Probabilistic MWe Estimation Using Experimental Design and Response Surface Methodology: Findings from Four Fields

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ABSTRACT

Stochastic power (MWe) capacity prediction from a calibrated reservoir model through building a polynomial model and implementing Monte Carlo simulation is the main focus of this work. The polynomial model is the fitted response of the numerical model to changes in the model's uncertain parameters. Six key stochastic parameter sets were chosen to build several versions of the numerical model using the Experimental Design (ED) and Response Surface Methodology (RSM) framework. This approach was tested and implemented in the calibrated reservoir model of the Rotorua, Ohaaki, Wairakei and Leyte Geothermal Fields using four Experimental Designs (ED): the three-level Full Factorial, two-level Full Factorial, three-level Box-Behnken and two-level Plackett-Burman design. Overall, the ED-RSM framework using the Plackett-Burman fractional design proved to be a practical approach for estimating potential capacity from a calibrated natural-stated model using the chosen six uncertain parameters: permeability in the x, y and z-direction, porosity, reinjection enthalpy (RI Enthalpy), and the fraction of reinjection (%RI).

1. BACKGROUND

The Experimental Design (ED) and Response Surface Methodology (RSM) is still a relatively new concept in geothermal resource assessment. This approach enables building a proxy model using multiple stochastic parameters while requiring only a relatively small number of experimental runs. Previous studies have outlined a framework to demonstrate its potential applicability and described promising results that motivated this work. These studies investigated building a simple regression model that describes the response of a reservoir model from various combinations of model parameter values. An example is by creating a polynomial equation model of power capacity or total cumulative steam as a function of key reservoir parameters by describing the relationship of these parameters one factor at a time (Acuna et al., 2002) or by systematically building multiple versions of reservoir models with different combinations of the uncertain parameters using the Experimental Design (ED) and Response Surface Methodology (RSM) approach (Hoang et al., 2005; Quinao and Zarrouk, 2014a, 2018; Pasikki et al., 2016; Ciriaco et al., 2018; Ciriaco et al., 2020a, 2020b).

The ED-RSM approach is a statistical technique used to investigate the relationship between uncertain parameters involved in an experimental study and provide insights typically for finding the optimal setting for maximum production or sensitivity analysis and uncertainty quantification for simulation-based assessment. The approach allows studying the behaviour of parameters at different conditions simultaneously, which is accomplished by building several versions of an experimental setup according to a specified design. The Experimental Design can be categorised into a Full Factorial or Fractional Factorial design. A Full Factorial design allows the evaluation of all possible parameter-level combinations. A two-level and three-level design are the most commonly used configuration. A two-level design requires specifying the minimum and maximum value of the uncertain parameters, while a three-level design needs a mid-value. Fractional Designs, on the other hand, require only a portion of the total possible parameter-level combinations. The two most commonly used Fractional Designs are the Plackett-Burman and Box Behnken designs.

2. ED-RSM FRAMEWORK AS APPLIED IN GEOTHERMAL RESERVOIR MODELS

The ED-RSM approach has been applied to a complex geothermal system to carry out uncertainty quantification and probabilistic resource assessment. Hoang et al. (2005) used the Plackett-Burman design to evaluate the risks and uncertainties associated with the different expansion options for the Darajat Geothermal Field, Indonesia. Quinao and Zarrouk (2014b) used the same design for the resource assessment of a generic green geothermal field using a TOUGH2-based reservoir model, then built a polynomial of MWe potential capacity as a function of uncertain reservoir parameters. In a further study, Quinao and Zarrouk (2018) reassessed the uncertainty in the generating potential of the Ngatamariki geothermal field. Pasikki et al. (2016) used the Plackett-Burman design to develop a polynomial model of generation potential, expressed in MWe, as a function of the average decline rate for evaluating green fields. Quinao and Zarrouk (2018) adopted the oil and gas industry ED-RSM framework shown in Figure 1. Their works have successfully demonstrated that the ED-RSM framework can be implemented on a numerical model for probabilistic resource assessment, effectively capturing and assessing relevant uncertainties.

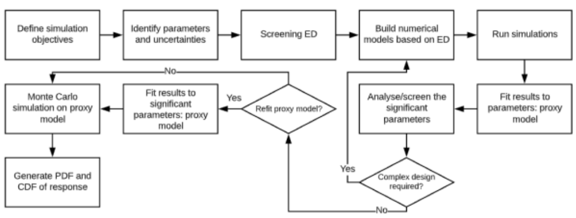

Figure 1. The ED and RSM workflow for probabilistic resource assessment using numerical models used in the oil and gas industry (after Quinao and Zarrouk, 2018).

