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Estimation of drilling risk of non-Artesian wells with the Monte Carlo method

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ABSTRACT

The drilling of a geothermal well has no guaranteed outcome. The drilling risk is taken in this paper as the risk of investing in a well which will not be economical for the system which it is intended to supply. This paper is only treating non-Artesian geothermal wells, where there is a water level down in the well in an undisturbed condition.

The parameters which are unknown prior to drilling the well are the drilling cost, the water temperature, the depth down to the undisturbed water level in the well, and the productivity index of the well. The productivity index of the well is understood to be the flow which can be taken from the well for each unit of drawdown of the well water level from the undisturbed level.

A life cycle cost model is made for the well, treating the well cost, the water temperature, the undisturbed water level, and the productivity index as stochastic variables with a given density function. A simple triangular density function is defined for each of the stochastic variables, having zero density below the minimum boundary ("worst case") and above the maximum boundary ("best case"), with a maximum density value in between ("most likely"). The density curve is linear between these points. These points can usually be defined by heuristics, which means the guess of the good and qualified specialist.

When a set of values has been drawn from the stochastic variables, the cost of the well pump can be estimated and the NPV of the pump electricity consumption. Each set of values will give some water production from the well which is of value to the downstream system. This value of the product is also defined by the market, so assumptions on how the water will be used and the income therefrom must be made.

The final risk estimation is then based on creating many (thousand) sets of values from the stochastic variables and present the probability density function of the score value, which is conveniently taken as the ration between lifetime income (NPV) and the well cost (including pump and NPV of electricity cost).

1. INTRODUCTION

A geothermal well is intended to supply heat for some project, which will generate value. There is always the risk of having an unsuccessful well, that is a well, which does not generate sufficient income to cover the investment cost of the well. Here an attempt is made to make this estimation by using the Monte Carlo simulation method.

1.1 Monte Carlo simulation

The Monte Carlo simulation is explained by Sawilowsky (2003) and a distinction is drawn between a simulation, the Monte Carlo method and a Monte Carlo simulation. The following description of these terms is based on his explanations:

Simulation: Drawing one pseudo-random uniform variable from the interval [0,1] can be used to simulate the tossing of a coin: If the value is less than or equal to 0.50 designate the outcome as heads, but if the value is greater than 0.50 designate the outcome as tails. This is a simulation, but not a Monte Carlo simulation.

Monte Carlo method: Pouring out a box of coins on a table, and then computing the ratio of coins that land heads versus tails is a Monte Carlo method of determining the behavior of repeated coin tosses, but it is not a simulation.

Monte Carlo simulation: Drawing a large number of pseudo-random uniform variables from the interval [0,1] at one time, or once at many different times, and assigning values less than or equal to 0.50 as heads and greater than 0.50 as tails, is a Monte Carlo simulation of the behavior of repeatedly tossing a coin.

1.2 The investment and income for a geothermal well

There are three cost factors for the geothermal well considered here:

The drilling cost: The drilling cost is all cost associated with the drilling of the well and its completion. It includes the wellhead and its valves, as well as the connection to the collection system on the wellfield. In short, all cost for having the well producing into the collection system other than the pump and its electricity consumption.

The pump cost: The cost of the pump is dependent on the pressure head which the pump has to overcome, and the flow which the pump delivers. The pump cost is thus dependent on the pump power required.

The cost of electricity for the pump: The cost flow due to the electricity consumption of the pump is simply the pump power multiplied with the price of electricity. This is calculated for a reference year by assuming a utilization time for the well. The total cost for the depreciation time of the project is then found by taking a *Net Present Value* of the yearly cost of electricity.

1.3. The income from the well

The well is assumed to be delivering heat to some revenue generating plant downstream of the well. A likely *plant return* or re-injection temperature is defined, and it is assumed that each kWh of heat delivered by cooling the well fluid down to this return temperature will generate revenue.

1.4 The score function

The score function is defined here as the ratio of heat delivered to the total well cost. The value of each unit of heat delivered is defined by the market for the project and is omitted here for simplification. That is the same assumption as to say that the price of heat from the well is known for the depreciation time of the project.

2. INDEPENDENT AND DESIGN VARIABLES

The input variables in the cost and income models can be divided into two groups, independent variables, and design variables.:

2.1 Independent variables

Independent variables are determined by nature and their value is unknown for the designer. These variables are essentially stochastic variables and have some probability density. It is common when simulating such stochastic variables to define:

a) A triangular probability density function
b) A worst case, which is the lower limit of the triangular probability density function
c) A most likely value, which is the apex of the triangular probability density function
d) A best case, which is the upper limit of the triangular probability density function

The “worst” and “best” cases are named so because of tradition, but there is nothing in these cases relating them to quality. Worst case is simply the lowest value of the independent variable, which has a non-zero probability. By the same token, the best case is the largest value of the independent value with non-zero probability.

