# Advanced ML and AI Approaches for Proxy-based Optimization of CO2-Enhanced Oil Recovery in Heterogeneous Clastic Reservoirs

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*This is an as-yet, no peer-reviewed preprint that has been submitted to the Journal of Petroleum Science and Engineering*

**Abstract**

Constructing a simpler model to represent a complex reservoir simulation that will be employed to define the optimum future development plans have been achieved through the use of different simulation techniques that include EOS-compositional reservoir simulation, Proxy Modeling as well as Design of Experiments. Once reliable history matching was achieved, the key five operational decision parameters were manupilated to find the optimum value to attain maximum objective function. A low-discrepancy and consistent procedure was used to generate several hundred simulation jobs or experiments to build a proxy metamodeling optimization by adopting the Latin Hypercube Sampling with the five decision parameters. At the end of the forecast case, the optimum cumulative produced oil resulted in achieving 4.6039 MMMSTB of oil production compared with 4.39 MMMSTB of oil production that was produced from the base scenario of the GAGD technique assessment of original decision parameters' conditions.

Lastly, four machine learning (ML) and Artificial Intelligence (AI) algorithms were considered as proxy metamodels as substitute to the large numerical simulation model: Quadratic Modeling (QM), Fuzzy Logic-Genetic Algorithm (FUzzy-GEnetic), Multivariate Additive Regression Splines (MARS), and Generalized Boosted Modeling (GBM). The cross validation of the Adjusted $R^2_{adj}$ along with the RMSE were the base to conclude the optimum proxy metamodel which provides the lowest varaince between the preicted and calcualted model considering the produced oil as response by CO2-GAGD technique. Consequently, GBM was determined to be the best shorten alternative metamodel for the performance of GAGD process.

*Keywords:* `Proxy modeling`, Experimental Design, LHS, Gas Injection, EOTR, Heterogeneous Reservoirs

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## 1. Introduction

The Gas-Assisted Gravity Drainage (GAGD) technique was patented to improved oil recovery in different immiscible and miscible injection modes (Rao , 2012). The GAGD process is attained by installing horizontal production wells at lower part of the target reservoir. Then, vertical wells used for imiscible or miscible gas injection at the reservoir crest (Rao et al. , 2004). Because of the distinct fluid densities and gravity segregation, the accumulative gas injection at the top of reservoir to generate a gas cap. This process will supply gravity stable oil sweep that moves the hydrocarbon to the bottom of the reservoir towards horizontal production wells which help to achieve improved sweep performance and optimum oil recovery. Mostly, the CO2 gas is favored for GAGD process as it provides optimum volumetric sweep efficiency, particularly when it is used in miscible injection processes. Furthermore, the ideal volumetric sweep performance enhances retarding CO2 arrival in production wells (Rao , 2012). Slowing down or diminishing the arrival of the injected gas minimizes concurrent gas-liquid flow, and later enhances gas injection to sustain the reservoir pressure. The GAGD process was adopted to ehance the oil recovery in the Rumaila oil field, Iraq.

The subjected oil field was first intiated in the end 1953 in southern Iraq. The field is located in the western part of Basra city with approximately 60 km distance (Al-Ansari , 1993). The field length is 100 km with 12-14 km width and located 3.2 km below sea level. South Rumaila oil field was found to be comprised of several oil bearing reservoirs intervals. Four key sectors were defined in South Rumaila field which are called Janubia, Rumaila, Shamiya, and Qurainat. Rumaila sector and only minor regions of Shamiya and Janubia sectors will be studied in this research. The selection of these parts was decided depending on the gathered reservoir data and the capability to characterize the major parts of the reservoir, where the wells are producing and water injection activities are performed, shown in Figure **??**. Two types of boundary conditions of ther reservoir: a no-flow N-S boundary and E-W aquifer. This assumption is acceptable as it mimics the reality since the reservoir adopted the balance production and injection rates. Whereas the E-W boundary were characterized by flow boundaries that symbolize the natural water drive to mimic the effects of the existing infinite aquifer (Al-Mudhafer et al. , 2010).

