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An Integrated Machining Learning-Based Workflow for CO2 Sequestration Optimization under Geological Uncertainty

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Abstract: Carbon dioxide capture and sequestration has attracted widespread interest worldwide due to greenhouse effect. Geological uncertainties affect final decisions of the injection work. Optimizing injection work under geological parameters can maximize the carbon dioxide injection efficiency and minimize the difference between the carbon dioxide storage target and actual injection volume. This work introduces an optimization workflow for decisions. It is composed of three steps. At first, generating samples as the initial data sets by using Latin Hypercube Sampling method. Secondly, a data-driven model is deployed to simulate the fluid movement in the reservoir using the samples generated in step 1. The surrogate model is optimized by tuning hyper parameters in neural networks and applying K-fold validation, which can mitigate the limitations of high-fidelity simulations. After optimization, the surrogate model is validated using full reservoir simulation. At last, with the help of genetic algorithm, both the critical pressure area and CO2 plume area reduce largely, and CO2 injection volume increases by 115*103 m3. This optimization can largely enhance CO2 sequestration efficiency. It introduces an efficient workflow to provide a reference to the decision-making process of CO2 injection location.

1. Introduction

Carbon dioxide capture and sequestration include the following processes: capturing, compressing, transporting and storing. In the petroleum industry, carbon dioxide will be transported by kinds of facilities like power plants, and stored in reservoir formation. In that case, carbon dioxide concentration in atmosphere can be controlled in a suitable range which helps reduce the greenhouse effect [1].

In this work, the geological sequestration method is mainly discussed. Typically, injected carbon dioxide will be stored in geological trappings, such as structural trapping which has low permeability, residual trapping (small amount of carbon dioxide are trapped in the rock pore space), and dissolution trapping (carbon dioxide is dissolved into the in-situ brine) [2].

Genetic algorithm is an optimization approach, based on Matlab Reservoir Simulation Toolbox (MRST), this algorithm can solve lots of simulation problems. It is similar to the theory of evolution proposed by Darwin, which involves selection and evolution [3]. It's mainly used to find out the most optimal solutions to the reservoir multiply questions. At the beginning, the initial data set should be created with the help of the Latin Hypercube Sampling method, then, after defining the objectives, simulated results that output by simulation model will be ranked to select the better solutions by Pareto Ranking, these data sets will generate next generation's data sets after selection, crossover and mutation. By repeating this process for enough times, the most optimal solutions will output as the final data sets.

When genetic algorithm is applied in MRST, it can help optimize objectives related to the reservoir properties. In this work, the objectives are maximizing the carbon dioxide injection volume, minimizing the critical pressure influencing area and carbon dioxide plume area.

2. Literature Review

Greenhouse effect is a natural phenomenon that has existed in the earth since it created. But with the development of human civilization, a large amount of carbon dioxide has been released into atmosphere, in order to reduce and limit the impact of the greenhouse effect, there are three main ways to reduce carbon dioxide concentration in the atmosphere.

First, Terrestrial Sequestration. This method relies on the photosynthesis of plants, this is the only storage method without side effects, but it could take 225 years [4] to decrease atmospheric carbon dioxide concentration with achievable land areas.

Second, Ocean Sequestration. Japan and Korea have used this method for a really long time. For example, Korea started a carbon management project called "Moving Ship" since 2002 [5], carbon dioxide will be liquefied into carbon dioxide droplets and these droplets will be released in mid-depth ocean (1000 to 2000 meters under the sea level).

Finally, Geological Sequestration. Jilin oilfield proved that a good carbon dioxide storage place should have the well-developed sand body and undeveloped fractures, this low permeability and low porosity condition ensures the stability of carbon dioxide sequestration. At the same time, the injected carbon dioxide can replace the trapping oil in the pore throat [2] to increase the oil production.