A random generator is then used to generate values for the independent variable in the interval [worst case, best case] with the triangular density function defined by the triple [worst case, most likely, best case].

The generated value is then used together with the values of the design variables as an input to the cost and income models.

A large number of sets of input values is then generated and used as an input to the cost and income models, and the results presented as probability density or distribution.

2.2 Design variables

Selecting a value of the design values lies in the hands of the designer. In some cases, the selection of a value of a design variable does not only have a direct influence on the cost and income models, but on the triple [worst case, most likely, best case] for an independent value. An example is the well diameter, which influences the pressure loss in the well directly, and the density function triple for the drilling cost and thereby has an indirect influence on the well cost.

The well diameter is selected before drilling commences, and after that nothing can be changed. This is different for the well pump power. The pump can be selected late in the process when results from the drilling are available and better information is available on the properties of the well. Here this is not considered, and the pump size is defined before the simulation is made. It is then sensible to repeat the simulation for some different pump sizes to help a good pump size selection.

2. THE GEOTHERMAL WELL

The geothermal well is assumed to be like a vertical pipe with constant diameter. The geothermal water flows into the well at some depth, and the up the well towards the surface. The distance from the inflow to the surface is the length of pipe, where there will be experience frictional resistance to the flow. A pump with given power is assumed to assist the flow. The fluid has a given pressure at the wellhead, so the pump head (pressure difference over the pump) will be the sum of the wellhead pressure, the pressure loss in the well and the lift from the drawdown water level in the well.

A schematic of the well is shown on Figure 1.

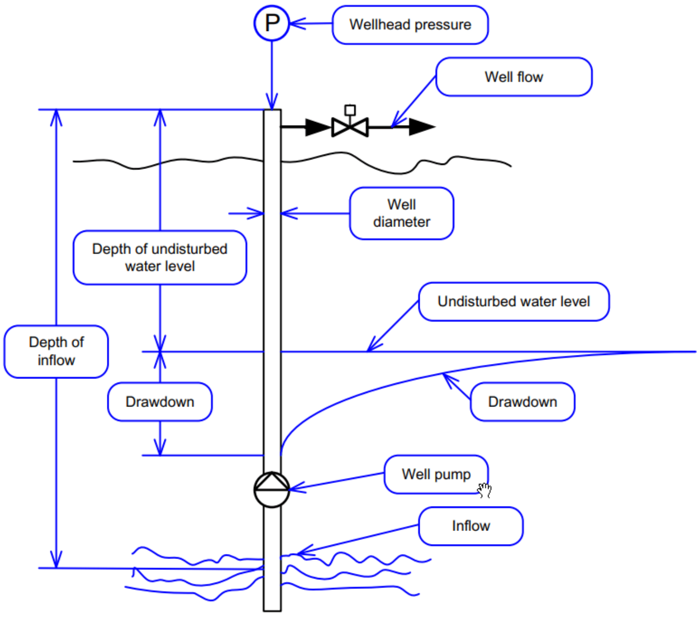

Figure 1: A schematic of the geothermal well model.

2.1 Design variables

The design variables in the model are as follows:

a) Pump efficiency
b) Pump electric power
c) Wellhead pressure
d) Well diameter
e) Well inside surface roughness
f) Price of electricity
g) NPV factor for electricity cost
h) District heating return temperature

2.2 Independent variables

The independent variables in the model have to be defined as stochastic variables with a set of triangular density function parameters (worst case, most likely, best cast). These variables are:

a) Productivity index (relates drawdown to the well flow)
b) Undisturbed water level in the well
c) Depth of the inflow into the well
d) Water temperature
e) Well cost (complete installation, including pump)

The Productivity Index is here defined as the ratio of the flow in kg/s to the drawdown in meters.

2.3 The score function

The score function which is used here assumes that the fluid from the well will be used for a geothermal district heating system with a given return temperature.

The cost of the well is the sum of the investment and a Net Present Value of the cost of electricity for the depreciation period of the well.

The NPV of electricity is approximated with a NPV factor of six, so the NPV is six times the electricity cost for the first year.