South Rumaila field was first developed on primary production in 1954 while water injection was commenced in 1980s to support the pressure of reservoir and to sustain the west flank aquifer support which is about 20 times stronger than the east flank aquifer (Kabir et al. , 2007, Al-Mudhafer et al. , 2010). Throughout field development, 40 production wells were drilled in the regions that are under the investigation of this research. The development of the South Rumaila field included shutting of some of the reservoir layers as they were reason of high water cut values that reached about 98%. Until 2004, the total volume of the injected water reached approximately 1.1 billion barrels with various rates of injection. The maximum injection rate value was 426,000BPD for two months in 1988. Since water cut hit 80% in some wells, artificial lift (ESPs) has been used to sustain production. The main pay in South Rumaila has an OOIP of 1950 MMSTB and the estimated recovery factor is around 54%. The studied sector in this research has an OOIP of 6.13 billion barrels.

## 2. Compositional Simulation of GAGD Process

Comprehensive compositional reservoir simulation has been constructed to optimize the recovery of the bypassed oil by GAGD technique. The geological description of South Rumaila depicts that it has three rock types: sand, shale and shaly sand which are distributed through the reservoir with different permeability ranges. A full detailed geostatistical model with approximately 2,000,000 grids with 69, 66, 12 grid dimensions to model lithofacies and petrophysical properties (Al-Mudhafar , 2016a). This model was the base to build the EOS-compositional simulation using CMG-GEM package (CMG , 2015). This model was then history matched to be used for the future filed development and planning by the trial and error technique depending on the production and injection rates along with the cumulative produced oil. The acquired matching is an excellent indicator of the model performance as it replicates water cuts and saturation distribution. The production and injection history that have been used in this research covered 56 years of production which is until the first quarter of 2010.

A total of 33 wells have been used to implement the key concept of GAGD process. At first, CO2 injection is commenced by the vertical injection wells at the shallower two layers. Simultaneously, the following three layers are utilized as a transition region to provide vertical space for gas gravity drainage. The next steps involve setting up the horizontal producers through layers 6-8 which contains the highest oil saturation in the reservoir. Eventually, the remaining four layers did not involve injection or production processes since the water saturation in these layers is 100% from the quifer. The reservoir model was later simulated to assess the CO2-GAGD method with 10 years duration starting from 2016 and ending in 2026. Figure 1 illustrates the 3-D reservoir model with the positions of injection and production wells that have been used for the CO2 injection in the GAGD method. Figure 1 shows the locations of injection and production wells.

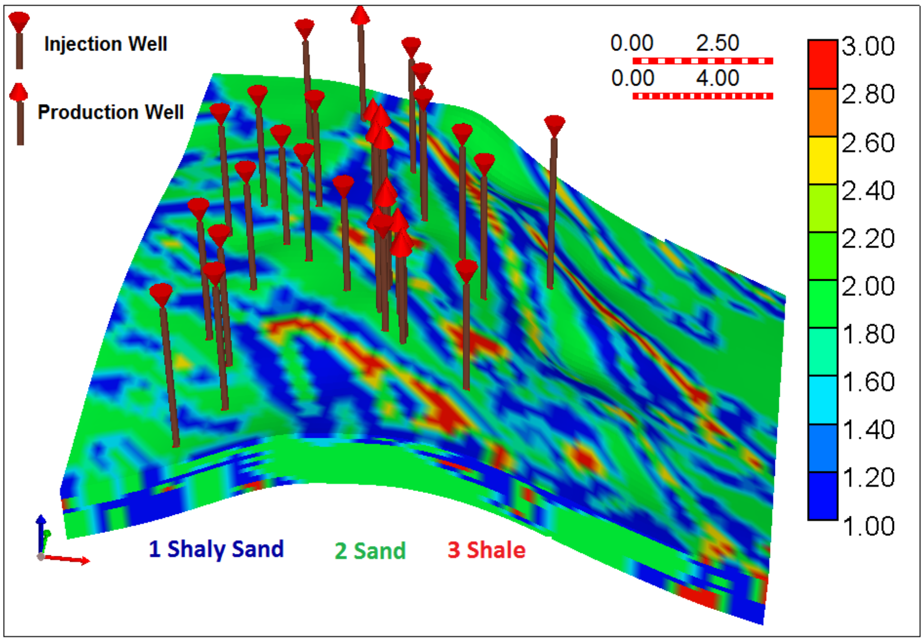


Figure 1: Locations of injection and production wells

Sand zones and shaly-sand zones (indicted in 1 and 2 respectively in figure 1) were perforated in production and injection wells since they are considered to be high permeable zones.

