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Analysis of Best Hydraulic Fracturing Practices in the Golden Trend Fields of Oklahoma

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Abstract

In the past decades several hundred stimulation procedures have been performed in the Golden Trend fields of Oklahoma. The outcome of these stimulation jobs have not been the same for all wells. The effectiveness of the stimulation is a function of several factors including reservoir quality, completion and stimulation techniques. Completion and stimulation techniques can be further itemized as completion type such as open hole versus cased hole, type and amount of fluids and proppant and the rate at which they are pumped into the formation.

This project was supported by DOE and GTI in connection with the DOE's Preferred Upstream Management Practices (PUMP) project. The project was implemented in three fields in the Golden Trend in Oklahoma. Detailed production and completion data analyses revealed that the most influential controllable parameter effecting the production rate and ultimate recovery was fracture stimulation, and as such, the bulk of efforts were focused on determination of optimized hydraulic fracturing procedure. Detail stimulation data from more than 230 wells in the Golden Trend fields of Oklahoma operated by three independent operators were collected and analyzed using a new best practices analysis methodology.

The study was performed for gas and oil bearing formations. Among the findings of this comprehensive study were the best stimulation practices in carbonate formations that are primarily gas producing, and clastic formations, from which both oil and gas are produced. During his study authors were able to identify the best type of fluid, the most optimal injection rate and proppant concentration for both types of formations.

In this paper application of a new methodology that was used to perform the best practices analysis on the Golden Trend fields of Oklahoma is presented.

Introduction

Identification of best practices in the oil and gas operations is gaining unprecedented momentum. Companies that have gathered large amounts of data now realize that they own a valuable commodity (above and beyond the hydrocarbon) that can play an important role in increasing efficiency in their day to day operations.

The question is how this vast amount of data can be used in order to help the company's bottom-line. This paper attempts to address this question by introducing a newly developed methodology that enables oil and gas companies to deduce information and knowledge from the existing data. The deduced information and knowledge can then be used in developing business rules and decision making.

The new methodology is named "Intelligent Best Practices Analysis" [1]. It incorporates a hybrid form of intelligent systems that includes artificial neural networks [2], genetic algorithms [3] and fuzzy logic [4] to achieve its objective that is the systematic analysis of large amounts of data in order to decipher and deduce relevant knowledge that can be used in business and engineering decision making.

In a previous paper [5] the theory and methodology of "Intelligent Best Practices Analysis" was presented in detail and therefore it will not be discussed in this article. This paper is dedicated to application of this methodology to a database of stimulation practices in the Golden Trend fields of Oklahoma to demonstrate its use and benefits.

In the Golden Trend fields of Oklahoma, like many other oil fields, the outcome of stimulation jobs have not been the same for all wells. The effectiveness of the stimulation is a function of several factors including reservoir quality, completion and stimulation practices. Detail stimulation data from more than 230 wells in the Golden Trend operated by three independent operators were collected and analyzed using this methodology.

Many companies in the oil and gas industry have been collecting large amounts of data over the past several years.

Hundreds of thousands of dollars have been invested in collecting and compiling various types of data. These databases cover all aspects of oil and gas business, from purely technical data that includes certain measurements from the reservoir or the surface facilities to non-technical data such as those related to economics or human resources issues. Now that all this data is available, following questions may be asked: "What can we do with this data?" "How can the company get a return on its data collection and preservation investment?" "Are there stories hidden in the megabytes, or sometime gigabytes of data?" "The collected data is a reflection of the history of the operations that have taken place and sometime are still taking place. What can we learn from our past practices?"

As the volume of data increases, human cognition is no longer capable of deciphering important information from it by conventional techniques. Data mining and machine learning techniques must be used in order to deduce information and knowledge from the raw data that resides in the databases. The Intelligent Best Practices Analysis – IBPA – incorporates the state of the art in data mining and machine learning to assist petroleum professionals in making the most of their existing data. Figure 1 is a schematic diagram of IBPA process in form of a flow chart.

Application to the Golden Trend Fields

In the previous paper [1] the principles of Intelligent Best Practices Analysis was covered in detail. In the next several sections of this paper these principles are applied to hydraulic fracturing practices of the Golden Trend fields of Oklahoma. This study was performed as part of a DOE sponsored project on determining Preferred Upstream Management Practices (PUMP).