The cost of electricity is not a stochastic variable. The pump power is a design variable, and with given NPV factor and price of electricity, the electricity cost is a single value and not a stochastic value. It is calculated as 1 576 800 $ as follows:

$$C_{electricity} = \dot{W}_{pump} \cdot 8760 \cdot f_{NPV} \cdot p_{electricity} \tag{1}$$

The mass flow from the well is found by iteration. A guess is made for the mass flow from the well and the pump power is calculated for that mass flow by:

$$\dot{W}_{pump} = \frac{\dot{m}_{well} \cdot g \cdot \left(h_{drawdown} + h_{water\,level} + h_{surface} + h_{friction}\right)}{\eta_{pump}} \quad (2)$$

where:

- g: The gravitational acceleration
- $h_{drawdown}$: The drawdown, calculated by dividing the mass flow by the productivity index
- $h_{water\ level}$: The depth of the undisturbed water level in the well
- $h_{surface}$: The pressure head at the surface, equal to the wellhead pressure divided by g and the water density
- $h_{friction}$: The frictional head loss in the well from the water inflow to the surface, calculated by the Darcy-Weisbach equation

The "Method of successive bisections" is then used to generate the next value of the well flow in the iteration, and the iteration continues until the pump power matches the given design value for the pump power.

The benefit of the well is the heat which is fed into the district heating network. The return temperature from the network sets the lower temperature limit of the utilization of heat from the well. The heat which the well can supply into the network is calculated by:

$$\dot{Q}_{district\,heating} = \dot{m}_{well} \cdot c_p \cdot \left(T_{well} - T_{return}\right) \quad (3)$$

A logical score function is the specific cost of heat, that is the cost of each kW of heat flow from the well. Equation (1) gives a score function V. The variables in the equation should be self-explanatory.

$$V = \frac{C_{well} + C_{electricity}}{\dot{Q}_{district\,heating}} \quad (4)$$

3. A SAMPLE SIMULATION

3.1 Input data

A simulation was made with the following design variables:

a) Pump efficiency = 70%
b) Pump electric power = 300 kW
c) Wellhead pressure 10 bar-abs
d) Well diameter = 200 mm
e) Well inside surface roughness = 0.7 mm
f) Price of electricity = 0.1 $/kWh
g) NPV factor for electricity cost = 6
h) District heating return temperature = 40 °C
i) Cost of electricity = 1 576 800 $ (see Equation 1)

The triangular density distribution of the independent variables is defined with the following values.

	Lower limit	Most likely	Upper limit
Productivity index [(kg/s) / m drawdown]	0.5	1	1,5
Depth of inflow [m]	1 500	2 000	2 500
Undisturbed water level [m]	50	100	150
Water temperature [°C]	110	130	150
Well cost [US $]	500 000	2 000 000	3 000 000

The random generator was used to generate 5 000 values for each of the stochastic variables. Histograms of the generated values are shown in Figure 2.