## 3. GAGD Optimization

Experimental Design is a numerical technique that generates a suitable group of experiments to be the base of the simulation runs. DoE is mainly utilized for determining the highest critical parameters that impact the response during the sensitivity analysis practice. DOE tool provide a way to acquire the most likely case which accomplishes the optimum response from a certain procedure (Lazic , 2006). DOE technique was demonstrated as an efficient tool for carrying out several tasks such as system optimization, variable screening, risk evaluation, and robust design (Amudo et al. , 2009). It is essential to accomplish the most precise experimental design model that imitates the physical model or process for faster, cheaper and more flexible implementation. To accomplish this task, the necessary group of elements and interactions have to be investigated in order to enable the analysis and implementation of results to be accurate and trustworthy (White and Royer , 2003).

The key terms ofExperimental Design are response parameter which basically symbolizes the result from a specific experiment and factor. The factors are described as a variable which impacts the response parameter and can be classified as primary and secondary based on the different level of sensitivity. The overall count of designed experiments is defined by an exponential relationship. For illustration, the experiments count with k variables and 4 levels will be equal to $4^k$. The Latin Hypercube Sampling (LHS) was implemented in this research to build proxy metamodel as a substitute model of the complex compisitional simulation of the GAGD process. From the aforementioned experimental design and proxy metamodel, four algorithms models were selelcted: QM, MARS, Fuzzy-Genetic, and GBM.

## 4. GAGD Production Optimization

The well constraints controlling the immiscible GAGD process performance: $(MAX\_STO)$, $(MIN\_BHP)$, and $(MAX\_WCUT)$ in oil producers. In adition, $(MAX\_BHG)$ and $(MAX\_BHP)$ in gas injectors. The default values of these five parameters were 350000 STB/DAY, 2000 PSIA, 0.95 in oil producers and 10E06 SCF/DAY and 300 PSIA in gas injectors. The aforementioned parameters levels were integrated by LHS approach to produce many simulation cases. Later, these cases were evaluated by the simulation model to estimate the total produced oil during 10 years of prediction period. The ideal solution represents the simulation case that provide the highest oil production. The total number of simulation cases that was created to perform GAGD simulation is more than 600 runs. Figure 2 depicts the optimum simulation case which provide the highest oil production during 10 years of prediction time.

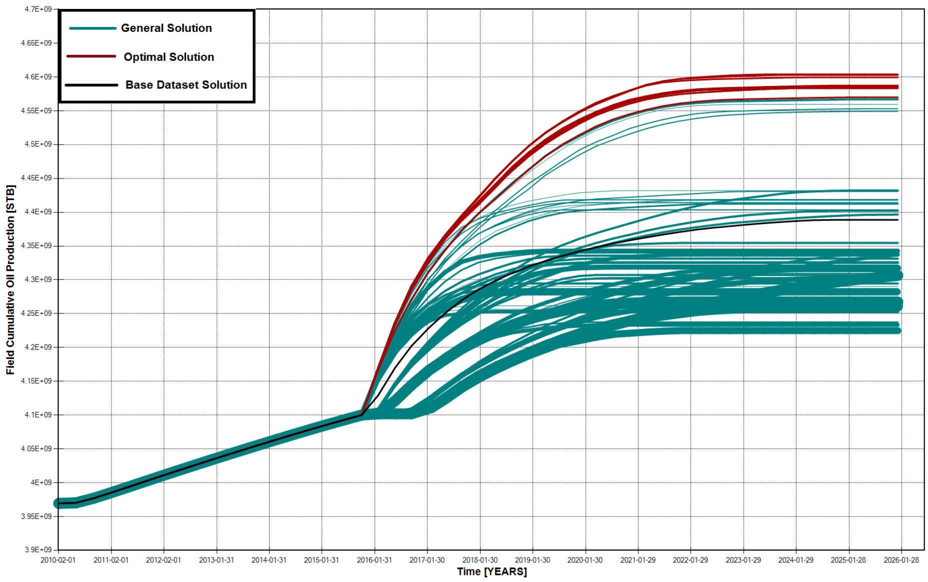


Figure 2: Optimal Solution among more than 600 Simulation Runs

The total produced oil during the future development scenario of GAGD technique estimated to be 4.39 bn STB. Nonetheless, the ideal solution based on the optimal case by LHS & proxy optimization, managed to enhance the total produced oil to 4.6 bn STB. Figure 3 shows total oil produced from the basesimlation case and the ideal simulation case.