The ED-RSM framework in Figure 1 was tested and implemented in this study. A staged approach was adopted, and the result of each stage of the experiment was used to determine the steps for the succeeding experiments. The number of simulation runs was determined based on Full Factorial and selected fractional designs and the chosen stochastic model parameters.

2.1 Parameters and Parameters Values

Six reservoir parameters were chosen in this study to build several versions of the reservoir model according to the experimental design set-up: horizontal (k_x and k_y) and vertical (k_z) permeabilities (mD), reservoir rock porosity, reinjected fluid enthalpy (kJ/kg) (RI Enthalpy), and the fraction of separated water that will be reinjected back into the reservoir (%RI). These rock parameters ((k_x, k_y, k_z and porosity) are the main calibration parameters that modellers adjust to simulate and match the measured temperature, pressure and enthalpy. The RI Enthalpy and %RI are dictated by the separator pressure, a critical parameter that affects the development strategy and sustainable output of the field.

The minimum (low) setting, mean value (mid), and maximum (high) values for each of these six parameters are tabulated in Table 1. This range of values accounts for possible uncertainty. In factorial designs, these settings are designated codes; -, 0 and +, respectively.

Table 1. Input parameters (variables) and values used to build the proxy model of numerical models.

Parameter / Variable	Unit	Low (-)	Mid (0)	High (+)
1 - $\boldsymbol{k_x}$ Permeability	$10^{-15}m^2$	1	500	1000
2 - $\boldsymbol{k_y}$ Permeability	$10^{-15}m^2$	1	500	1000
3 - $\boldsymbol{k_z}$ Permeability	$10^{-15}m^2$	1	500	1000
4 - Porosity		0.01	0.155	0.3
5 - Injection fluid enthalpy	kJ/kg	334.9 (80 °C)	503.8 (120 °C)	675.6 (160 °C)
6 - Fraction of extracted mass flow reinjected into the reservoir (%$\boldsymbol{RI}$)	(%)	50	70	90

There are other possible uncertain model parameters (e.g., the location of the upflow, reservoir model boundaries, dual-porosity configuration, fixed mass or productivity index). These parameters are impossible to measure on a reservoir scale. It can only be estimated, but it takes expert judgment to assess if the estimated values are reasonable and realistic.

It is also important to mention that the location and number of production and injection wells are the most difficult to set in designing the experiment. This is where subject matter expertise and the unique field setting play an important role. Experience has shown that the following criteria should be met in assigning the wells and feed zones:

- Production well block temperature of at least 220 °C
- Production well block permeability of at least one millidarcy (1 mD)
- A distance of at least 200 m between feed zones
- Provision for make-up (additional or replacement) wells.

The required output from the simulation experiment is the power capacity expressed in power output. The equation to calculate the power in MWe from the results obtained from the numerical simulation is provided below:

$$MW_e = \left[\sum_{i=0}^{i=n} \dot{m}\, (t_{i+1} - t_i) \times h\, (t_{i+1} - t_i) \right] \times \eta_c \qquad (1)$$

where:

$\dot{m}$ is the total mass flow rate (kg/s)

h is the flowing enthalpy (kJ/kg)

t_i is the time step (seconds)

η_c is the overall conversion efficiency (%)

Conversion efficiency of η_c= 12% was used for converting thermal power to electrical power, as suggested by Zarrouk and Moon (2014).

3. DISCUSSION OF RESULTS

The experiment resulted in a trial-and-error process. The most challenging part of the iterative process was finding the appropriate number of wells and feed zones and the mass flow distribution that will allow them to produce for up to 50 years for Rotorua, Ohaaki and Leyte and 100 years for Wairakei.

3.1 The Rotorua Geothermal Field

Three different Experimental Designs (ED) were utilised to investigate the power potential of the deeper part of RGF: three-level Full Factorial, two-level Full Factorial and three-level Box-Behnken. The regression analysis was carried out using statistical software R.

