model, this is indicated by a low standard error of regression (S) value of 0.27 MWe and a high R-square ($R^2$) of 99.72%.
   4. The probabilistic power capacity using Monte Carlo based on Box-Behnken design for 30 years production for P10, P50, and P90 are 11.7 MW, 18.2 MW, and 25.6 MW respectively.

References
[1] Quinao J J and Zarrouk S J 2015 Probabilistic resource assessment using the Ngatamariki numerical model through experimental design and response surface methods (ED and RSM) *Proceedings of 37th New Zealand Geothermal Workshop*
[2] Manggala Putra R P, Sutopo S and Pratama H B 2019 Improved natural state simulation of Arjuno-Welirang Geothermal Field, East Java, Indonesia *IOP Conference Series: Earth and Environmental Science 2019* 254
[3] Hidayat I, Sutopo, and Pratama H B 2018 Probabilistic approach of resource assessment in Kerinci geothermal field using numerical simulation coupling with monte carlo simulation *IOP Conference Series: Earth and Environmental Science 2018* 103
[4] Pradhipta Y D, Sutopo S, Pratama H B and Adiprana R 2019 Natural state modeling of Mataloko Geothermal Field, Flores Island, East Nusa Tenggara, Indonesia using TOUGH2 simulator *IOP Conference Series: Earth and Environmental Science 2019* 254
[5] Kurniawan I, Sutopo S, Pratama H B and Adiprana R 2019 A natural state model and resource assessment of Ulumbu Geothermal Field *IOP Conference Series: Earth and Environmental Science 2019* 254
[6] Ashat A and Pratama H B 2017 Application of experimental design in geothermal resources assessment of Ciwidey-Patuha, West Java, Indonesia *Proceedings of 6th ITB International Geothermal Workshop*
Geothermal Workshop (IIGW) 2017 IOP Conference Series: Earth and Environmental Science 103

[7] Ashat A, Pratama H B and Itoi R 2019 Comparison of resource assessment methods with numerical reservoir model between heat stored and experimental design: Case study Ciwidey-Patuha Geothermal Field IOP Conference Series: Earth and Environmental Science 2019 254

[8] Prabata W, Sutopo S and Pratama H B 2019 Experimental design and response surface method application in resources assessment: Case study Karaha-Talaga Bodas, West Java, Indonesia IOP Conference Series: Earth and Environmental Science 2019 254

[9] Supijo M C, Wahyono A D, Lesmana A, Harahap A H and Berian H. 2018 Updating conceptual model using numerical modelling for geothermal green-field prospect area in Atadei, East Nusa Tenggara, Indonesia Proceedings of 6th Indonesia International Geothermal Convention & Exhibition (IIGCE) 2018

[10] Aslan N and Cebeci Y 2007 Application of Box-Behnken design and response surface methodology for modeling of some Turkish coals Journal of Fuel 8690–97

[11] Ferreira S L C, Bruns R E, Ferreira H S, Matos G D, David J M and Brandao G C 2007 Box-Behnken design: An alternative for the optimization of analytical methods Journal of Analytica Chimica Acta 597179-186