Genetic algorithm plays a main role in this work. It is a effective algorithm to solve multiply questions which contain various parameters and bases on artificial neural network. It can be used in various reservoir simulations. For example, this technique was used in permeability simulation and had a successful application in the L58-2 Fault-Block of Linpan Oilfield and N12 Fault-Block of Qinghe Oilfield, etc [6]. After applying this approach, the mentioned oilfields decreased reservoir heterogeneity and had a better reservoir performance.

Except from reservoir simulation, genetic algorithm also can be used in other researches widely, such as drilling engineering, genetic algorithm is used to determine the suitable rate of penetration of the drill bit and optimize it in a more safe and stable conditions.

3. Methodology

To make sure the randomness and accuracy of the output data sets generated by the genetic algorithm, the first important step is sampling that can output the initial data sets. There are two sampling methods can be chosen:

First, Monte Carlo Sampling: It is an approach which is used to generate samples from input parameters. In this way, each sample is half of a solution or result of reservoir simulation questions. To generate a sample, random parameter values are drawn from the specified probability of each uncertainties in the model.

The other one is Latin Hypercube Sampling method [7]. This is a more sophisticated sampling method that can ensure the data sets are distributed in the defined parameter space efficiently. Latin Hypercube Sampling will divide space into possible intervals, in that case, each sample will be selected only for one time. Thus, the more data available, the better this approach is. When a large number of samples are needed in genetic algorithm, comparing with Monte Carlo Sampling, it is much better to choose Latin Hypercube Sampling for saving costs.

After getting the samples generated by Latin Hypercube Sampling method, genetic algorithm need to start working:

1. Evaluation: Based on the defined objectives, the initial data sets will be simulated in model from MRST co2lab. And these data will be ranked by Pareto Ranking method, for finding out the solutions with better fitness in this work;

2. Selection, Crossover, and Mutation [8]: These individuals who have higher fitness will be selected to create the next generation’s individuals, but in order to avoid duplication of the previous generation, some changes need to be added into generating process, such as time steps, injection rate. In this step, new individuals can inherit the previous generation’s genetic information to make the solutions better and better;

3. Replacement: New generation’s individuals will not only combine with the individuals in same generation, but they will also combine with the individuals in the previous generation, therefore, good genetic information will be increasingly enriched, resulting in better and better solutions.

4. Output: When the highest ranked data sets are generated by genetic algorithm, this data sets will be regarded as final data sets and output themselves as the results.

4. Analysis

In this work, there are three objectives considered: the critical pressure area, CO_2 plume area, and carbon dioxide injection volume.

For the pressure area, the distribution of reservoir pressure is very complex. But, with the help of MRST, the reservoir pressure map can be divided into many grids, and reservoir pressure values can be displayed in different colors. After defining the boundary conditions, relevant pressure difference functions provided by MRST co2lab will be used in simulating the pressure distribution [9,10]. In Fig.1, the reservoir’s central part with higher pressure has the deeper color, but as for the reservoir boundary grids with lower pressure , the color is light yellow.

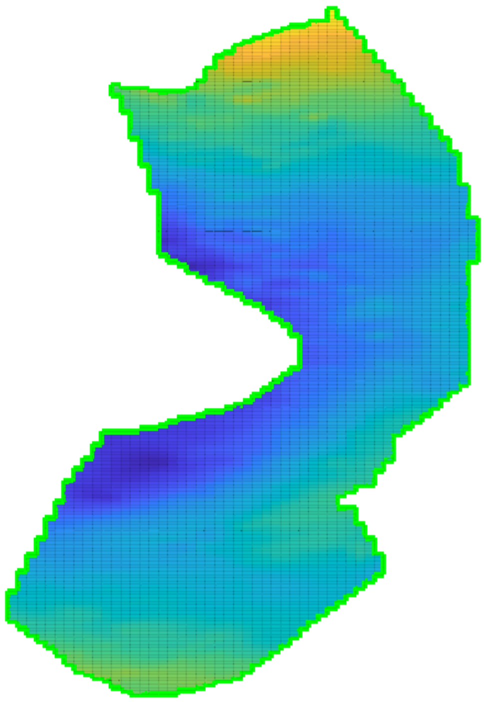

Figure 1. Distribution of Reservoir Pressure Example

In this project, the initial pressure has been set up by MRST co2lab “example 3D” model, thus, the pressure change need to be calculated [11].