A cut-off pressure of 80 bar at the feed zone depth was set in the experiment. Feed zones that are way below this pressure were removed from the reservoir model. Some wells with a block pressure a little lower than 80 bars but with higher enthalpy and still have at least 9 bar pressure at the wellhead were retained. Wells that did not meet the 50 years criteria can be considered make-up wells. Results of the experiment suggest that RGF can sustain production if produced at -1100 MASL.

A more detailed discussion of the results of applying the ED-RSM approach to the Rotorua geothermal model is found in a paper published by Ciriaco et al. (2020b). Overall, the findings revealed that a second-order polynomial model built from a three-level Full Factorial design was a statistically acceptable proxy model of the numerical model. Furthermore, this case study successfully demonstrated that a two-level Full Factorial design was useful for screening significant parameters. The significant predictors of MWe from the three-level Full Factorial design were the same as the two-level Full Factorial design. Furthermore, the predicted MWe tabulated in Table 2 is similar for all three designs.

The final polynomial model of the Rotorua production model using the three-level Full Factorial model is given in Equation 2. Using Equation 2 and a simple triangular distribution for all the parameters, a probabilistic distribution of MWe was generated using a Monte Carlo method. The results shown in Figure 2 suggest that the Rotorua geothermal field has an MWe capacity of 262 MWe (90th percentile), 263 MWe (50th percentile) and 265 MWe (10th percentile). Although the Rotorua geothermal field is a protected system, the Rotorua township is located on top of this system (which limits access to the reservoir). The ED-RSM framework confidently estimated the power potential of the field to be at least 262 MWe.

$$\begin{aligned} \boldsymbol{MWe} = {} & 263.1 + 5.06e11 \times k_x - 4.59e11 \times k_y - 2.8e12 \times k_z \\ & - 0.53 \times porosity - 0.000001 \times RI\ Enthalpy + 1.74 \times \%RI \\ & - 2.37e23 \times k_x^2 + 6.21e22 \times k_y^2 + 1.46e24 \times k_z^2 \\ & - 3.16 \times RI\ Enthalpy^2 - 5.844e22 \times k_x \times k_y \\ & - 5.42e22 \times k_x \times k_z - 8.32e4 \times k_x \times RI\ Enthalpy \\ & - 1.986e11 \times k_x \times \%RI + 3.64e23 \times k_y \times k_z \\ & + 2.66e5 \times k_y \times RI\ Enthalpy + 1.11e11 \times k_y \times \%RI \\ & - 2.48e5 \times k_z \times RI\ Enthalpy + 8.06e11 \times k_z \times \%RI \\ & + 0.00000448 \times RI\ Enthalpy \times \%RI \end{aligned} \tag{2}$$

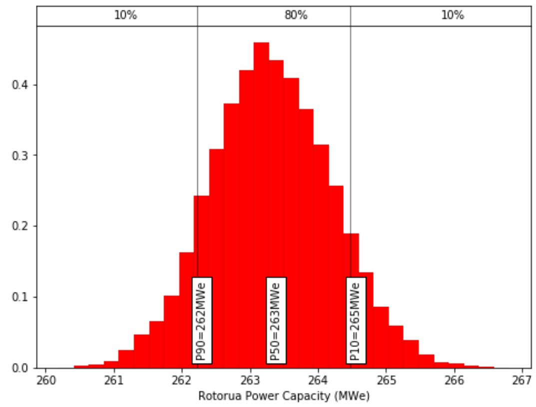

Figure 2. ED-RSM probabilistic resource assessment of the Rotorua Geothermal Field using the three-level Full Factorial design.

Table 2. Summary of estimated potential MWe of the Rotorua Geothermal Field using the two-level and three-level Full Factorial and Box Behnken designs.

	Three-Level Full Factorial	Two-Level Full Factorial	Box-Behnken
90th percentile (MWe)	262	263	262
50th percentile (MWe)	263	264	263
10th percentile (MWe)	265	265	265

Another interesting finding from this case study is that it suggests that a Box Behnken fractional factorial design may be suitable for building a proxy model. The results further suggest that the ED-RSM workflow for geothermal probabilistic assessment can be carried out using the workflow described in Figure 3.

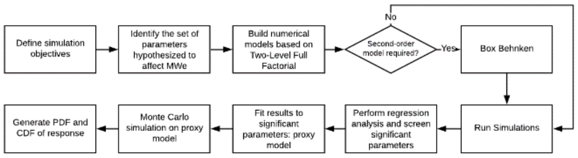

Figure 3. The improved ED-RSM workflow for geothermal probabilistic resource assessment.

