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# Retrospective Resource Assessment Study Using Experimental Design and Response Surface Methodology: The Ohaaki Geothermal Field, New Zealand

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## ABSTRACT

The Ohaaki geothermal field celebrated its 30 years of production in 2018. The field has suffered from several production issues, including the inability of the resource to meet the installed generation capacity at a sustainable production level for a certain prolonged period. Numerical reservoir simulations have been instrumental in understanding the shortfall in the supply of steam and in predicting the future deliverable power of the field at various operating scenarios. Given the substantial amount of production information, it would be interesting to look back and examine how the field would have behaved if it were assessed differently during early exploration.

In this study, the performance of the Ohaaki geothermal resource is investigated using three different approaches: the volumetric stored heat method, deterministic prediction from the calibrated natural state model and experimental design (ED) and response surface methodology (RSM). A probabilistic distribution of power potential will be generated both from the volumetric method and ED/RSM approach by applying Monte Carlo simulation to the equation and polynomial model, respectively.

The results suggest that; among the three competing models, the ED/RSM approach yields the most conservative MWe estimate suggesting that the Ohaaki geothermal field has a power potential of 66 to 69 MWe for 50 years of operation. This reveals the potential of ED/RSM as a good risk-averse approach and as a useful tool in estimating the sustainable development of a geothermal resource in an efficient and reliable manner.

## 1. INTRODUCTION

Resource assessment is undertaken primarily to come up with a collective understanding of a geothermal resource, based on evidence collected and inferred from geological, geophysical, geochemical exploration and reservoir engineering data. Depending on the stage of the project, the information derived from a resource assessment study provides insights into the resource and serves as a guide for making an informed business decision. It is critically important to perform a resource assessment study as soon as there is sufficient data about the resource in order to evaluate the commercial viability of the project.

If the power potential (in MWe) capacity of a geothermal field could be predicted with certainty, the worldwide electricity generation from geothermal energy would increase exponentially, and there would be less untapped geothermal resources across the globe. Unlike the other forms of clean energy, the upfront cost and risk-associated in the geothermal business is high. Even the cost of delineating a geothermal resource is relatively higher than the rest of the renewable energy sources (IRENA, 2018). Estimating how much thermal energy is extractable for a given resource with a lower level of uncertainty is crucial as it provides confidence to both new players in the industry and existing developers.

Although the geothermal energy as an industry is already mature and widely established, it has not come to a level yet where there is standard practice for identifying and characterizing a resource. More often than not, the way it has been done is ad hoc, through either a field-dependent or user-dependent assessment. As a result, different resource assessment methodologies and versions of the original models became available. Among these, the volumetric stored heat method and numerical reservoir simulation are the most widely used techniques (Ciriaco et al., 2019). The former method is useful when there is limited available information. It was introduced by the United States Geological Society (USGS) when it conducted a regional assessment of the geothermal resources in the United States (Muffler and Cataldi, 1978). The simple equation used to calculate the stored heat has evolved into several versions. Several parameters were added to the original governing equation according to the need and justification of the users. Majority of the existing operating fields have adopted this technique during their early stages of development.

The numerical reservoir simulation is, by far the only tool that can represent the intricate details of an actual geothermal reservoir more accurately. The time required to build and calibrate a numerical model varies depending on how detailed the model configuration is and the available calibration data. More often, a longer time is needed before a calibrated reservoir model becomes available and useful for making future predictions about the resource. Hence, some authors prefer the volumetric method as it provides quick and insightful results.

Due to the inherent uncertainty of the parameter values used in the estimation process, a probabilistic way of predicting the power potential is required. This resulted in incorporating Monte Carlo simulation into the process. The volumetric method lends itself well to the Monte Carlo method. The reservoir simulation approach, however, produces deterministic results and quantifying the uncertainty using this technique is still being investigated.

Building a polynomial model in lieu of the reservoir model bridges the gap of generating a probabilistic distribution of the MWe potential using Monte Carlo simulation. Quinao and Zarrouk (2017) and Ciriaco and Zarrouk (2018) have successfully implemented this technique in the Ngatamariki and Rotorua geothermal fields, respectively. This research adopts the same methodology of utilizing experimental design (ED) and response surface methodology (RSM) using the existing model of the Ohaaki geothermal field (Rataouis et al., 2017).

## 2. PROXY MODELLING: EXPERIMENTAL DESIGN AND RESPONSE SURFACE METHODOLOGY

Proxy modelling is the process of building an empirical model that describes the relationship of an output variable to a set of input variables. Experimental design and response surface methodology is a widely used technique for building a polynomial model. It was first successfully applied in the agriculture and manufacturing industry (Ramachandran and Tsokos, 2015; Garud, 2017). Sir Ronald Fisher demonstrated the effect of soil condition, temperature and rainfall in an agricultural experiment while Dr Genichi Taguchi implemented ED in designing products.

The design of an experiment allows a scientific investigation to be carried out in a strategic and systematic manner. It enables identifying the important parameters to reduce the number of variables included in the investigation process and minimize cost and time. Applications of ED include in the field of engineering, science, and medicine. In the energy sector, it was first applied in the oil and gas industry for uncertainty quantification (Damsleth, 1992; Amudo et al., 2008). In recent years, the geothermal industry is exploring its applicability for resource assessment studies.