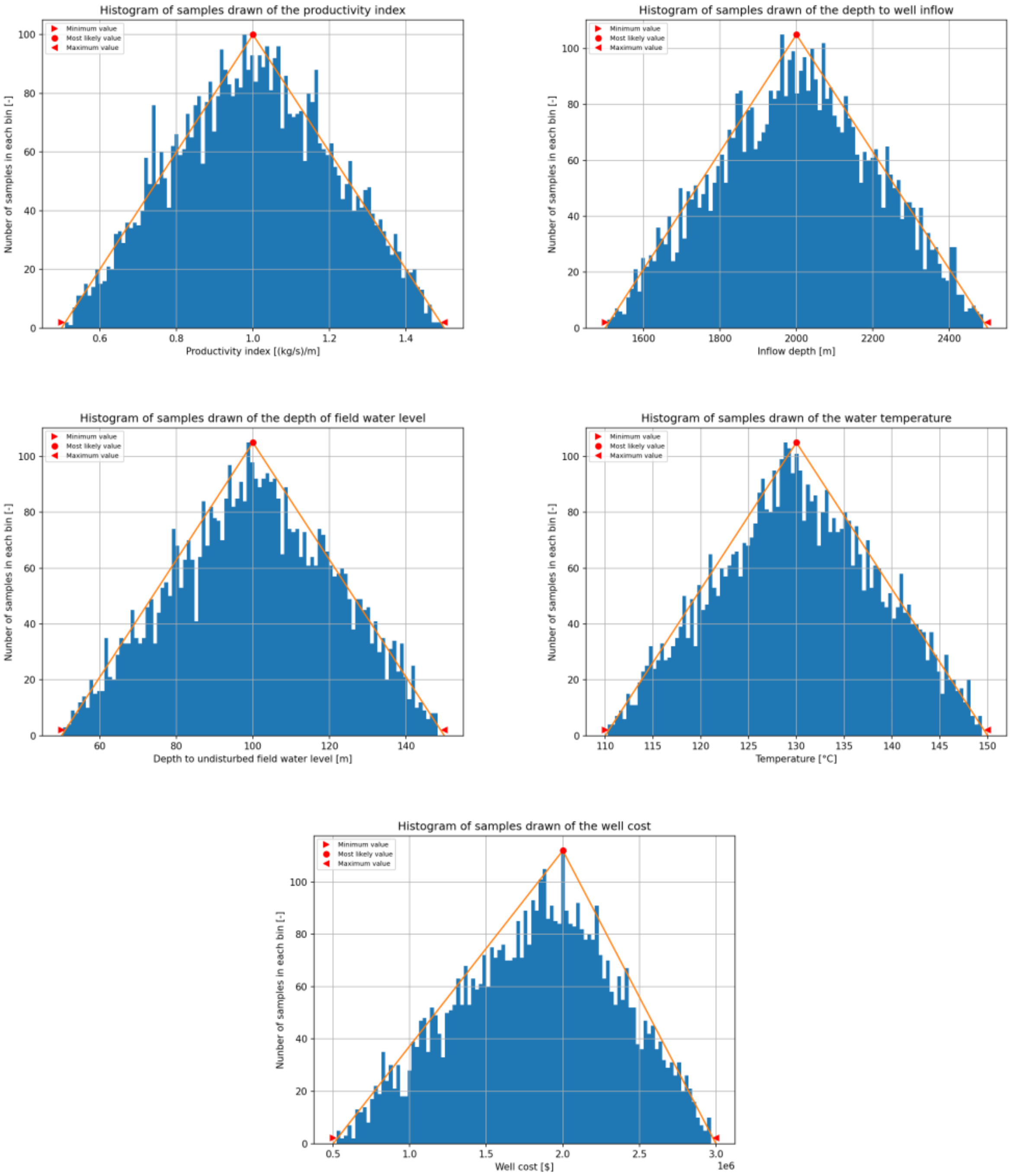

Figure 2: Histograms of the random values generated for the stochastic variables.

3.2 Simulation results

The cost of electricity is not a stochastic variable. The pump power is a design variable, and with given NPV factor and price of electricity, the electricity cost is a single value and not a stochastic value. It is calculated as 1 576 800 $ as follows:

$$C_{electricity} = \dot{W}_{pump} \cdot 8760 \cdot f_{NPV} \cdot p_{electricity} = 300 \cdot 8760 \cdot 6 \cdot 0.1 = 1\,576\,800 \text{ \$} \quad (5)$$

The results of the simulation are presented as cumulative distribution functions. Please note that the functions are always plotted from the lowest value to the highest. This means that the feasible part of the distribution may be either at the high or low end of the x-axis.