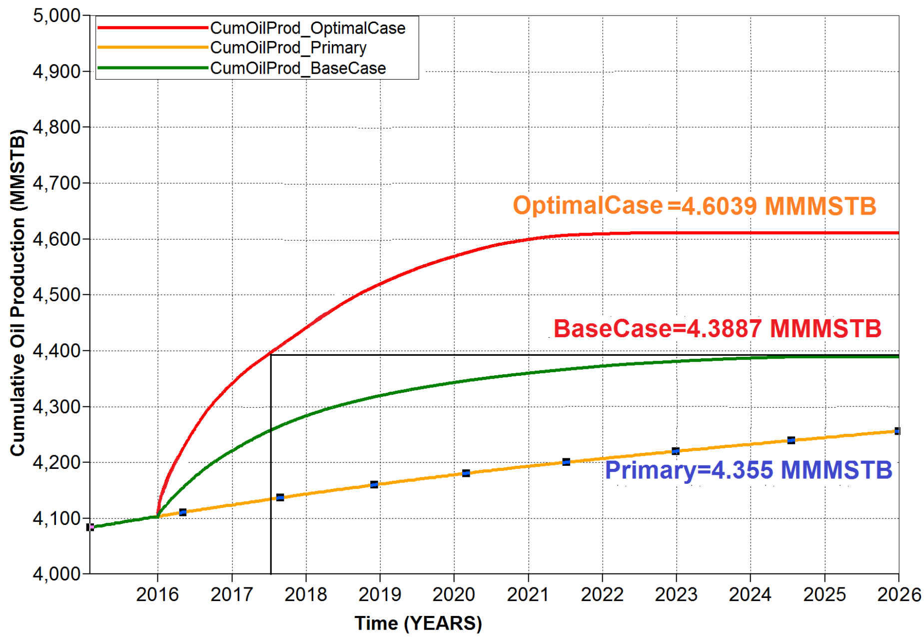


Figure 3: Comparison of Oil Production between Primary, Base, and Optimal Cases

### *4.1. Evaluation and Validation of the Proxy Models*

The complete steps of proxy optimization was explained based on the iterative technique of building a quadratic model (QM). The 600+ simulation runs were utilized to compare building new proxy models based on four different technique. This method combines multiple techniques such as cross validation, Root Mean Square Error and $R^2_{adj}$ aiming to identify the optimum proxy model that is possible to be assumed as an ideal metamodel of the CO2-AGD process.

The dataset of the 600+ jobs were divided into 75% training subset and 25% testing subset meaning that the model was trained based on approximately 450 simulation runs and prediction effectivness was tested based on the rest runs.

The Root Mean Square Error and $R^2_{adj}$ were computed in order to differentiate the estimated cumulative produced oil from the simulation model and the forecasted through the proxy model. Figures 4, 6, 8, and 10 illuminate the matching of the estimated cumulative produced oil from the observed, which is from the simulation model, and the forecasted from the four proxy models based on the test subset jobs for the QM, MARS, FUzzy-GEnetic, and GBM, respectively. Figures 5, 7, 9, and 11 depict the matching of the estimated cumulative produced oil from the simulation model (Observed) along with the forecasted based on the proxy models (Predicted) with respect to the full dataset jobs for the QM, MARS, FUzzy-GEnetic, and GBM, respectively.