The general steps for conducting experimental design and building a polynomial model is outlined below:

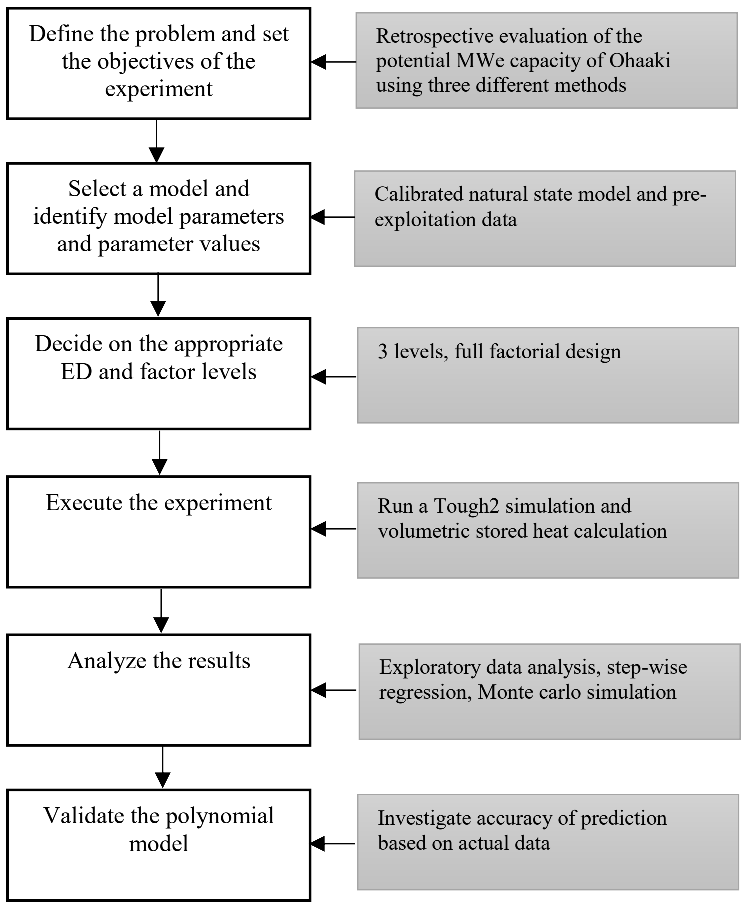



**Figure 1: The general workflow for carrying out experimental design and polynomial building.**

### 2.1 Experimental Design

The design of an experiment is a tool for understanding the relationship between a variable of interest and the factors affecting it. In computer experiments, the variable of interest or the response or dependent variable is the result or output of the simulation runs. In geothermal reservoir simulations, the main interest is the resource capacity in terms of MWe while the factors that influence the output of the simulation experiments include rock and fluid properties such as porosity, permeability and enthalpy. These factors are also known as the explanatory or independent variables. In this paper, the terms response and dependent variable, and explanatory and independent variable are used interchangeably.

To illustrate the experimental design workflow in Figure 1, a reservoir simulation study using the Ohaaki numerical model is carried out. The goal is to maximize the amount of information that can be derived from the reservoir model at a minimum number of simulation runs. By implementing ED, only the parameters that have a significant effect on MWe will be used in the model fitting.

### 2.2 Model fitting

Data derived from an experiment are used to build a regression model that describes the relationship of the response variable $y$ to a set of input variables. A polynomial model containing first and second-order terms is usually sufficient to describe this functional relationship and can be written as:

$$y\,(x) = f(x, \beta) + \varepsilon \qquad (1)$$

The polynomial function $f(x)$ is a low order polynomial. It can either be linear or quadratic. A least squares regression is used to determine the coefficients of the parameters $\beta$. The random component, error term $\varepsilon$, of the polynomial function is assumed to be normally distributed. A plot of the residuals and the predicted value is used to diagnose whether this assumption is valid or violated. Results of previous simulation studies using geothermal reservoir model suggest that fitting of modelling results requires building a second order polynomial model (Ciriaco, et al., 2018).

## 3. METHODOLOGY

This experiment aims to compare the result of ED/RSM from the results of volumetric method and the deterministic method of making predictions from a calibrated model. Calculating the theoretical stored heat from the Ohaaki resource is straight forward. Converting the calibrated natural state model into a production model to perform a deterministic forecast run would need to introduce the production and injection data into the model and may not be that difficult to do. However, building a polynomial model that approximates the calibrated natural state of Ohaaki takes time to build. In the subsequent sections, the main focus will be on planning the experimental design to build a proxy for the numerical model.