Descriptive Best Practices Analysis

The descriptive best practices analysis incorporates fuzzy logic in order to detect any patterns in the records that are in the database. The descriptive best practices analysis can be performed on all the variables available in the database. Table 1 shows the list of parameters that will be analyzed during this study. The list in Table 1 shows 18 parameters that are present in this database. The parameters that will be used during the predictive best practices analysis (next section) are shown in the rows with shades of green. There are 8 parameters that will be studied in detail during the predictive best practices analysis.

The descriptive best practices analysis starts by identifying a parameter that would be used to partition the wells in terms of their productivity. In other words, what constitutes a well to be a poor, an average or a good well. For this study it was decided that the "30 Year EUR" would be the indicating parameter. The "30 Year EUR" has been calculated for all wells using decline curve analysis.

This simply means that, for this analysis, a well that produces up to 30,000 barrels of oil during 30 years is identified as a poor well. A well that produces up to 60,000 barrels of oil during the 30 years is identified as an average well, and wells that produce more than 90,000 barrels in 30 years are considered as good wells. Please note that these ranges are arbitrary and can be changed based on the economic practices of each operator.

Of course we know that in reality there is little difference between a well that produces 1000 bbls/yr and one that produces 1010 bbls/yr. Therefore we will not impose an artificially crisp boundary between such wells. Instead, we define a series of "fuzzy sets" that would resolve such unrealistic situations. This is done by identifying ranges of productivity within which wells are both poor and average and ranges of productivity within which wells are both average and good. This means that in our classification each well is poor to a degree and average to degree, or average to a degree and good to a degree. Let's define these ranges and provide some examples to clarify these definitions before starting the analysis. Based on the fuzzy sets shown in Figure 2, the range between poor and average wells is from 30,000 to 60,000 barrels in 30 years or about 1000 to 2000 bbls/year. The range between an average well and a good well would be from 90,000 to 120,000 barrels in 30 years or about 3000 to 4000 bbls/yr.

In order to clarify the classifications mentioned above please note the following example. In Figure 3 there are five graphs each pertaining to a particular well. In the first row the graph on the left belongs to *well A* which is a well operated by *Company One*. The "30 Year EUR" for this well is 23,402. This productivity makes this well to be a poor well. As shown in this figure *well A* has a member ship of 1.0 in the set of poor wells. In the first row the graph on the right shows the "30 Year EUR" of 35,958 for *Well B* also operated by *Company One*. This level of productivity makes this well to have a membership of 0.8 in set of poor wells and a membership of 0.2 in set of average wells.

In the second row on the left *Well C*, that is operated by *Company Two*, has a "30 Year EUR" of 65,996 that makes it an average well. On the right, *Well D*, has a '30 Year EUR" of 112,163 barrels. This well has a membership of 0.26 in the set of average wells and a membership of 0.74 in the set of good wells. On the bottom, *Well E* has a "30 Year EUR" of 333,940 that makes it clearly a good well.

Now that we are familiar with the classification lets see the existing practices in this field. First of all lets look at the distribution of wells in the database as far as the "30 Year EUR" is concerned. Figure 4 shows this distribution in terms of percentages. As shown in this figure, based on our classification about 85% of the wells are poor, about 35 % of them are classified as average and 9% are classified as good wells. Since we are not using conventional or crisp mathematics the percentage need not to add to 100%. In this methodology if a well has membership in more than one fuzzy set it will contribute to both classes. This simply means that in this database 85+35+9=129-100=29, 29% of the wells belong to more than one set.

In the next several figures we show the distribution of different parameters in our database as a function of the well quality. For example we will analyze the data to identify the number of poor wells that were hydraulically fractured using a particular fluid and compare it to the number of good and average wells that have been hydraulically fractured using the same fracturing fluid and look for trends. Hopefully these trends will show us if certain parameters and attributes are more predominant in certain quality wells more than others.

For the purposes of this article we will not show the parameters that seem not to have any effect on the well quality. The main fracturing fluids used in the stimulation jobs in the Golden Trend are "Acid", "Water" that includes slick water, salt water, treated water, and fresh water, "Oil" that is predominantly diesel and the last category is "Other". If the majority of the fluid used during the stimulation job was not identified as water, oil, or acid, then it was classified as "Other" which included entries in the database such as mostly "Unknown", some "Gel", and a few "Waxsol".

Figure 5 shows the results of the analysis on these main fracturing fluids. Based on this figure "Water" seems not to be contributing to good fracturing results since the set of poor wells have the highest average value (almost 0.6) of formations that have been fractured using water as the main fluid. This value is about 0.42 for average wells and good wells have an average value of slightly higher than 0.1.