This case study has challenged the conventional approaches to performing a probabilistic resource assessment and discovered that the ED-RSM approach is a practical and efficient technique for deriving insights. To further confirm the results from this study, the three experimental designs (three-level Full Factorial, two-level Full Factorial and Box-Behnken) were used in the next case study: the Ohaaki geothermal field.

3.2 The Ohaaki Geothermal Field

The Ohaaki reservoir model used in this study was calibrated using actual temperature and pressure measurements and estimated production enthalpy data. There was no additional calibration performed when the model was used to implement the ED-RSM framework.

Like the Rotorua case study, three different Experimental Designs (ED) were utilised to investigate the power potential of the deeper part of RGF: three-level Full Factorial, two-level Full Factorial and three-level Box-Behnken. Furthermore, the Ohaaki experiment also resulted in the process of finding the appropriate number of wells and feed zones and the mass flow distribution that will allow them to produce up to 50 years.

A complete discussion results of the Ohaaki case study are discussed by Ciriaco et al. (2020b). Equation (3) was used to generate a probabilistic distribution of MWe using a Monte Carlo method. A simple triangular distribution was assigned to each parameter. The results from the three-level Full Factorial design summarised in Figure 4 suggest that the Ohaaki geothermal field has an initial (pre-development) capacity of 65 MWe (90th percentile), 66 MWe (50th percentile) and 67 MWe (10th percentile).

Figure 4 provides a very interesting estimation of the power potential of the Ohaaki geothermal field. The ED-RSM forecast suggests that Ohaaki could only sustain about 65 MWe for 50 years. This is much lower than the installed initially 116 MWe power plant. Furthermore, the ED-RSM forecast results support the decision made by Contact Energy, Ltd of de-rating the Ohaaki geothermal plant as there is a clear indication that the reservoir cannot support the 116 MWe generation long term.

$$
\begin{aligned}
\boldsymbol{MWe} = 70.41 &- 3.107e12 \times k_x - 6.860e11 \times k_y - 1.659e12 \times k_z \\
&- 1.467 \times porosity - 5.446 \times \%RI + 1.326e24 \times k_x^2 \\
&- 1.063e23 \times k_y^2 + 5.202e23 \times porosity^2 + 2.850 \times \%RI^2 \\
&+ 4.374e23 \times k_x \times k_y + 2.811e23 \times k_x \times k_z \\
&- 4.128e11 \times k_x \times porosity + 1.086e12 \times k_x \times \%RI \\
&- 9.986e22 \times k_y \times k_z - 3.309e11 \times k_y \times porosity \\
&+ 1.031e12 \times k_y \times \%RI + 3.862e11 \times k_z \times porosity \\
&+ 1.016e12 \times k_z \times \%RI + 0.5457 \times porosity \times \%RI
\end{aligned} \tag{3}
$$

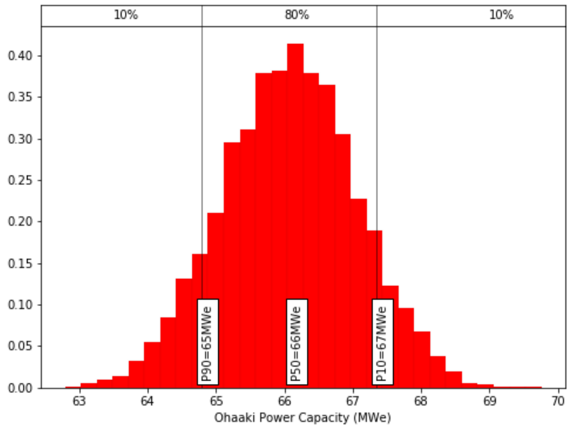

Figure 4. The geothermal probabilistic resource assessment of Ohaaki Geothermal Field using the three-level Full Factorial design.

Table 3. Summary of estimated potential MWe of the Ohaaki Geothermal Field using the two-level and three-level Full Factorial, and Box Behnken designs.