### 3.1 Establish baseline results using the volumetric method

Using the simple volumetric method in Equation 1 (Muffler and Cataldi, 1978), the theoretical thermal energy using the simple version of the volumetric method can be calculated (Ciriaco et al., 2019).

$$q = \rho_r c_r V(T_i - T_f) \qquad (2)$$

where:

| | |
|---|---|
| $q$ | thermal energy stored in the reservoir (MJ) |
| $\rho_r c_r$ | Volumetric heat capacity of the reservoir rock, J/°C m$^3$ |
| $V$ | Volume of the productive reservoir. Product of area $A$ and thickness $h$ of the reservoir ($V = A \times h$), m$^3$ |
| $T_i$ | Initial temperature of $i^{th}$ lithology, °C and |
| $T_f$ | Cut-off or final abandoned reservoir temperature, °C |

The MWe potential can then be computed by multiplying the thermal energy with a certain recovery factor and conversion efficiency and divide everything by the product of plant life and load factor as given below:

$$MW_e = \frac{q \times R_f \times \eta_{conv}}{F \times L} \qquad (3)$$

where:

| | |
|---|---|
| $MW_e$ | power potential, MW$_e$ |
| $R_f$ | recovery factor |
| $\eta_{conv}$ | conversion efficiency (%) |
| $L$ | plant life (seconds) |
| $F$ | capacity or load factor (%) |

### 3.2 Establish baseline results using the deterministic approach

The steps involved in building a proxy model is outlined in Figure 1. The key factors in this step are to clearly define the objective of the study and to be able to identify and select the critical parameters that will be used in the experiment.

### 3.3 Parameter Selection for the ED/RSM approach

3.3.1 Parameter selection

Below is a list of the possible model parameters that can be included in the design of the experiment.

1. Porosity
2. Horizontal (kx and ky) and vertical (kz) permeability
3. The fraction of injected fluid in relation to the geothermal fluid produced.
4. Enthalpy of injected fluid
5. Location of production and injection wells
6. Number of production and injection wells
7. Upflow parameters: mass flow and temperature

8. Reservoir thickness

To simplify the numerical experiment, the parameters will be limited to porosity, permeability, fraction and enthalpy of injected fluid as previous experiments have shown that these are the most significant parameters so far (Ciriaco et al., 2018).

3.3.2 Production and Injection Wells Identification

Selection of wells is not influenced in any way by existing knowledge about the production history of the field. The idea is to determine the maximum possible number of wells that can be placed within the boundary defined by MT or as delineated from the known data. There should be only one feed zone per block to avoid feed sharing. A wellbore simulation is necessary to determine the wellhead/discharge pressure. It is also important to determine the bottom of the clay cap as defined by the MT surveys .

3.3.3 Termination criteria

A successful simulation experiment is terminated when the simulation run reaches the predefined end time.

## 4. IMPLEMENTATION

### 4.1 The Ohaaki Geothermal Field

The Ohaaki geothermal field is a medium-temperature two-phase geothermal system. It lies on the eastern margin of the Taupo Volcanic Zone (TVZ) as shown in Figure 1. Drilling commenced in 1965. A total of 44 wells had been drilled in 1984 followed by testing which lasted until 1988 before the power plant was commissioned with a capacity of 116 MWe. Operating the field at a maximum sustainable capacity was rather challenging. Withdrawal of a significant amount of mass from the reservoir resulted in pressure drawdown and subsidence (Newson and O'Sullivan, 2001).

Several versions of the numerical models of the Ohaaki system have been developed over the years. The latest version of the model developed in 2017 will be used in this study (Ratouis et al., 2017). The grid structure is shown in Figure 2. The model blocks range from 1k by 1km at the fringes of the model to 250 m by 250 m in the central part of the model. A small part of the model has a block size of 125 by 125 m – this is where the North-West Bank is situated. Local grid refinement in the North West section of the field was implemented to reduce the number of wells sharing the same block (Ratouis et al., 2017).

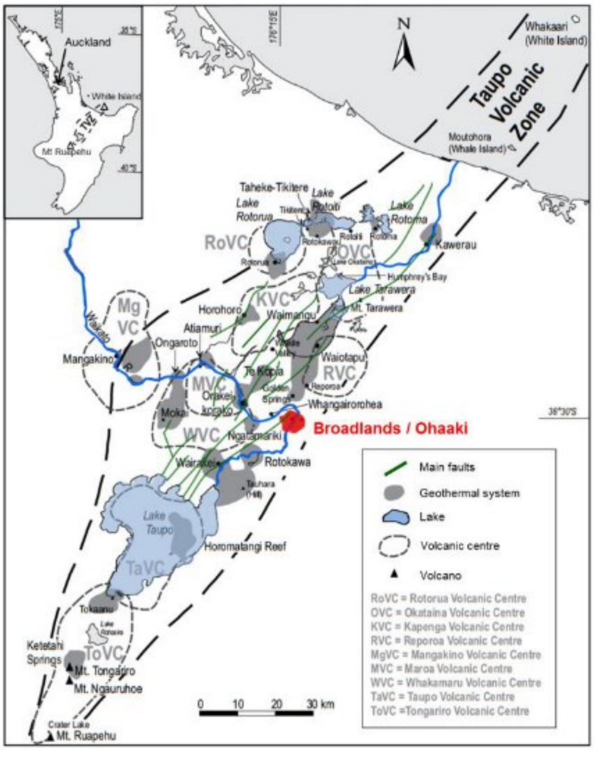



**Figure 2: The location of the Ohaaki geothermal field in the Taupo Volcanic Zone (from Ratouis et al., 2017).**

Three different competing models are presented in this study; these are:

1. Analytical solution using the stored heat/volumetric method.
2. Deterministic forecasting using the calibrated natural state model.
3. Experimental Design and Response Surface Methodology.