Please note that the average value is a fraction since many wells have been completed in several formations. The numbers that you see in these figures are simply averages over many wells. Oil as main fracturing fluid shows exactly the opposite trend as water. Better wells have been predominantly fractured using diesel oil as the main fracturing fluid. From this figure it is concluded that for those formations that are producing oil, future hydraulic fracturing procedures in this field should be performed using diesel oil as the fracturing fluid, and use of water as the main fracturing fluid should be avoided.

Figure 6 shows the analysis on four stimulation parameters on "per foot of total perforated pay thickness" bases. These parameters are total shots, total fluid amount, total proppant amount, and average injection rate "per foot of total perforated pay thickness". Looking at Figure 6 it seems that there is not an identifiable trend in the average value of "Shot/ft" for different well qualities. Furthermore, it is shown that good wells have been fractured using a lower than average amount of fluid "per foot of total perforated pay thickness". While the average for all the wells is about 1.6 Mgal/ft (which does not change for poor and average wells) the average amount of fluid pumped in good wells is about 1.0 Mgal/ft.

Amount of proppant used during the hydraulic fracturing treatment according to Figure 6, shows a general pattern of higher proppant amounts per foot of pay thickness for average and good wells as compared to poor wells. Given the trend identified for fluid amount, this means that the pattern favors higher proppant concentration for better wells. Average rate of injection "per foot of total perforated pay thickness" indicates that it is preferable for the fluid and proppant to be pumped at lower rates. It seems that the good wells have been pumped at about 0.12 BPM/ft. This may point to the fact that there may not be a significant in-situ stress contrast between the pay zones and the barrier formations.

Predictive Best Practices Analysis

Now that the Descriptive Best Practices Analysis has been completed, let's look at the predictive analysis. The next several sections will cover this analysis for oil production from the Golden Trend fields.

The main idea behind the predictive analysis is to fill the gaps in the solution space in order to make a comprehensive analysis possible. The predictive model that is developed, calibrated and verified based on the existing data provides a continuous hyper -dimensional surface that is full of hills and valleys. This surface covers the entire solution space that the records in the database are discrete points on this surface. Goal of predictive analysis is two folds. First, to develop a predictive model that can accurately approximate this solution space. This goal is achieved using artificial neural networks [2]. The 30 year EUR is used as the network's output and several independent variables (as will be discussed in the next section) are used as the network input. It is important to use the proper variables as the input to the neural network. The input variables have to sufficiently represent the process being modeled and include parameters that identify the uniqueness of each record (well) in the database. Second goal of the multiple-parameter analysis is to exhaustively search through, and query the solution space in order to identify patterns that can be used as guides in the decision making process. This step of the analysis is performed using genetic algorithms [3]. The neural network model developed in the first step is used as the objective function of the genetic algorithms.

Neural Network Modeling

Upon performing some preprocessing on the data and identifying the best set of input parameters to be used during the neural model building a neural model was trained. Table 2 shows the list of the input parameters used in the neural network model.

As shown in this table there are two parameters that have been extracted from the Decline Curve Analysis of the production data. These are Qi (initial flow rate) and Di (initial decline rate). There are two parameters that identify the location of each well, latitude and longitude. These parameters can also be a proxy for the geology of the reservoir at the location where the well is drilled. The two parameters, RRQI and Sub RRQI, relative reservoir quality indices, developed using a process called Intelligent Production Data Analysis [6] and are further indication of the reservoir quality in addition to latitude and longitude.

Number of perforations per foot of the pay zone (Shot / ft) is the parameter that identifies the completion of the well. The next seven parameters out of the total of fourteen are stimulation related. The first one, Date of the First Stimulation, identifies a time stamp for the well. The next four parameters identify the type of fluid that was used as the main fluid in the stimulation job. The next two parameters identify the amount of fluid and proppant and the rate of injection per foot of the pay zone.

The output of the neural network model is the “30 Year EUR”. The data set was divided into three smaller sets. The training data set included 147 records (wells). The calibration data set included 17 records (wells) and the verification data set included 18 records (wells). The training set was used to train the neural network model. The calibration data set was not used for training but served as a criterion in order to identify when the training process has been completed. Finally the verification data set (blind data) served as judging the goodness of the model. Figures 7 and 8 show the results of the model performance on calibration and verification data sets.