	Three-Level Full Factorial	Two-Level Full Factorial	Box-Behnken
90th percentile (MWe)	65	67	66
50th percentile (MWe)	66	68	67
10th percentile (MWe)	67	70	68

This case study was intended to repeat the experiment performed using the Rotorua numerical model and uncover patterns or consistencies that would guide the succeeding steps in testing the ED-RSM framework in geothermal resource assessment. Below is a summary of the results so far:

- A three-level Full Factorial design captured all the information in the data contained in the results of varying different combinations of parameters at different levels. However, it was expensive to run an experiment using the three-level Full Factorial design. Six parameters at three levels required 729 reservoir model runs.
- The two-level Full Factorial (first-order) and Box-Behnken (second-order) were useful designs for reducing the required number of simulation experiments.
- The two-level Full Factorial is a first-order experimental design that requires only two levels per factor. It served as a screening design and a guide for building polynomial models from the results of the Box-Behnken design experiments.
- The significant variables from a three-level Full Factorial design second-order polynomial model were almost the same as the significant variables from a two-level Full Factorial design first-order polynomial model.
- While it is essential to satisfy the statistical requirement to accept a regression model, this study demonstrated that a two-level Full Factorial is sufficient for developing a proxy model of computer simulation models.
- A two-stage approach was necessary for a second-order polynomial model, and the sequence should be a two-level Full Factorial design first, followed by Box-Behnken design.
- All the six parameters, including the reinjection enthalpy, were important predictors of MWe based on the results of the two-level Full Factorial. The significant effect of reinjection enthalpy on sustaining the production is particularly critical for a small-sized field like Ohaaki.
- The refined ED-RSM approach can produce a probabilistic MWe estimate of a geothermal field from a calibrated reservoir model in an efficient manner, which may mitigate the risk of over-developing a field.
- The retrospective study of the Ohaaki geothermal field gave a power potential of 65 MWe (P90) for 50 years, indicating that the installed capacity of 116 MWe in 1988 was an overestimate of the Ohaaki geothermal reservoir can sustain long term.

One significant discovery from the two case studies is the evidence that a two-level Full Factorial is sufficient for developing a proxy model of numerical models. To further test the applicability of the ED-RSM framework for a probabilistic estimate of geothermal resource capacity, two Experimental Designs will be implemented: two-level Full Factorial and Plackett-Burman designs. These two designs will be used to determine a more practical approach for building polynomial models and tested using the calibrated reservoir model of the Wairakei geothermal field.

3.3 The Wairakei Geothermal Field

The full results of testing the ED-RSM approach using the 2014 Wairkei model is presented in the paper of Ciriaco et al. (2022a).

In this study, we did not attempt to improve the model's natural state and production history match. Instead, we extracted information from the model that is useful in testing and implementing the ED-RSM framework. It is important to note that implementing the ED-RSM framework on the 2014 Wairakei model is a retrospective examination. This numerical model covered the Wairakei, Te Huka, Tauhara and the Rotokawa areas. However, since we are only interested in Wairakei, we designed the experiment to only produce and inject in the Te Mihi, Poihipi, Western and Eastern Borefield and Otupu areas of the Wairakei geothermal field and exclude Te Huka, Tauhara and Rotokawa in the investigation.

The experiments performed for this case study is divided into two parts. First, we tested two ED-RSM designs for estimating the initial capacity of Wairakei using the calibrated natural state model: the two-level Full Factorial design and the Plackett-Burman design. The second part of this study involved simulating the MWe potential of Wairakei for 50 years and 100 years using the Plackett-Burman design.

Four parameters turned out to be significant predictors of MWe, and it is the same in both designs. These parameters are k_x, k_y, k_z and %RI. Inspection of the polynomial equations reveals that the coefficients of each of the parameters have relatively similar values. The sign of the coefficient of all four individual parameters indicates that each has a positive value. A positive coefficient implies that the MWe moves in the same direction as the value of these parameters. That is as the value of k_x, k_y, k_z and %RI increases, the MWe increases. There is also an appreciable interaction between these four parameters in the final polynomial model. The coefficient of all the interactions except the interaction of k_y and %RI is negative. The interaction of k_x with k_z and %RI has a significant impact on MWe.

k_x, k_y, k_z and %RI are crucial reservoir parameters, and the results are consistent with our understanding of the reservoir. The sign of the coefficients of the parameters is consistent with our understanding of the relationship of these parameters with production capacity.

$$\begin{aligned} \boldsymbol{MW_e Plackett - Burman}\ (\boldsymbol{50\ years}) \\ &= 248.00 + 5.69e^{13} \times k_x \\ &+ 1.02e^{13} \times k_y + 4.41e^{13} k_z \\ &+ 28.2 \times \%RI \\ &- 9.23e^{24} \times k_x \times k_y \\ &- 2.74e^{25} \times k_x \times k_z \\ &- 4.23e^{13} \times k_x \times \%RI \\ &- 5.98e^{24} \times k_y \times k_z \\ &+ 1.063e^{13} \times k_y \times \%RI \\ &- 1.55e^{13} \times k_z \times \%RI \end{aligned} \tag{4}$$

Table 4. Summary of estimated potential MWe for 50 years of the Wairakei Geothermal Field using the two-level Full Factorial and Plackett-Burman designs.