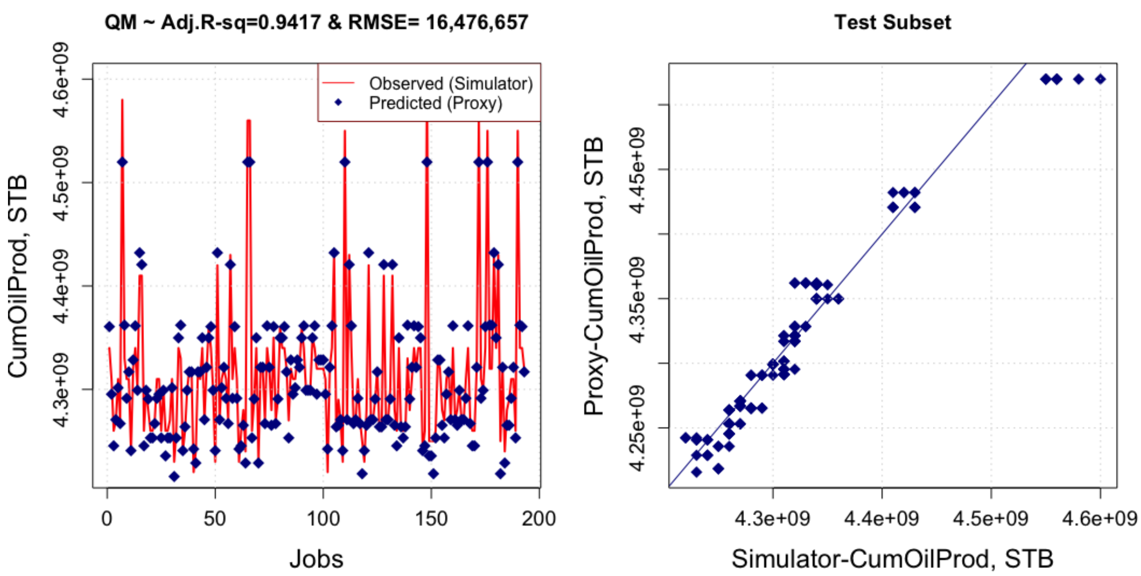


Figure 4: Matching of Calculated and QM Predicted Given the Test Subset

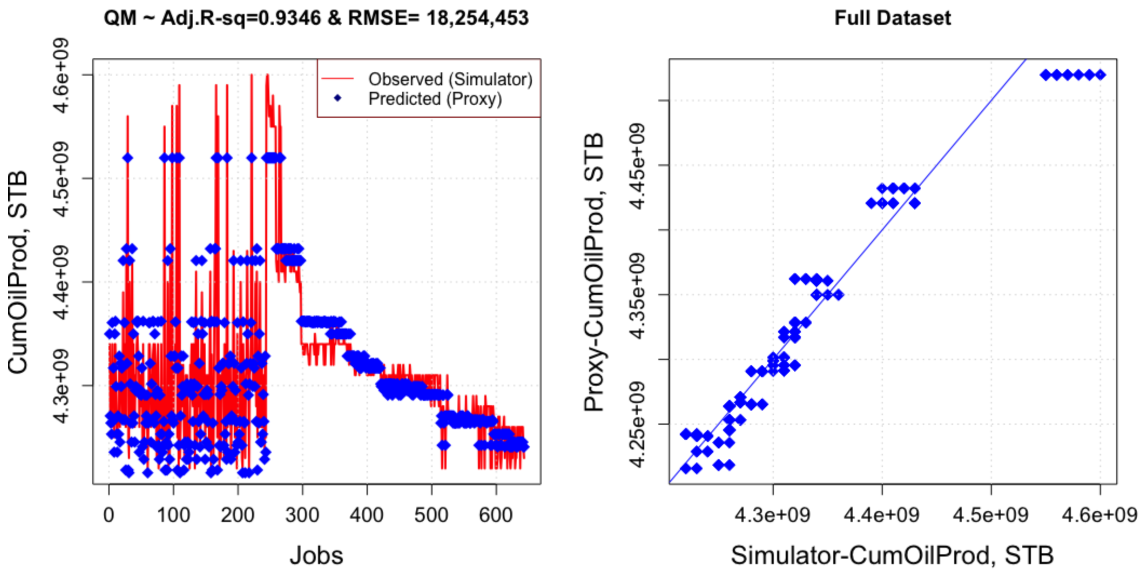


Figure 5: Matching of Calculated and QM Predicted Given the Full Dataset