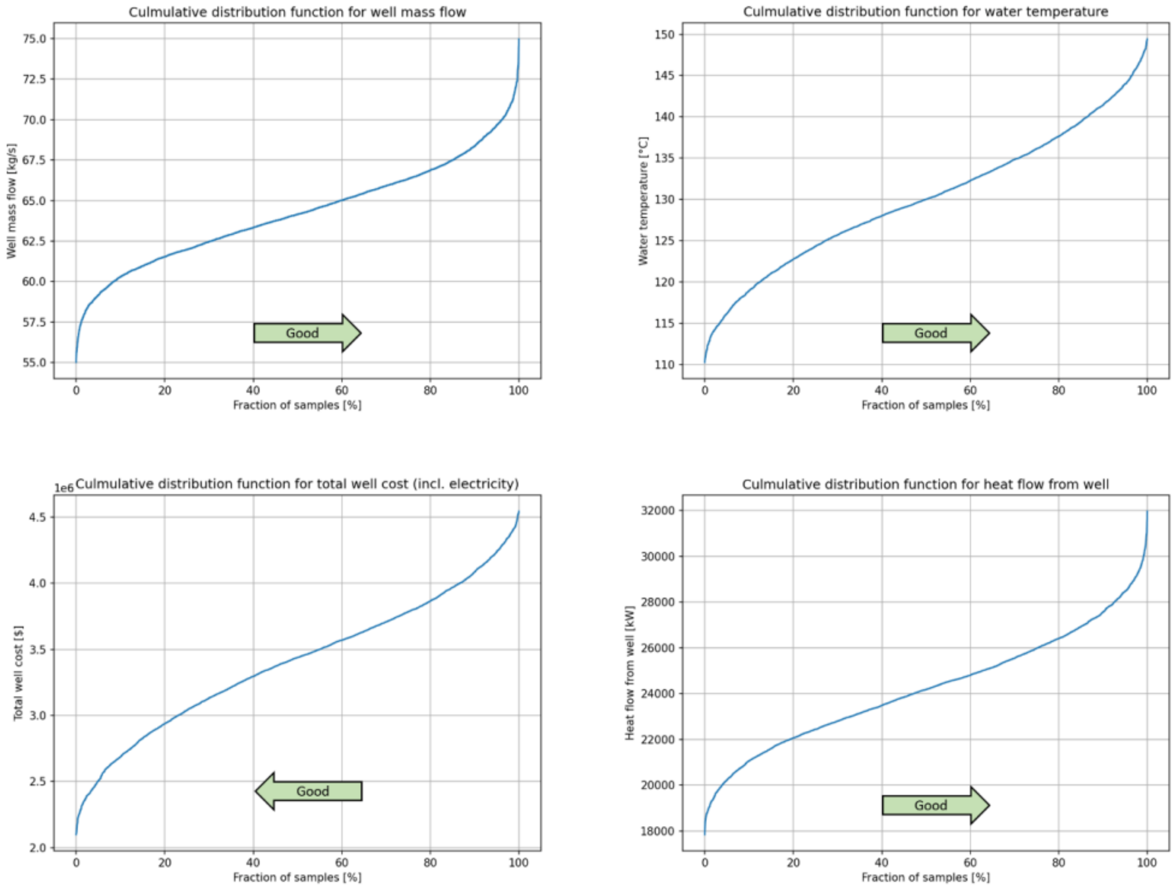

Figure 3: Cumulative distribution functions for well mass flow, water temperature, total well cost and heat extracted from the well.

The final decision if this well is a good idea or not lies in the specific cost of the heat extracted for the district heating. The cumulative distribution function will give the likelihood of getting a certain specific cost for the extracted heat, or lower.

The cumulative distribution function for the specific heat cost is shown on Figure 4.

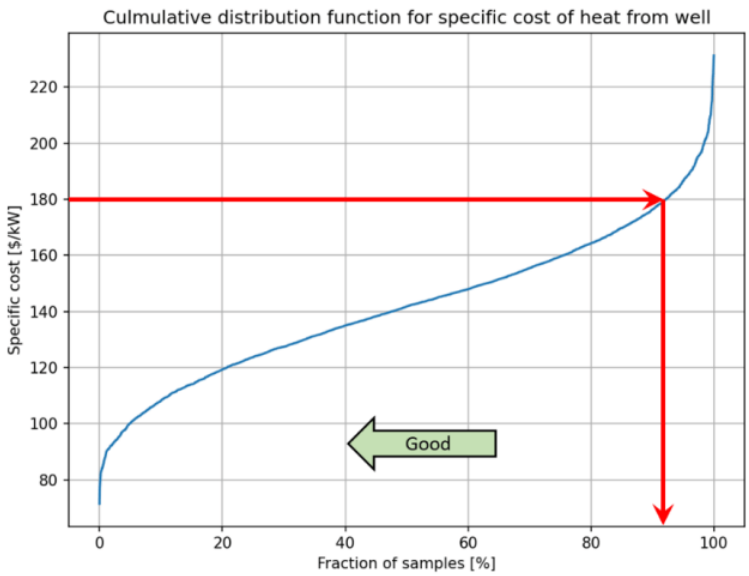

Figure 4: The cumulative distribution function for the specific heat cost.

Here it can be seen that if the break-even cost of heat for the project is 180 $/kW, then the probability of success is 92% and the probability of failure is 8%.

4. CONCLUSION

The Monte Carlo method is a powerful tool to estimate the risk in project, where only heuristic knowledge is available for the input variables. A qualified scientist is usually able to define the likely boundaries of the values of the uncertain variables. An intelligent division between deign variables, where the project designer has control and the uncertain stochastic variables, where nature (or external conditions outside of the control of the designer) will have the final word.

A relatively simple calculation model based on this approach is presented here, and is able to give valuable information on the economic risk of the project.

The simulation here is done with the programming language Python, see Python Software Foundation (2023).

The Monte Carlo method will be able to quantify the economic risk of drilling a well, by using a simple mathematical model and heuristic knowledge of the good engineer and good scientist.

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