The pressure change formula is:

$$P(z) = \int_0^z \rho(z) g dz \quad (1)$$

When starting injecting carbon dioxide, an additional pressure at wellbore bottom is needed to be calculated:

$$\frac{\Delta P}{g} = (z_v - z_I)(\frac{\lambda - \zeta}{2}(z_v - z_I) + \rho_{I,\lambda} - \rho_I) \quad (2)$$

where g is the gravity constant (9.8 m^2/s), and where ΔP represents the pressure change value in the injection formation, λ and ξ are linear coefficients (-1.16*10^{-5} and 3.75*$10^{-7,}$ kg.L^{-1}.m^{-1}). $\rho_{I\lambda}$ is density at depth z_I after CO_2 injection. ρ_I represents the density at depth z_I initially. z_v and z_I are the top of injection formation and the base of USDW (An underground source of drinking water) [11].

After getting the pressure difference, reservoir pressure can be calculated by summing initial pressure and pressure difference. Then, pressure data can be exported as an image, . Because in each grid, there is a defined threshold value used for judging if the grid’s , when the simulated pressure value is larger than the threshold value, the matrix’s value in this grid is expressed as 1. For example, if the pressure threshold value is 90 kPa, all the grids’ simulated value are larger than threshold will output as 1 due to the characteristic of the matrix. In this work, CO_2 saturation threshold is 5%, if the simulated CO_2 saturation is larger than 5%, this grid should be regarded as one of the CO_2 plume area.