The assumptions used to carry out a volumetric stored heat calculation was based on the work of SKM (2002). A full factorial experimental design will be used to determine the significant predictors of power potential before building a polynomial model.

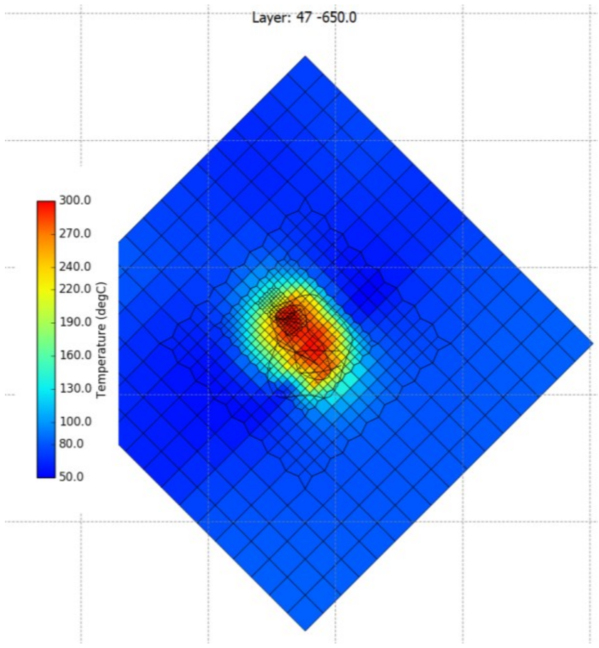



**Figure 3: The numerical model grid structure of the Ohaaki reservoir model showing the pre-exploitation temperature distribution at – 650 mRSL.**

## 5. RESULTS

The results from the three different competing choices of evaluating the potential of Ohaaki resource in retrospect will be discussed in this section. Each approach will be evaluated according to the ease of use, nature of data and data sources, and accuracy of prediction. To present the discussion in a logical way, the techniques will be grouped into two: analytical and numerical methods.

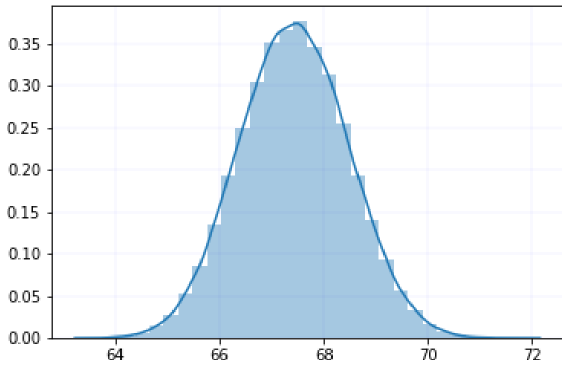
### 5.1 Analytical method: Stored heat/volumetric method

Calculating the MWe potential using the volumetric stored heat method is straight forward. A simple triangular distribution was assigned to each parameter. By substituting the collected values for the parameters in the equation and running a Monte Carlo simulation, a probabilistic distribution of MWe was generated. The parameter values used is summarized in Table1, and the MWe distribution plot is shown in Figure 4.

**Table 1. Values for the parameters in the stored heat calculation**

| Parameter | Parameter Value (minimum, most likely, maximum) |
|---|---|
| **Resource area ($km^2$)** | 6, 10, 12 |
| **Resource thickness (km)** | 1.8, 2.1, 2.5 |
| **Porosity** | 0.06, 0.08, 0.1 |
| **Temperature (°C)** | 260, 270, 280 |
| **Conversion Efficiency** | 0.07, 0.12, 0.17 |
| **Recovery Factor** | 0.1, 0.125, 0.15 |
| **Reference Temperature (°C)** | 20, 100, 180 |

The results suggest that the MWe capacity of the Ohaaki field to be in the range of 140 MWe (P10), and 61 MWe (P90), with a P50 of 94 MWe.




| | *MWe* |
|---|---|
| *P10* | 140 |
| *P50* | 94 |
| *P90* | 61 |

**Figure 4: A probabilistic distribution of capacity (MWe) using the volumetric method.**

The strength of the volumetric method lies in its simplicity to use. The other significant reservoir processes are represented in this equation by the recovery factor. However, assuming a range of value for this parameter may not be sufficient to completely account for everything else that the stored heat equation has not considered. This and other intricate details of the geothermal resource are what the numerical reservoir model is trying to fill in.

5.2 Numerical method: Deterministic and ED/RSM

A numerical computer simulation is by itself deterministic. Using the same parameter values will yield the same calculation even if run several times. In this study, the ED/RSM approach was used to build a proxy model as an approximation of the numerical model. This polynomial model was then integrated with Monte Carlo simulations to generate a probabilistic distribution of MWe capacity.