	Two-Level Full Factorial	Box-Behnken
90th percentile (MWe)	266	266
50th percentile (MWe)	287	286
10th percentile (MWe)	307	307

The Plackett-Burman design requires only 12 different versions of model runs, while the two-level Full Factorial involves 64 different models. It is evident from the results obtained in this experiment that the Plackett-Burman design is sufficient to describe a calibrated numerical model and produce a prediction that is comparable to a two-level Full Factorial design.

While the results of both the Plackett-Burman and two-level Full Factorial are similar and could give confidence with the predicted values, it is still encouraged to take caution in using and interpreting the results. Here are some of the things to take into consideration:

- The MWe was calculated using equation (1). This simple equation calculates MWe at a feed zone level. While this equation may capture the effect of enthalpy changes due to pressure and temperature drawdown, the equation may still have oversimplified the actual conversion from thermal energy to MWe. The conversion of the produced fluid to MWe in an actual geothermal field still varies depending on the separation technology and power plant settings. Furthermore, any improvement in the performance of the surface facilities efficiency is not accounted for in the formulation of the experiment, thus in the final polynomial model as well.
- The feed zones were produced at a fixed mass flow, and only the feed zones that sustained production for up to 50 years were considered in the calculation of MWe. To simplify the experiment, the wells that died before 50 years were treated as replacement wells. Production from these short-lived wells could increase the MWe estimate. Further investigation is required to evaluate its impact on the prediction. In the meantime, the authors believe that they could serve as replacement wells when the output of the final model feed zones declines with time or becomes non-commercial due to reservoir processes such as scaling and injection returns.

There are some aspects of the actual reservoir that the polynomial model may have oversimplified. The permeability of rocks, for example, varies spatially and temporally. It differs for each lithologic unit, varies with depth and changes with time once production starts, and may not be fully represented by a single parameter or a single value in equation (1). The polynomial model also does not account for any deficiency in translating the essential aspects of an actual reservoir into computational blocks. Also, the effect of grid block sizes, numerical (dispersion) errors produced by numerical methods in solving the complex partial differential equations and errors in the calibration data may not have been adequately captured.

The motivation of the work is to provide a way to represent the calibrated reservoir model as a polynomial model, similar to the simple volumetric stored heat equation, in which Monte Carlo simulation can easily be implemented.

Since we have demonstrated that a Plackett-Burman design, which resulted in 12 different configurations of the calibrated numerical model, is sufficient to carry out an experimental study involving six (6) uncertain reservoir parameters for building a polynomial model of MWe, a 100-year MWe first-order regression model was also built using the Plackett-Burman design.

The resulting regression model for the 100-year MWe model is shown in equation (5), while the probabilistic distribution for the 100-year MWe estimate is shown in Figure 5. The results are almost exactly similar to the 50-year model except for the sign for the interaction term of k_y and k_z and k_z and %RI. In the 50-year model, the sign of the interaction of k_y and k_z is positive while the interaction term k_z and %RI has a negative sign. In the 100-year model, it is the other way around. The results suggest that Wairakei has an indicative capacity of 248 MWe (P90), 273 MWe (P50) and 297 MWe (P10).

$$\begin{aligned} \boldsymbol{MW_e Plackett - Burman\ (100\ years)} \\ &= 232.5 + 6.22e^{13} \times k_x \\ &+ 3.13e^{13} \times k_y + 3.78e^{13} k_z \\ &+ 20.12 \times \%RI \\ &- 1.44e^{24} \times k_x \times k_y \\ &- 3.16e^{25} \times k_x \times k_z \\ &- 3.39e^{13} \times k_x \times \%RI \\ &- 1.26e^{25} \times k_y \times k_z \\ &- 8.25e^{12} \times k_y \times \%RI \\ &+ 4.99e^{12} \times k_z \times \%RI \end{aligned} \tag{5}$$