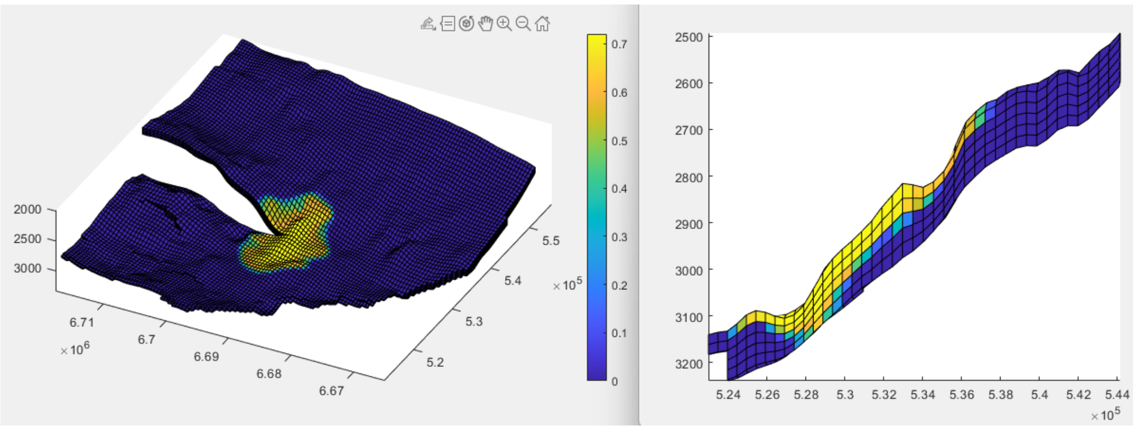

Figure 2. CO2 Plume Area after CO2 Injection for 500 years

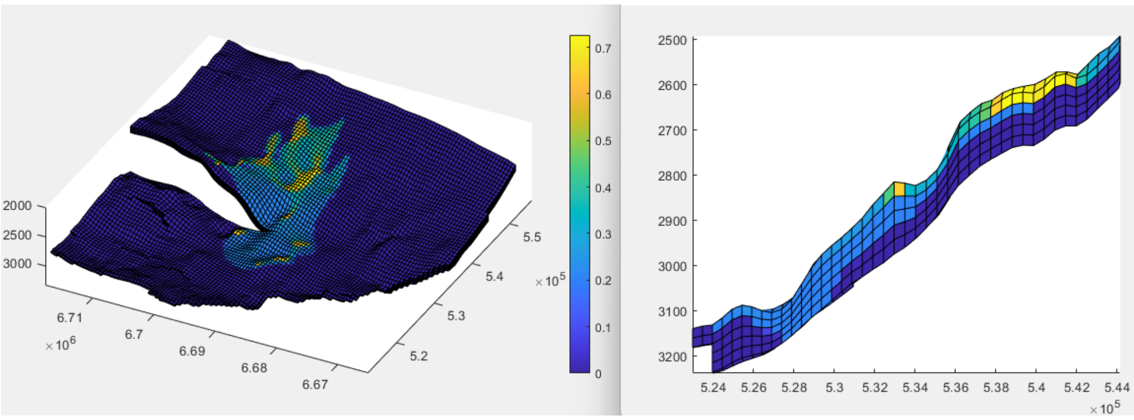

Figure 3. CO2 plume area after CO2 Injection for 1000 years

As Fig.3 shown, the yellow part is the CO_2 plume area after CO2 injection. But comparing Fig.2 with Fig.3, the CO_2 plume area in each layer is different, thus, we need to make a superposition of the CO_2 plume area of each layer and calculate the maximum area, rather than lightly to the maximum value of a certain layer. An another important thing is how to displace these objective function values. After finishing the sampling part, these initial populations should be put into genetic algorithm and let it output one generation's objective functions' values. Just as Fig.4 shown below:

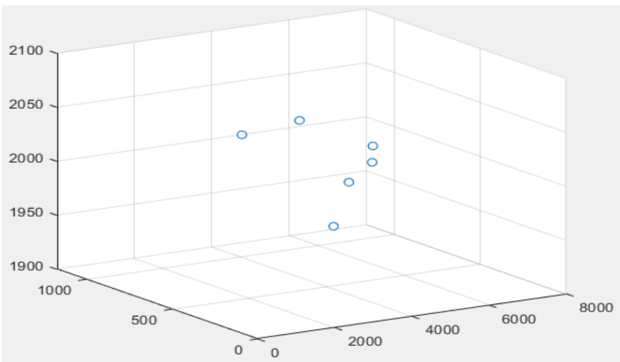

Figure 4. Objectives' Values in Three-Dimensional Coordinate System

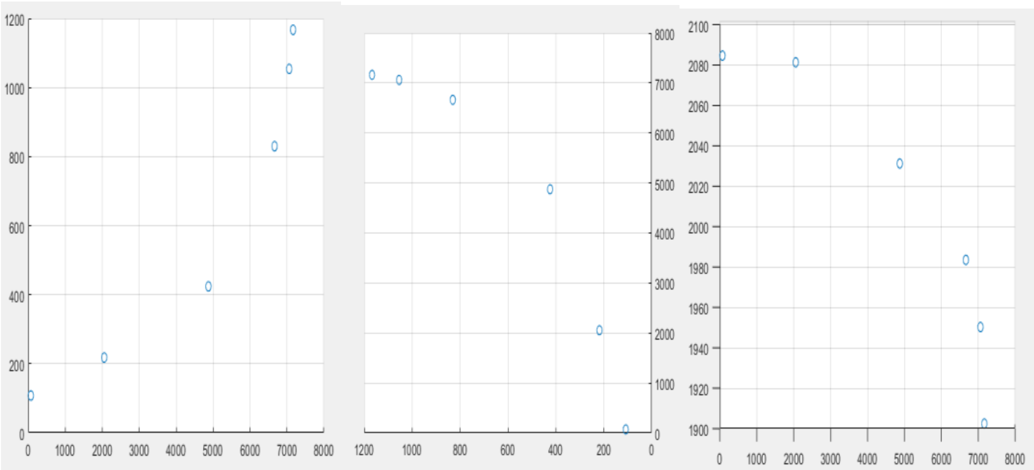

Figure 5. Objectives' Values in Two-Dimensional Coordinate System

Shown in Fig.5, the objective function values are shown as blue points, the objective function values are: critical pressure area (X-axis), CO_2 plume area (Y-axis), the difference between the target CO_2 injection volume and the simulated CO_2 injection volume (Z-axis).