The R^2 for the training data set was 0.904 and the correlation coefficient was 0.951. The calibration data set has a R^2 of 0.642 and a correlation coefficient of 0.801. The R^2 and correlation coefficient of the verification data set are 0.905 and 0.951, respectively.

Full Field Analysis

The full field, predictive best practices analysis looks at all the wells in the database and identifies the major trends in the process. The adjective “Predictive” implies the fact that some of the patterns that are identified may not have been already practiced. The analysis would predict what could have potentially happen if certain practices had been employed.

The results of full field predictive hydraulic fracturing best practices analysis in the Golden Trend is summarized in the “Recommendation Matrix” presented in Table 3. This matrix combines the results of single parameter and combinatorial analysis and provides best practices recommendations. Details on how such recommendation matrix is constructed have been presented in [5].

Recommendations are made when both the single parameter analysis and the combinatorial analysis seem to be pointing at the same direction. A good example of such case is use of diesel oil as the main fracturing fluid. During both analyses the dominant trend is toward using diesel oil in order to increase the well productivity.

Other parameters that seem to show clear signs of specific trends are number of perforations per foot of pay thickness, injection rate, and proppant concentration. Number of perforations per foot of the pay thickness is recommended to be on the side of smaller numbers (mainly around one shot per foot). Low injection rates are preferable specifically when the increased proppant concentrations are recommended. Figure 9 and 10 shows the results of combinatorial analysis for full field analysis.

Groups of Wells Analysis

The predictive best practices analysis based on groups of wells are covered in this section. Upon completion of the full field analysis the wells in the database are classified and the process is repeated for each class (category or cluster) of the wells. The classification can be based on several criteria. If there is a class indicator in the database (natural or native classifier) it can be used as the basis for the classification. In the case where each record in the database represents a well in a field (as the case in this application) the classification of the wells can be based on any predetermined classifier such as well quality, operating company, well locations, geology, reservoirs involved, or any other classification that makes sense. In cases that such native (natural) classifier is not present in the database, k-mean clustering or fuzzy c-mean clustering can be used in order to cluster the records in the database. For this study wells were once grouped base on their quality, and once based on the operator. Three operators had participated in this study. In this article only the results that was achieved based on the operators is presented.

Grouping Based on Operators

In this section the predictive best practices analysis is performed on wells grouped based on their operators. This means that the wells in the database are divided into three groups based on the operators i.e. *Company One, Two, or Three*. Initially one might consider this grouping as arbitrary. But we think that valuable information might be deduced using this grouping. This grouping has the potential to shed light on positive or negative practices (regarding hydraulic fracturing) that might exist in a company which can be attributed to the culture (the way things are down around here) within each company. These cultural attributes may contributes to the success of certain practices, in which case must be nurtured, or they may prove not to be very productive, in which case the management may want to revisit them. Some of such attributes may exist in an implicit fashion rather than being enforced explicitly. In such cases studies such as this one may prove helpful in starting productive discussions in the company.

It is a well known fact that certain things are done in certain ways in some companies that might be different from others. Usually the way things are done in a company has its roots in the previous successes that it has brought about and management is reluctant to change things once they have proven to be successful. But sometimes what used to be true may no longer be true, due to changes in the operational landscape. Other factors may have entered the equation, which necessitate another look at the way things were done in the past. On the flip side, by regularly examining the effectiveness of the common practices in a company the management can reinforce the successful productivity of those practices.

Figure 11 shows the location of the wells being in our database that are operated by different companies in the Golden Trend. The Recommendation Matrix for each of the operators is shown in the Tables 4, 5, and 6. For wells operated by *Company One* it is concluded that diesel oil is the most effective fracturing fluid. This conclusion is reached since diesel oil is the only fracturing fluid that results in consistent increase in “30 year EUR” (with the highest range) in both single parameter and combinatorial analysis. Furthermore, it is recommended to use high proppant concentrations injected at low rates into wells that are completed with about one shot per foot of pay for wells operated by *Company One*.

Table 5 show the combination of the single parameter analysis with the combinatorial analysis for wells operated by *Company Two*. The conclusions reached in this table are analogous to those from *Company One* although some differences appear in the single parameter analysis. These differences are not in directions that would change the recommendations but to make them more or less assertive in different cases. Engineers need to keep an eye on these trends in order to make necessary adjustments when designing new treatments for wells operated by *Company Two*.