A calibrated natural state model is a prerequisite to both approaches. The most challenging part was finding the appropriate location and number of wells that will allow sustained production up to 50 years. The maximum number of feed zones for each well was set to two. In reality, some wells could have more than two feed zones. Based on the experience of the authors, unless otherwise necessary, wells with multiple feed zones are usually lumped together and limited to a maximum of two for calibration purposes. For well design and simulation purposes, the casing shoe is usually set to the projected depth of 220 °C (Ciriaco et al., 2019). The 220 °C is found at 20 mRSL in the calibrated natural state model of Ohaaki. Since we are more interested in the deep reservoir, the authors set the shallow feed zone at -650 mRSL, where the temperature is more 280 °C. A total of 33 wells was initially identified at the start of the simulation. There were no make-up wells added in the simulation

The experiment resulted in a trial and error process and revealed that production wells could not sustain production if the bottom feed zone is set at -1600 mRSL. Furthermore, the maximum fixed mass flow per feed is only 25 kg/s. The equation used to calculate the MWe from the simulation is shown below:

$$MW_e = \left( \sum_{i=0}^{i=n} mf\,(t_{i+1} - t_0) \times h\,(t_{i+1} - t_0) \right) \times CE \qquad (4)$$

where:

$mf$ = mass flow, kg/s

$h$ = enthalpy, kJ/kg

$t$ = time step, seconds

$CE$ = conversion efficiency, %

Conversion efficiency of 0.12 was used in the calculation, as suggested by Zarrouk and Moon (2014).

5.2.1 Deterministic solution

The results of the deterministic run suggest that Ohaaki could have a potential capacity of around 130 to 140 MWe in the first ten years and would gradually decline to 115 MWe for the next ten years before it will maintain generation slightly above 110 MWe until the 50$^{th}$ year. Applying equation four suggests that Ohaaki has a potential capacity of 120 MWe for 50 years.

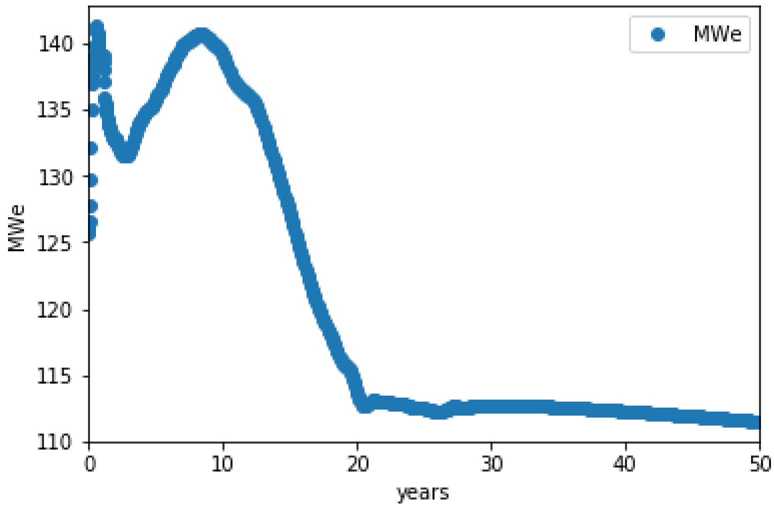



**Figure 5: Calculated MWe using the deterministic approach.**

A total of 16 production wells sustained production for a time horizon of 50 years. Running the calibrated natural state model in a deterministic fashion meant not having to vary the calibrated parameter values. In effect, this run did not in any way alter the calibrated pre-exploitation state of the Ohaaki field.

5.2.3 ED/RSM approach

Six different parameters were selected in building a polynomial model of MWe capacity. These parameters are porosity, permeability in the horizontal and vertical directions, and enthalpy and fraction of injected fluid. A full factorial design was implemented, which required a total of 729 simulation runs to complete the investigation process. Not all the scenarios ran up to the specified end time. There were a total of 29 simulation configuration that failed to reach the 50–year simulation end-time and the unsuccessful runs could be attributed to the following scenarios:

1. Regardless of the porosity value and RI enthalpy used, if the rest of the parameters have a minimum value.
2. Minimum permeability, mid and max RI enthalpy, regardless of porosity and RI enthalpy.
3. Mid and High kz but minimum for all the rest.

Results from the remaining 700 successful runs were used to build the polynomial model. To understand the underlying structure of the simulated data, four different plots of MWe were generated: normal Q-Q plot, box plot, histogram and run sequence plot. A collection of these plots is shown in Figure 6. The data appears to be skewed based on the normal Q-Q plot and histogram while the box plot and run sequence plot suggest the presence of possible outliers. There were around 51 possible outliers that lie on the high side of the box plot and run sequence plot. Further inspection of the results revealed that the simulated MWe from these 51 scenarios was not significantly different from the rest. It was decided not to treat these data as outliers and proceed with the regression analysis.