After all generations finishing, all the objective function values can be shown in one three-dimensional coordinate system, as Fig.6 shown below. Based on Fig.6, each generation's objective function values are getting closer to the origin of the coordinate system, it proves this genetic algorithm works well.

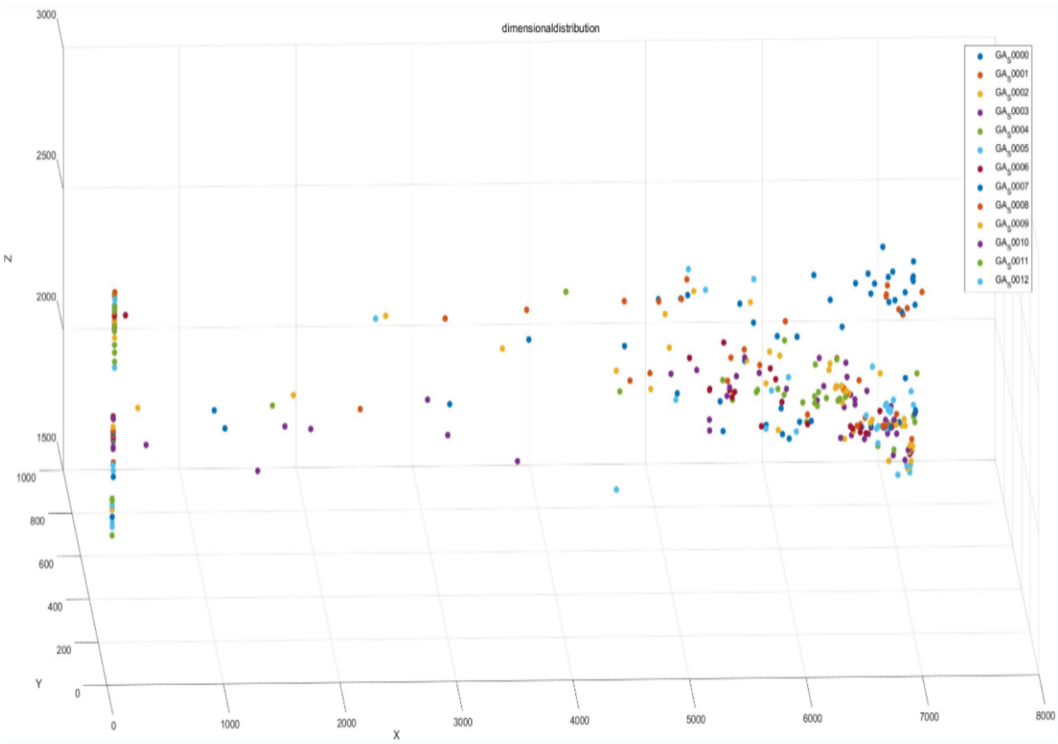

Figure 6. All Generations' Objective Values in Three-Dimensional Coordinate System