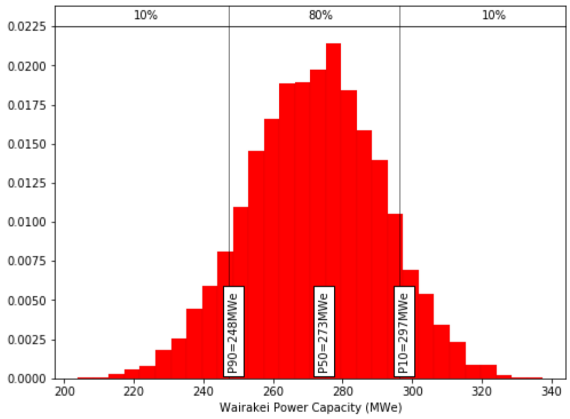

Figure 5. Plackett-Burman 100-year probabilistic resource assessment of the Wairakei Geothermal Field.

The results of the 3 case studies reveal that the ED-RSM framework for building polynomial models that approximate numerical models works well with geothermal numerical models. To conclude our investigation, we implemented the Plackett-Burman design in the probabilistic resource assessment using a calibrated model of our last case study: The Leyte geothermal field, Philippines.

3.4 The Leyte Geothermal Field

The complete discussion of the results of the Leyte case study is presented in the paper of Ciriaco et al. (2022b).

Initially, the twelve (12) Plackett-Burman designs of the numerical model of Leyte was built using two-feed production and injection wells. After running several designs, the preliminary results indicate that the shallow reservoir is turning into a dry steam region. Only a couple of feed zones producing from this region could sustain production for up to 50 years. This necessitated adding another layer as a feed zone, making the total feed zone layers three. For Tongonan, the feed zones are located at layers 5, 13 and 21. The Mahanagdong reservoir was produced from layers 10, 14 and 19.

Equation (6) shows the final polynomial equation for predicting the MWe capacity. Implementing Monte Carlo simulation to equation (6) suggest that the Leyte geothermal field has an indicative capacity of 670 MWe (P90), 730 MWe (P50) and 790 MWe (P10) if produced for 50 years (Figure 6). However, the estimated values should be used with caution as the effect of cold Paril and acidic fluids are not accounted for in the estimation.

$$\begin{aligned} \boldsymbol{MW_e} &= 350.00 + 2.97e^{14} \times k_x \\ &+ 1.78e^{14} \times k_y \\ &+ 1.65e^{14} \times k_z \\ &- 127.00 \times porosity \\ &+ 2.22e^{-05} \times RI\ Enthalpy \\ &+ 290.00 \times \%RI \\ &- 2.45e^{26} \times k_x \times k_y \\ &- 2.92e^{08} \times k_x \\ &\times RI\ Enthalpy \end{aligned} \tag{6}$$

Substituting the low, mid, and high values of the six uncertain parameters in Table 1 to equation (6) shows that %RI appears to have the highest impact on the estimated MWe. This is an indication that the injection of the separated fluid plays an important role in the sustainable production at Leyte, possibly by providing pressure support to the reservoir.

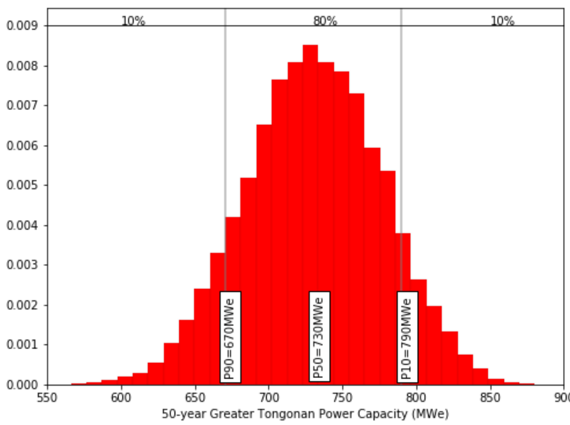

Figure 6. The probabilistic MWe distribution of Leyte for a 50-year sustainable period using the Plackett-Burman design to build 12 different models of the calibrated natural state model and implement Monte Carlo simulation on the regression model of MWe.