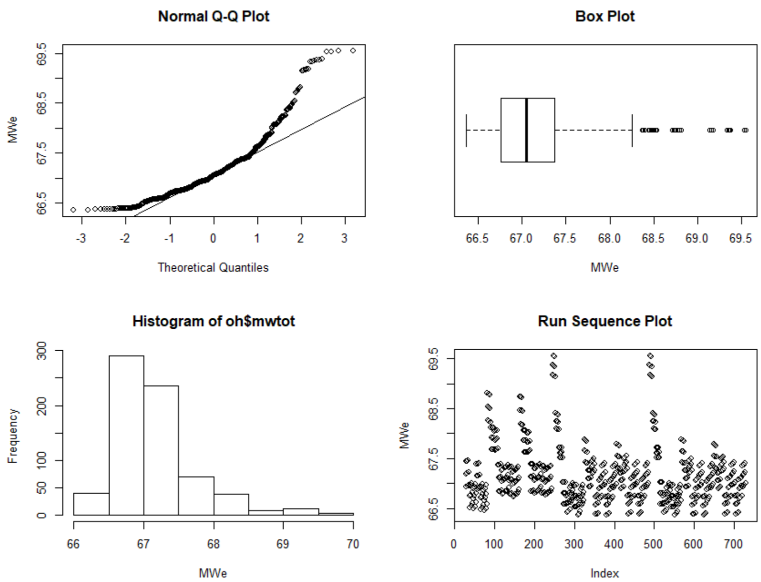



**Figure 6: A normal Q-Q plot, histogram, box and lag plots of the resulting MWe.**

Previous studies of proxy modelling of computer experiments using ED/RSM have already demonstrated the inadequacy of a first order polynomial model to describe the relationship of response variables to explanatory variables (Ciriaco, 2018; Simpson, 1998). However, for the purposes of comparison, a first order model was first generated from the results of the simulation runs. It is clear from the residual plots shown in Figure 7 that the residuals are not normally distributed and requires building a second order polynomial model.

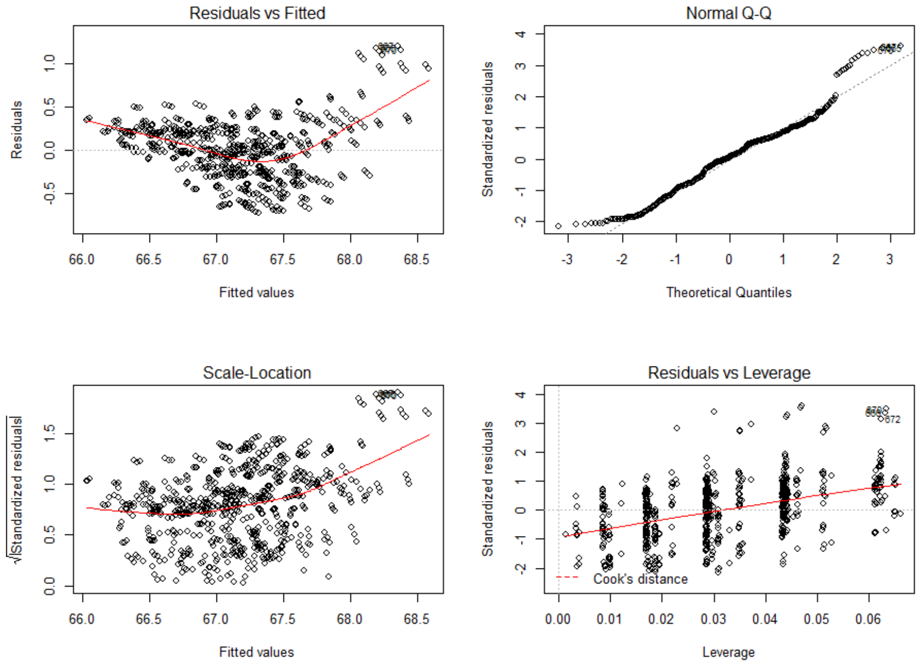



**Figure 7: A residual plot of the first order model.**

The parameters that turned out to be significant predictors of MWe after fitting the results to a second order polynomial model are summarized in Table 1.

**Table 2. Significant predictors of MWe**

| Parameter | p-value |
|---|---|
| **Porosity (A)** | $5.73\times10^{-5}$ |
| **% RI (C)** | $<2\times10^{-16}$ |
| **kx (D)** | $<2\times10^{-16}$ |
| **ky (E)** | $4.25\times10^{-10}$ |
| **kz (F)** | $<2\times10^{-16}$ |

The final polynomial model of the Ohaaki production model is given below:

$$\boldsymbol{MWe} = 70.41 - 1.4A - 5.445\,C - 3.107e12D - 6.860e11E - 1.658e12F - 0.2151Asq + 2.849Csq + 1.326e24Dsq - 1.061e23Esq + 5.201e23\,Fsq + 0.5455A*C - 4.135e11A*D - 3.313e11A*E + 3.860e11A*F + 1.086e12C*D + 1.031e12\,C*E + 1.016e12C*F + 4.375e23D*E + 2.809e23D*F - 9.991e22E*F$$