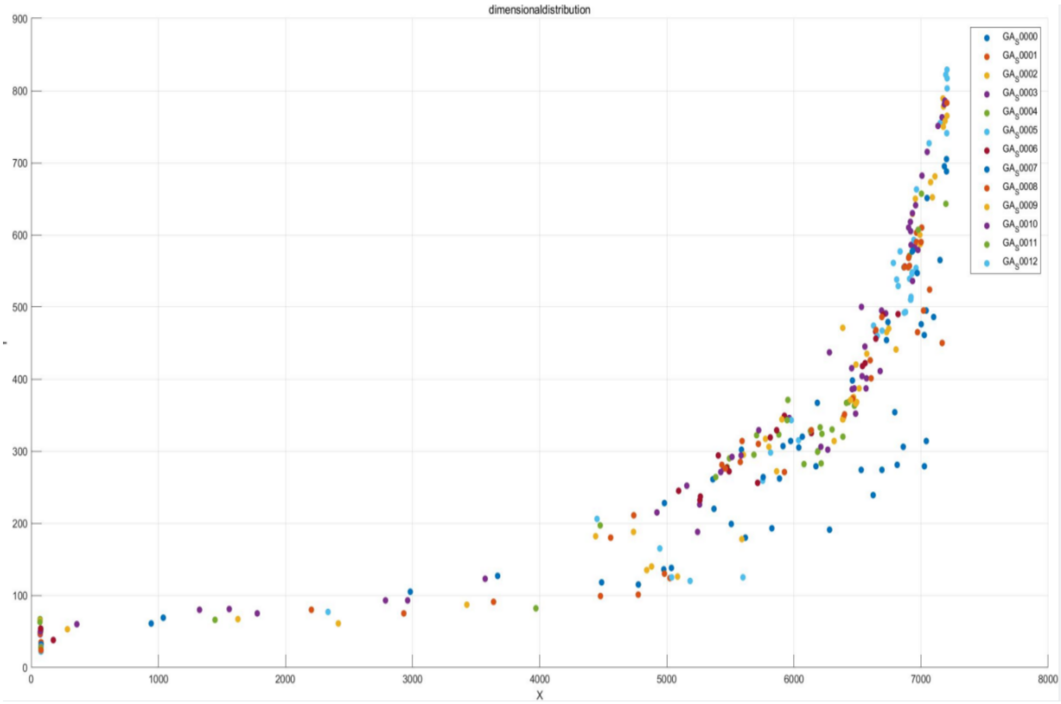

Figure 7. All Generations' Objective Values in Two-Dimensional Coordinate System

Based on objectives, the points that are closer to the origin of coordinate system should be regarded as the more optimal solutions.