All the six uncertain parameters except the RI Enthalpy are significant predictors of MWe. The interaction of kx with ky and RI Enthalpy is also statistically significant. %RI has the highest impact on the estimated MWe - an indication of the

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importance of the injection of separated fluid for providing pressure support to the reservoir resulting in a sustainable MWe generation. The enthalpy of the injected fluid (RI Enthalpy) is the only parameter that is not significant based on the interpretation of its p-value. However, the pair-wise relationship of RI Enthalpy and k_x is statistically significant. Also, the interaction of k_x and k_y is statistically significant as well. The coefficient of the interaction of these two pair-wise relationships is negative. This means that the calculated MWe will decrease as their values increase.

The results from the four case studies indicate that the refined Experimental Design (ED) and Response Surface Methodology (RSM) framework shown in Figure 3 is applicable to any numerical reservoir model, as demonstrated from the studies conducted using the Rotorua, Ohaaki, Wairakei and Leyte numerical models.

4. CONCLUSION

This study has successfully implemented the Experimental Design (ED) and Response Surface Methodology (RSM) for probabilistic resource assessment using calibrated reservoir models of Rotorua, Ohaaki, Wairakei and Leyte geothermal fields. The results of this study are ssummarised as follows:

- Three Experimental Designs were used in testing the ED-RSM framework for building a proxy model of the calibrated numerical model of the Rotorua geothermal field. These designs were three-level Full Factorial, two-level Full Factorial and three-level Box Behnken. The polynomial models built from the simulation experiments gave almost similar predicted MWe. The results from the two-level Full Factorial suggested that the Rotorua geothermal field has a power (MWe) capacity of 263 MWe (90th percentile), 264 MWe (50th percentile) and 265 MWe (10th percentile) for 50 years. The ED-RSM framework confidently estimated the power potential of the field to be at least 262 MWe. The results of the ED-RSM workflow implied a higher MWe potential for commercial use and that permeability plays a crucial role in sustainable production, providing a pathway for natural recharge.
- Using the three Experimental Designs as the Rotorua case study, the retrospective study of the Ohaaki geothermal field revealed a lower indicative capacity of 67 MWe (90th percentile), 68 MWe (50th percentile) and 70 MWe (10th percentile) for 50 years compared to the 116 MWe actual installed capacity. This study uncovered a clear overestimate of Ohaaki's long term sustainable capacity.
- Wairakei is the longest and largest New Zealand geothermal field. The ED-RSM approach adopting the Plackett-Burman design predicted its capacity as 286 MWe (50th percentile) for 50 years and 273 MWe (50th percentile) for 100 years. A minimal output decline is expected between the 50th year and the 100th year, indicating the presence of significant recharge into the main reservoir. The Wairakei (excluding Tauhara) model also shows that the field can support further power generation beyond 100 years of production.
- The Leyte Geothermal Field in the Philippines has a potential capacity of 670 MWe (90th percentile), 730 MWe (50th percentile) and 790 MWe (10th percentile) if produced for 50 continuous years. It is the world's largest two-phase geothermal system. For such a big field as such, it was no surprise that the RI Enthalpy turned out to have a negligible impact on the estimated MWe.
- The results of the present study have also confirmed that the Experimental Design (ED) and Response Surface Methodology (RSM) framework works well with numerical models for probabilistic estimates of potential capacity (MWe). Clearly, a skilled Subject-Matter-Expert (SME) coupled with an experienced reservoir modeller is fundamental to the successful implementation of the workflow. Prior experience and knowledge on geology, geochemistry, geophysics and reservoir engineering are essential in interpreting the reasonableness of the results uncovered by the experiment.

One interesting, yet significant finding of this work is that the ED-RSM workflow was able to uncover a relationship between the reinjected fluid enthalpy and the size of the resource. The final polynomial model of the Ohaaki numerical model suggested that the RI Enthalpy is a significant factor of the field's MWe potential. The results even revealed the importance of the interaction between the RI Enthalpy with the %RI parameter. On the other hand, these parameters are not that crucial for a bigger field like the Leyte geothermal field. Therefore, this study has clearly shown that for a small field like Ohaaki, the reinjected fluid enthalpy (or brine temperature) has a higher impact on the reservoir model's indicative capacity than a much larger geothermal fields like Leyte.

In terms of what Experimental Design to use, this work has proved that the Plackett-Burman is the most practical to use compared to the three-level Full Factorial, two-level Full Factorial and three-level Box-Behnken. This study has also strengthened the notion that while it is essential to satisfy the statistical requirement to accept a regression model, as long as the results are dependable and agree with reality, there is merit in using the ED-RSM approach for the same use.

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