**where:**

$A$ = porosity

$C$ = fraction of injected fluid, kg/s

$D$ = horizontal permeability in the x-direction, $m^2$

$F$ = horizontal permeability in the y-direction, $m^2$

$G$ = vertical permeability, $m^2$

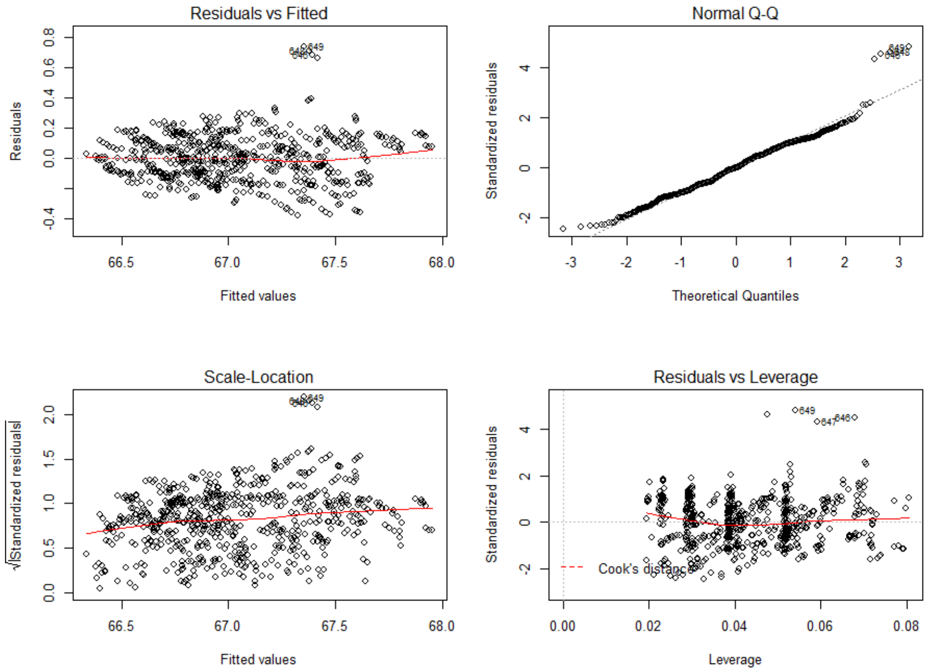



**Figure 8: A residual plot of the second order model.**

The regression model has an R-squared and adjusted R-squared of 0.8404 and 0.8353, respectively. The result of the Shapiro-Wilk test gave a p-value of 0.2.245e-09, suggesting that the residuals are normally distributed. This is also evident in the Normal Q-Q and Residual plots are shown in Figure 8.

A plot of the results generated from the calibrated natural state model is shown in Figure 9. A total of 11 production wells sustained generation up to 50 years. The predicted MWe is around 70 to 80 MWe at the start and slowly declines to 65 MWe after 20 years. From then it stays at around 65 MWe down to 50 years. A total of 11 production wells sustained production till the 50$^{th}$ year.

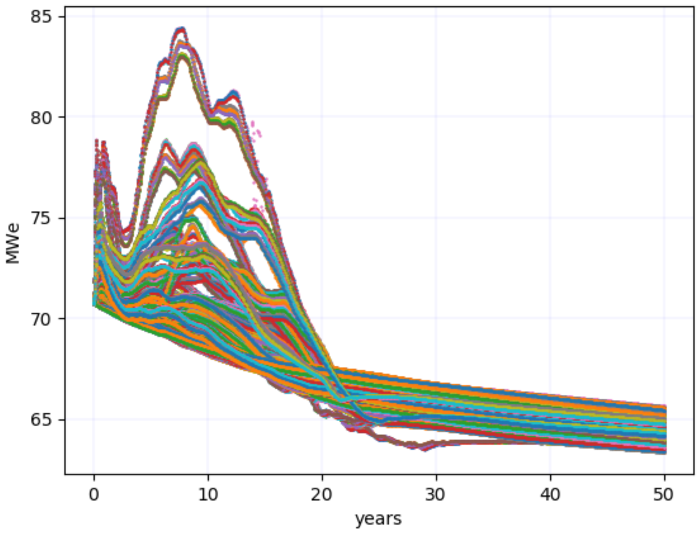
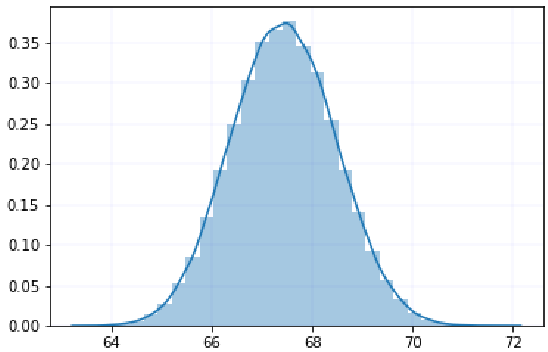



**Figure 9: Calculated MWe using the ED/RSM approach.**

After applying Monte Carlo simulation into the polynomial model, the Ohaaki field has a P10, P50 and P90 of 66, 67 and 69 MWe respectively. The probabilistic distribution of MWe is shown in Figure 10.




| | *MWe* |
|---|---|
| *P10* | 69 |
| *P50* | 67 |
| *P90* | 66 |

**Figure 10: A probabilistic distribution of MWe using the ED/RSM approach.**

The range of parameter values set for each parameter was based on expert knowledge about the geothermal resource. Other experts of the field may use different parameter values. The authors are already looking at doing a parameter estimation to let the model determine the sensible range of parameter values. Moreover, as mentioned in section 3.3.1, there are still other parameter values that can be included in the experiment. Parameter estimation could also be used in identifying which parameters to include in the simulation experiment.