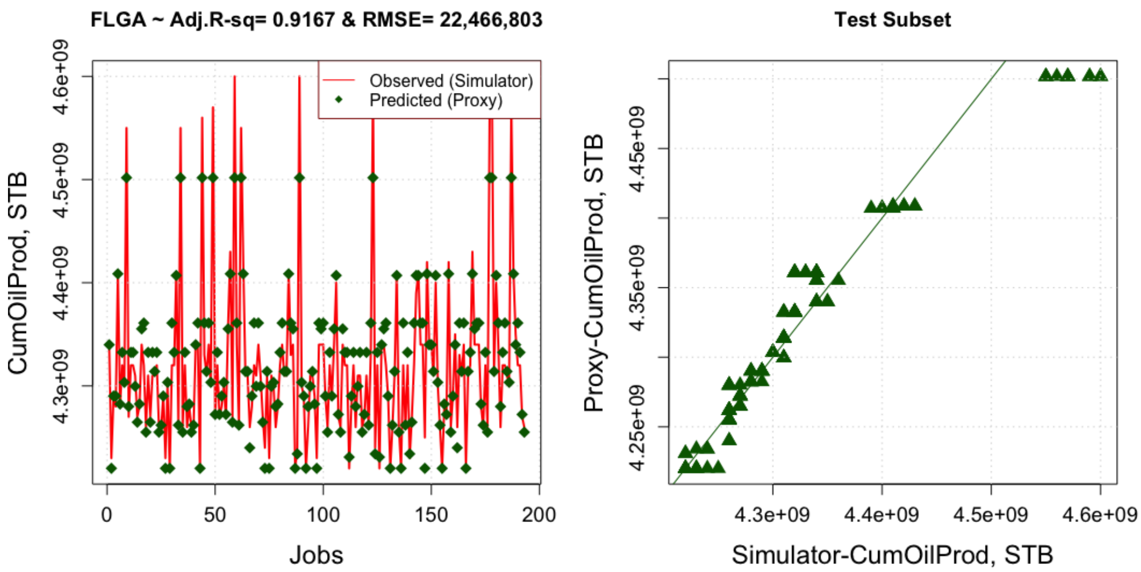


Figure 6: Matching of Calculated and FUzzy-GEnetic Predicted Given the Test Subset

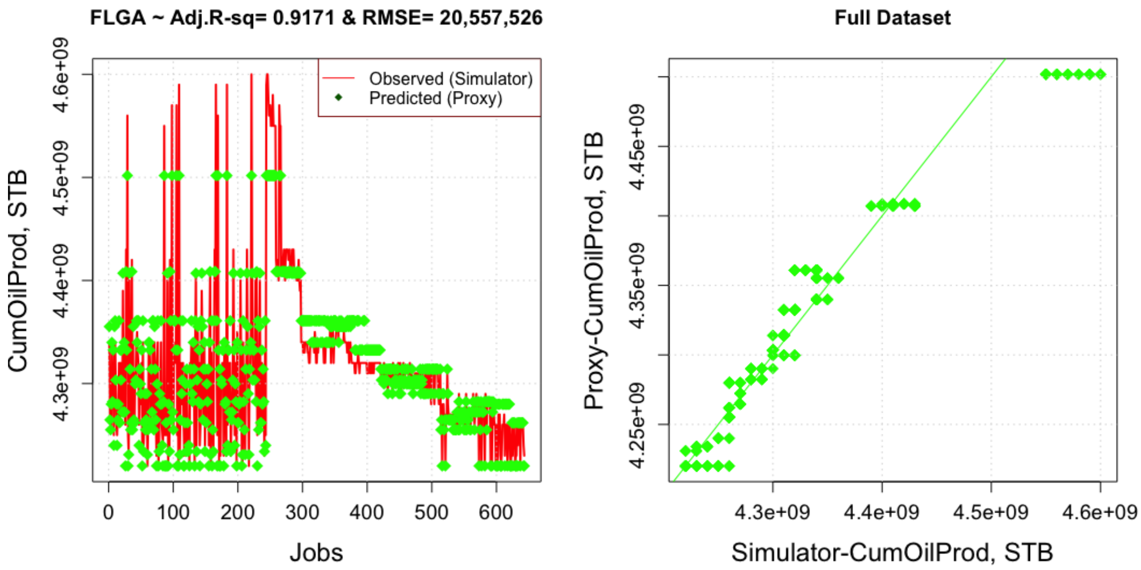


Figure 7: Matching of Calculated and FUzzy-GEnetic Predicted Given tThe Full Dataset