In Table 6, where the conclusions for the *Company Three* are presented, the main fracturing fluid seems to still be the diesel oil. But in the case of wells operated by *Company Three* Acid as the main fracturing fluid may provide results that are not so different from oil and in some cases it might even outperform diesel oil. Therefore, for situations that use of diesel oil may not be realistic (for whatever reason) Acid may be the reasonable alternative fluid.

Similar to wells operated by *Company One* and *Company Two*, wells operated by *Company Three* seem to benefit from high proppant concentrations injected at low rates into wells that are completed with about one shot per foot of pay thickness.

The major difference between full field analysis and those made for wells grouped by operators was the clarification of lower number of perforations per foot of pay thickness along with high proppant concentrations.

Individual Well Analysis

Upon completion of full field and groups of wells analysis, the last part of the predictive best practices analysis is the analysis of individual wells. Usually by the time we get to the individual well analysis we have a clear idea of the best practices in a particular field. This is true in the case of the Golden Trend.

The essence of individual well analysis is to look into details of a hydraulic fracture treatment with all the specifications of a particular well. Therefore, an individual well analysis includes running the simulation model for the well that is being considered for a stimulation treatment.

Single Parameter Analysis – Individual Wells

During the single parameter analysis, all the inputs for the well will be kelp at the original value and one by one the controllable parameters will be changed as explained in previous sections. Figure 12 shows the results of the sensitivity analysis for four wells in the database. The reason the following several figures are presented is to show that different behaviors might be observed from different wells.

For example in Figure 12 the top left graph shows the sensitivity of *Well A-1* operated by *Company One* to water as the main fracturing fluid. The blue dot in the graph shows the status of the well in the database. This well did not use water as the fracturing fluid and has two formations present where only one of them has been hydraulically fractured. The fracturing fluid that was used for this well was diesel oil. The graph in Figure 12 shows that if instead of oil, water was used during the fracture treatment for this well, its long term production would have decreased, a practice that would not be recommended for this well.

On the other hand, the graph in the lower right of the Figure 12 shows the hydraulic fracturing behavior for *Well A-4* operated by *Company Three*. This well shows that if instead of one, two of the formations present in this well were treated with water; it would have a positive long term effect on this well's productivity. There are four formations present in this well were three formations were hydraulically fractured using acid as the main fracturing fluid.

Combinatorial Analysis – Individual Wells

The combinatorial analysis for the individual wells can be performed by identifying two or more parameters at a time. First let's examine the situation where two parameters at a time are examined. Figure 13 shows the three-dimensional graphs that are used to show the sensitivity analysis for two parameters simultaneously. The X and Y axes of the three dimensional graphs are "Shot/ft" and "Injection Rate (BPM/ft)". The Z axis of the graph is the "30 Years EUR".

These wells show different types of responses as the number of perforations and average rate of injection per foot of pay thickness changes. As expected all show high production values at low injection rates and number of perforations. The production response is different for each of these wells as number of perforations and the average injection rates start to increase. Well number three shows a monotonic decline in production as these values increase while well number 2 increase to values that are quite high at higher numbers of perforations and injection rates. All three wells show the same kind of behavior at small numbers of perforations that favors lower injection rates.

If more than two parameters are going to be analyzed, then using two and three dimensional graphs will be ineffective. In such cases a Monte Carlo simulation process is used to perform the analysis. To perform a Monte Carlo simulation following procedure must be followed:

- Identify the number of parameters that are going to be studied simultaneously.
- Identify a probability distribution function for each of the parameters.
- Identify the number of simulation runs that should take place.
- Make the simulation runs and plot the results as a probability distribution function.

The result of such a process as mentioned in step 4 would be a probability distribution function that identifies the most probable "30 Year EUR" that would result from the probability distribution functions that have been assigned to each of the parameters. Figure 14 shows the results of two different Monte Carlo simulations for *Well C-1* operated by *Company One*.

The probability distribution function of the “30 Year EUR” on the left represents 1000 simulation runs when the three identified parameters were selected for the analysis. These parameters were “Shot/ft” that was assigned a skewed triangular distribution function toward lower values, “Proppant Concentration” that was assigned a skewed triangular distribution function toward higher values, and “average injection rate” that was assigned a skewed triangular distribution function toward lower values. The “30 Year EUR” shows a probability distribution function that is skewed toward 29,000 barrels. The figure shows that the probability of long term production slowly reduces toward the 60,000 to 70,000 barrels mark.

The probability distribution function of the “30 Year EUR” on the right represents 1000 simulation runs when all the parameters were assigned a uniform probability distribution function. In this case the probability distribution function of the “30 Year EUR” is closer to a Gaussian distribution than the graph on the left. The mean value of long term production seems to be closer to about 34,000 barrels.