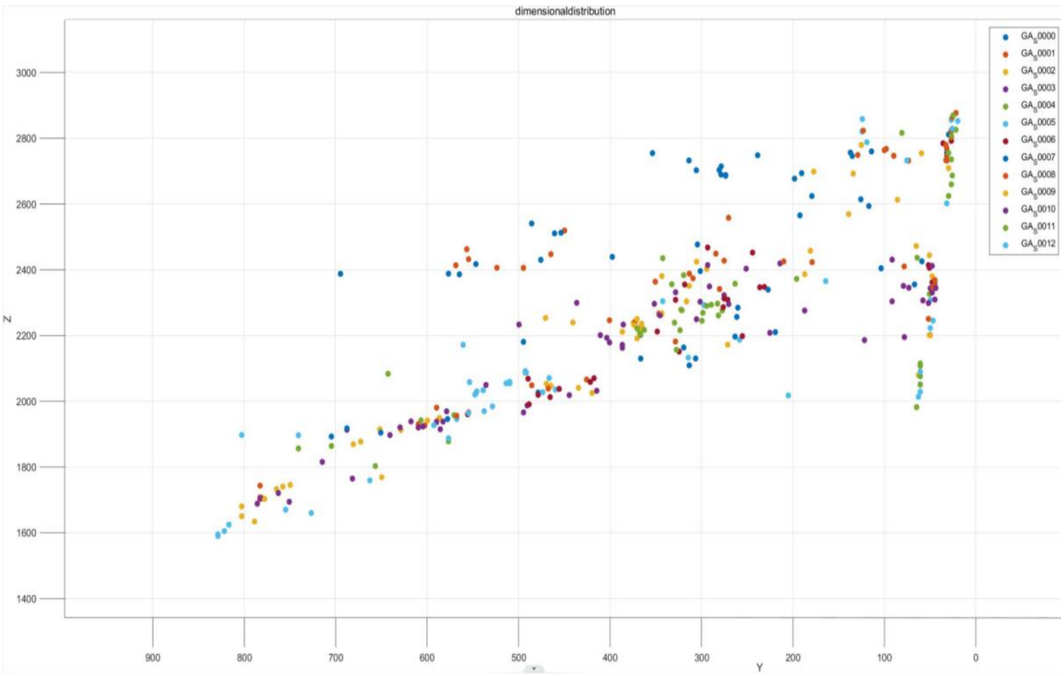

Figure 8. All Generations' Objective Values on Z-axis

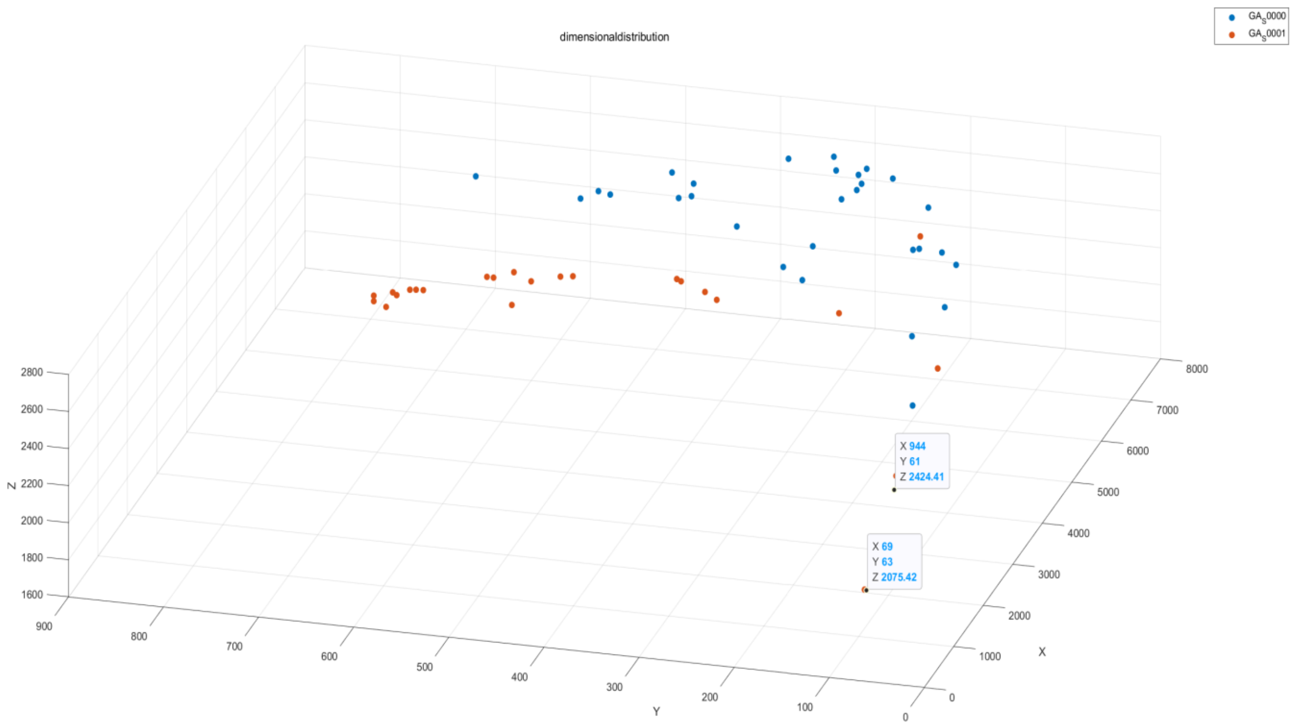

Figure 9. 10th Generation's Objective Values

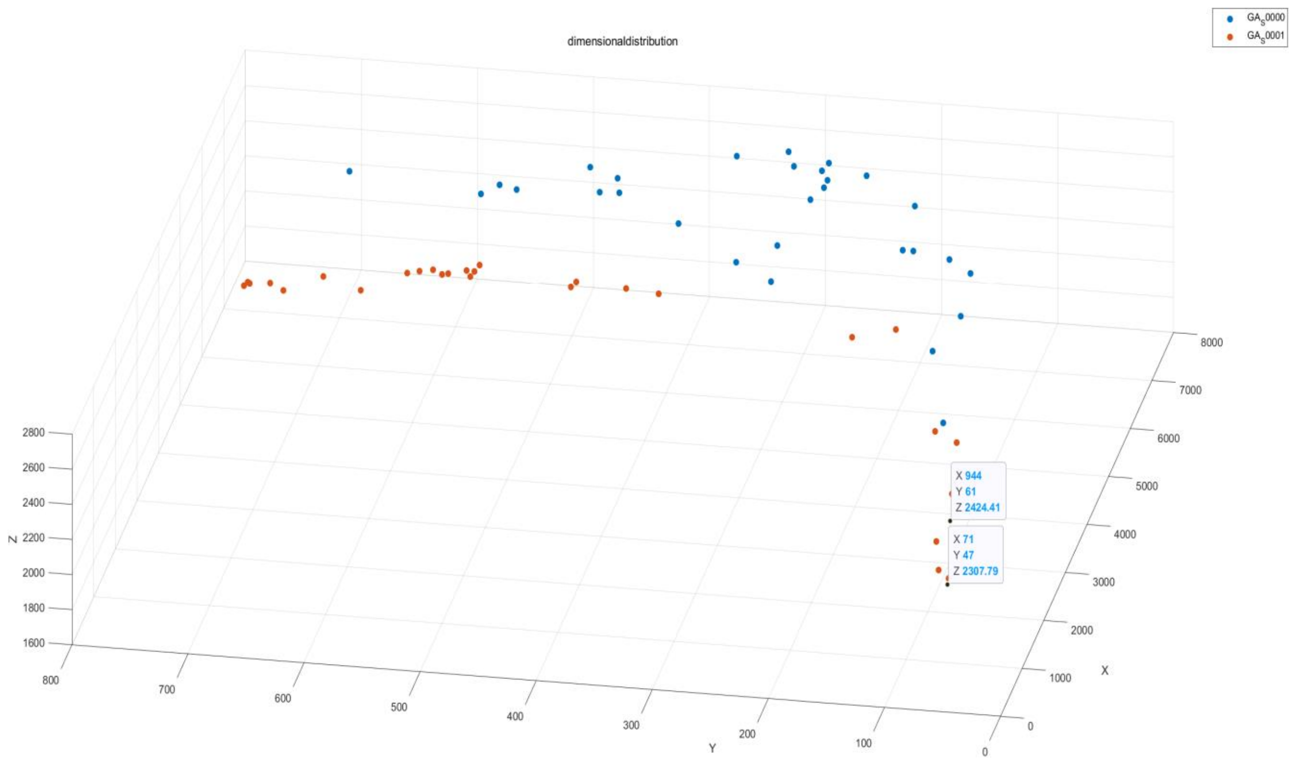

Figure 10. 11th Generation's Objective Values

In Fig.9 and Fig.10, the blue points represent the initial data sets, orange points represent the final data sets.

Table 1. Comparison between Initial Generation and 10th, 11th Generation

Generation	X (critical pressure area)	Y (CO_2 plume area)	Z (the difference between the target CO_2 injection volume and the simulated CO_2 injection volume)
Initial	944	61	2424.41
10^{th}	69	63	2075.42
11^{th}	71	47	2307.79

By comparing objective function values, it is clearly that the critical pressure area decreases largely, and the difference between 10^{th} and 11^{th} generation models are the CO_2 plume area and the CO_2 injection volume difference. Which model will be accepted depends on the judgement made by reservoir engineers.

5. Conclusion

By using the grid numbers in MRST model to represent the area, the area of critical pressure and CO_2 plume is easier to calculate and display, comparing with the abstract number, reservoir engineers can solve questions and make further plans in a more straightforward way. With the help of non-dominated sorting genetic algorithm, the critical pressure area and CO_2 plume area can be limited in a really small range, which means USDW can be protected from reservoir liquid pollution. At the same time, the injected CO_2 volume can increase largely. This is the advantage of using genetic algorithm.

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If any, should be placed before the references section without numbering.

Data Availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Conflict of Interest

The author states that this article has no conflict of interest.

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