Furthermore, the natural state parameters, such as temperature and pressure, are sensitive to permeability. Setting a range of permeability values for this approach would result in varying the calculated natural state condition. This is the effect of accounting for the uncertainty in the propagation. There are other sources of uncertainty that is still not accounted for by this approach, including isolating the effect of measurement error.

5.2.4 Comparison of the results from the three approaches

The results from the three approaches are summarized in Table 3. A plot of the calculated MWe with time using the deterministic approach and ED/RSM is shown in Figure 11. The difference in the simulated MWe is attributable to the number of wells that sustained production for 50 years. There were 16 production wells that managed to produce until the 50$^{th}$ year while only 11 wells reached this desired period in the ED/RSM. Overall, it can be inferred from the results that the volumetric stored heat method gives a wide range of possible estimated MWe. Interestingly, the MWe calculated using the numerical deterministic approach falls within the P10 of the volumetric method, while the results generated from the numerical ED/RSM approach is within the P90 of the volumetric method.

**Table 3. Calculated MWe from the three different approaches**

| Technique | MWe |
|---|---|
| **Analytical stored heat volumetric method** | 61 (P90), 94 (P50), 140 (P10) |
| **Numerical deterministic approach** | 120 |
| **Numerical ED/RSM approach** | 66 (P90), 67 (P50), 69 (P10) |

Each method has its own advantages and disadvantages. The volumetric method is, no doubt the simplest and easiest to use. The numerical deterministic approach is much easier to carry out as it only needs one successful run. Unlike the numerical ED/RSM approach, depending on the number of parameters that will be included in the experiment, would require up to as much as 700 simulation runs.

However, considering the knowledge about the actual production history of the Ohaaki field, it appears that the numerical ED/RSM approach gives a result that is closest to reality among the two other approaches. This is a very interesting discovery as it underscores the potential of EDRSM for estimating the MWe potential of a geothermal field. Furthermore, the generated MWe with time from the ED/RSM approach can also be modelled using Time Series analysis and can be used for predicting MWe at a certain period of interest.

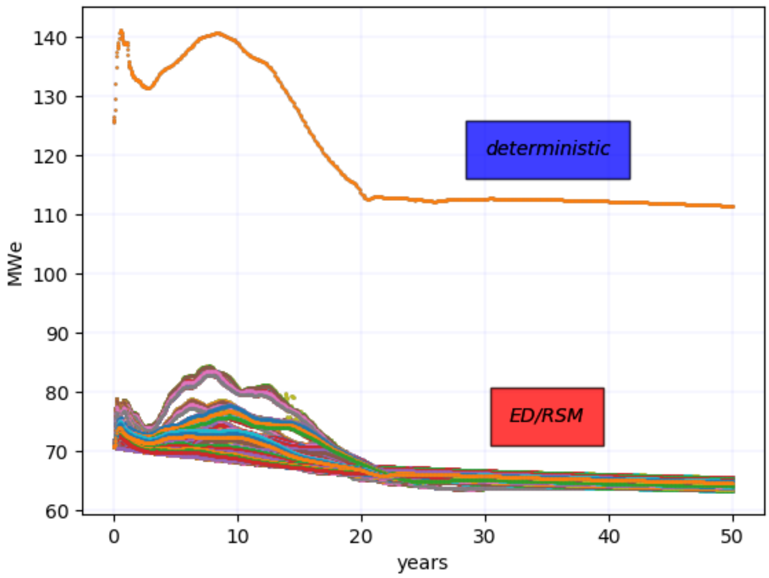



**Figure 11: Plot of predicted MWe with time showing the results from deterministic and ED/RSM runs.**

## 6. CONCLUSION

A retrospective resource assessment of the Ohaaki geothermal field was carried out, and the results suggest that:

- Using the volumetric stored heat method, the Ohaaki field has a potential of P10, P50 and P90 are 140 MWe, 94 MWe and 61 MWe respectively while the deterministic approach suggested an MWe potential of 120 MWe and the based on the ED/RSM approach, it is around 60 to 70 MWe.
- The calculated MWe using the deterministic approach is comparable to the P10 obtained from the volumetric method, while the MWe estimated from ED/RSM is close to the P90 of the volumetric method.
- Comparing the results from the actual production history of the Ohaaki field, it appears that the ED/RSM approach gave the closest estimate of MWe potential. This highlights the potential of using this approach for estimating the potential capacity of a geothermal resource provided that there is a calibrated natural state model.

## 7. ACKNOWLEDGEMENT

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