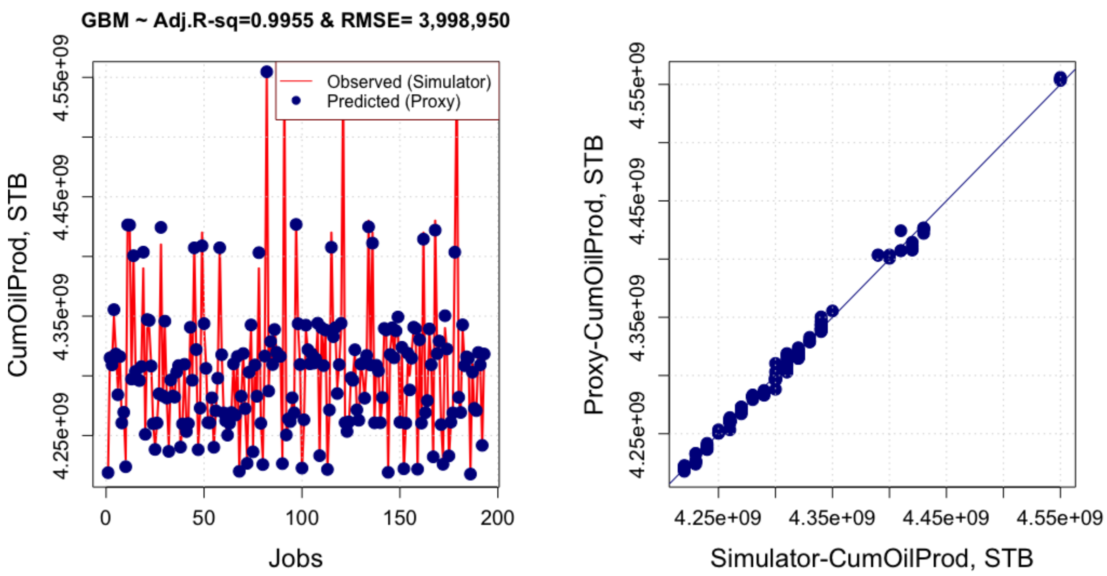


Figure 8: Matching of Calculated and GBM Predicted Given the Test Subset

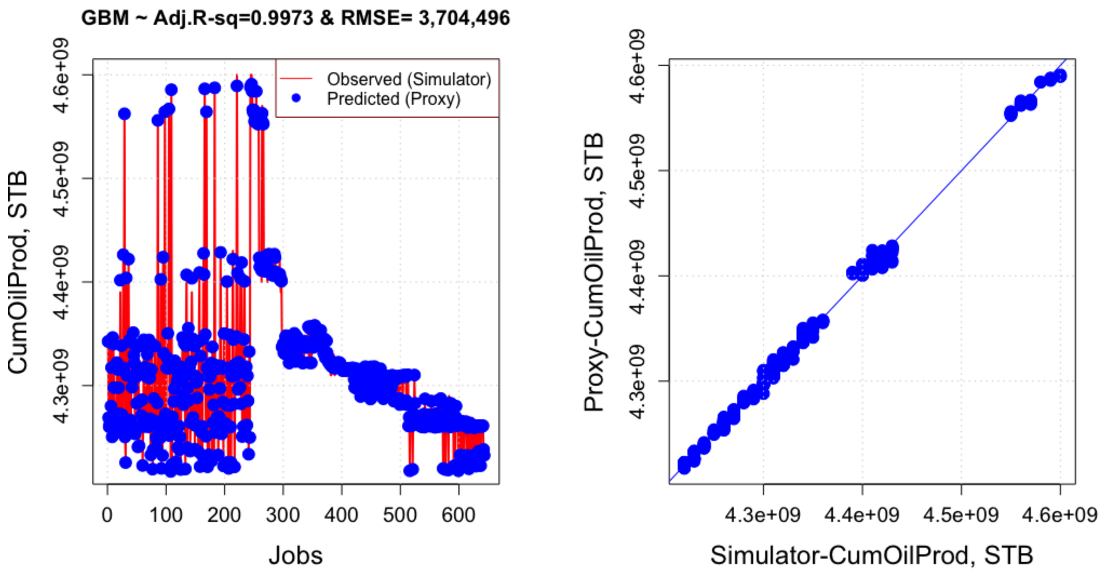


Figure 9: Matching of Calculated and GBM Predicted Given the Full Dataset

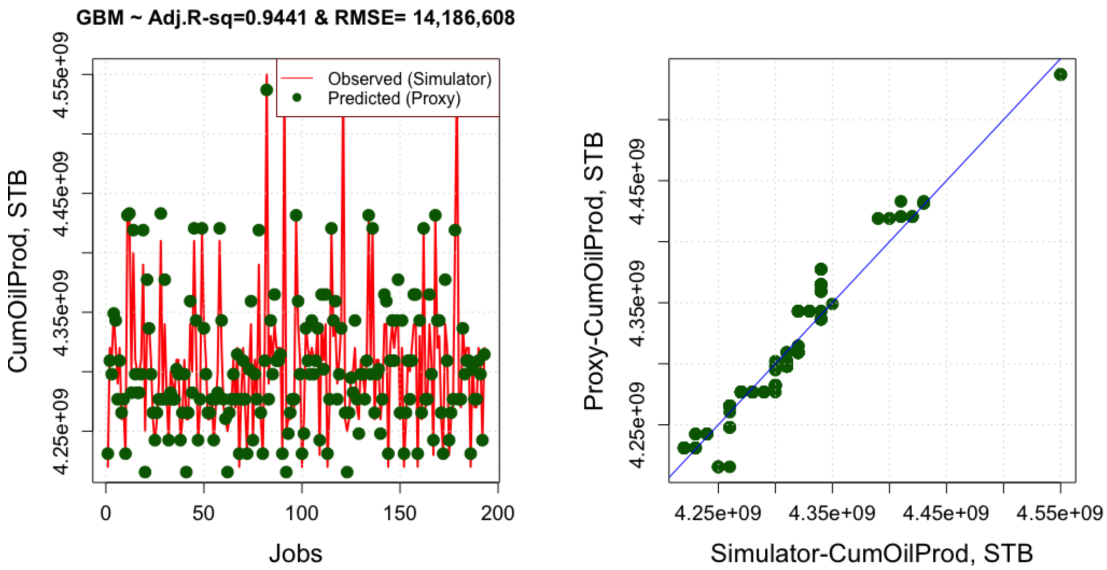


Figure 10: Matching of Calculated and MARS Predicted Given the Test Subset

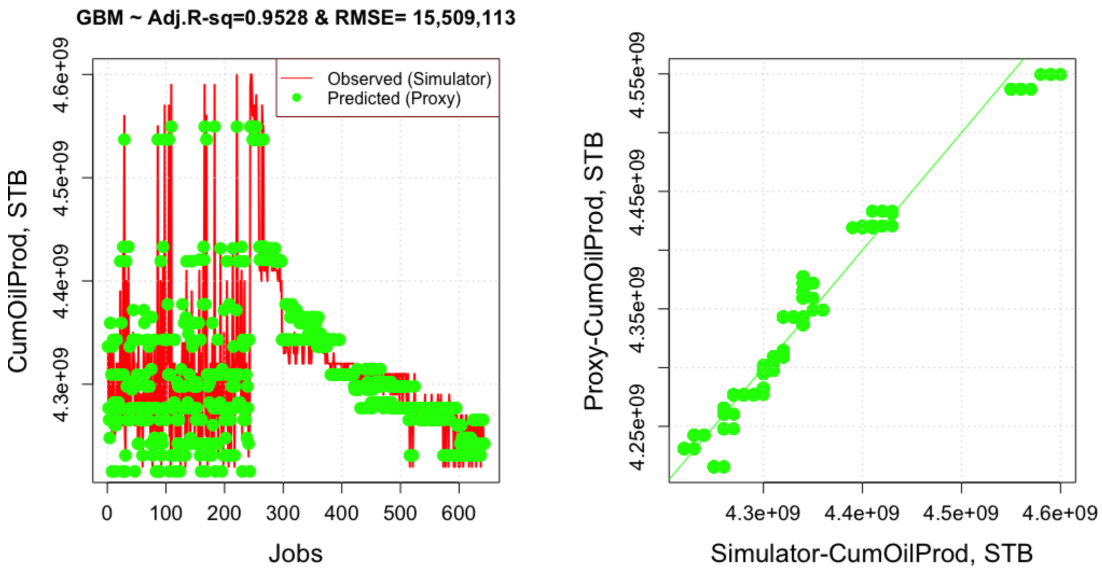


Figure 11: Matching of Calculated and MARS Predicted Given the Full Dataset

## 5. Summary and Conclusions

The reservoir model was simulated for the GAGD process within nonhomogeneous main pay reservoir in South Rumaila. After obtaining a proper history matching, 10 years of production was utilized as a prediction period to acquire the optimum recovery ratio through changing the operational parameters which govern injection and production processes. The Latin Hypercube Sampling was implemented in order to generate several hundreds of trails and cases to be assessed through the simulation model in order to identify the optimum recovery ratio and to construct the proxy model.

That DoE and proxy modeling used to determine an ideal group of parameters in GAGD technique. The parameters are CO2 injection and highest BHP of injection besides the highest oil production and lowest BHP, and maximum water cut in the horizontal producers.

The GBM model was the most exact model for the GAGD technique as it attains the minimum RMSE and the maximum adjusted R2 adj that both reflect the lowest mismatch of the cumulative produced oil estimated through the simulation model and forecasted through the GBM-proxy models. Furthermore, MARS model was the second ideal matching model, followed by the polynomial and FUzzy-GEnetic proxy models. Additionally, the cumulative produced oil of both the simulation and proxy models from the GBM has better scatter points matching than the MARS, QM and FUzzy-GEnetic. As a result, the GBM can be implemented as a simplified substitute model instead of the high resolution reservoir model by the GAGD technique assessment and forecast.

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