This exercise clearly shows that each well has to be analyzed individually in order to see how the general best practices would apply to it.

Application to Gas Production

The Golden Trend includes several formations. Some of these formations are clastic that are believed to be the main sources of oil production and some others are carbonate that are believed to primarily produce gas. The study detailed in this paper was performed separately for oil production and gas production. The concluding remarks that will follow summarize the conclusions achieved after both analyses had been completed.

Conclusions

Intelligent Best Practices Analysis (IBPA) is a two-step process that includes a descriptive and a predictive analysis. During the descriptive analysis the productivity of the wells in the database is divided into several fuzzy sets and fuzzy-averages of several parameters are then calculated to identify the trends that are present in the database. These trends and patterns usually provide a pretty strong foundation for the best practices that are ultimately identified.

Predictive best practices analysis is a drill-down process where we start with the full field analysis and end with individual well analysis. During the full field analysis we identify the best practices based on all the wells in the database. We then divide wells into groups, based on different criteria, and look at each group more closely and either, verify, refine or dispute the best practices that were identified during full field analysis. The last step of the predictive analysis is working with individual wells and using the results of past two steps as a guide to enhance the production of an individual well. We showed that although the best practices that were identified during the full field and groups of wells analysis would work for most of the wells (since that is how they were identified), there will be wells in the database (or new wells) that would not necessarily follow the identified trends as expected. This makes refining of the design by individual analysis a highly recommended exercise.

All the analysis mentioned above are based on a predictive neural network model that is developed from the data available in the database. Following paragraphs highlights the identification of best practices in the Golden Trend.

Formation Isolation before Stimulation

Wells in the Golden Trend are completed in several formations. The formations that are present in almost all of the wells can be divided into two major categories, clastic and carbonate. Oil production in the Golden Trend is predominantly from the clastic formations while substantial amount of gas is produced from carbonate formations and some from the clastic formations. Based on the findings of this study, formations in the Golden Trend respond positively to different types of hydraulic fractures. Therefore, it is highly recommended that the clastic and carbonate formations be isolated prior to stimulation jobs in order to achieve the best results.

Main Fracturing Fluid

It was identified that the recommended main fracturing fluid for the clastic formations in the Golden Trend is “Diesel Oil”. It is concluded that the clastic formations that are producing oil in the Golden Trend seem to have certain amount of clay that is contributing to damage of the reservoir near the well bore by developing hydration spheres, a process that seem to be reversible as long as the water saturation in the reservoir is not at irreducible saturation. This phenomenon has shown to have negative effect on short and long term production. Scientists at the Core Labs, Inc. have concluded that at gas to water permeability ratios (k_g/k_w) of higher than 3 (where Kilnkenberg gas permeability has been measured under reservoir stresses) oil seem to be a better choice for fracturing fluid [7].

On the other hand it was identified that the carbonate formations that produce mainly gas in the Golden Trend, respond positively to acid as the main fracturing fluids. It was further identified that “acid fracs” and not “acid jobs” are the stimulations that should be performed in these formations.

Number of Perforations

It was identified that a relatively low number of perforations (may be less than or equal to one shot per foot of pay thickness) would be the most appropriate practice of completion for wells in the Golden Trend. This seems to be true for both clastic and carbonate formations.

Proppant Concentration

It was identified that higher proppant concentrations work better in the Golden Trend. Figure 15 shows a logarithmic distribution function of the proppant concentration in the

Golden Trend. This figure shows that most of the fracture treatments have used low proppant concentrations (less than 1.0 lbs/gal/ft). The recommendation is to use proppant concentrations of higher than 1.0 lbs/gal/ft.

Average Injection Rate

It is recommended to use average injection rates of less than or equal to 0.2 BMP per foot of pay thickness while stimulating the formations in the Golden Trend. The combination of above three parameters, namely injecting higher proppant concentrations at lower injection rates into smaller numbers of perforations is targeted at avoiding increasing of the bottom-hole pressure during the treatment. While higher proppant concentrations provide a better conduit for the fluid flow and stronger support for keeping the fracture open for longer periods of time, its combination with lower numbers of perforations may contribute to higher bottom-hole pressures that might impede short and long term production. By injecting the treatment at lower injection rates we will try to keep the bottom-hole pressure low. It has been shown that there is a correlation between low bottom-hole treating pressures with higher production indicators [8].

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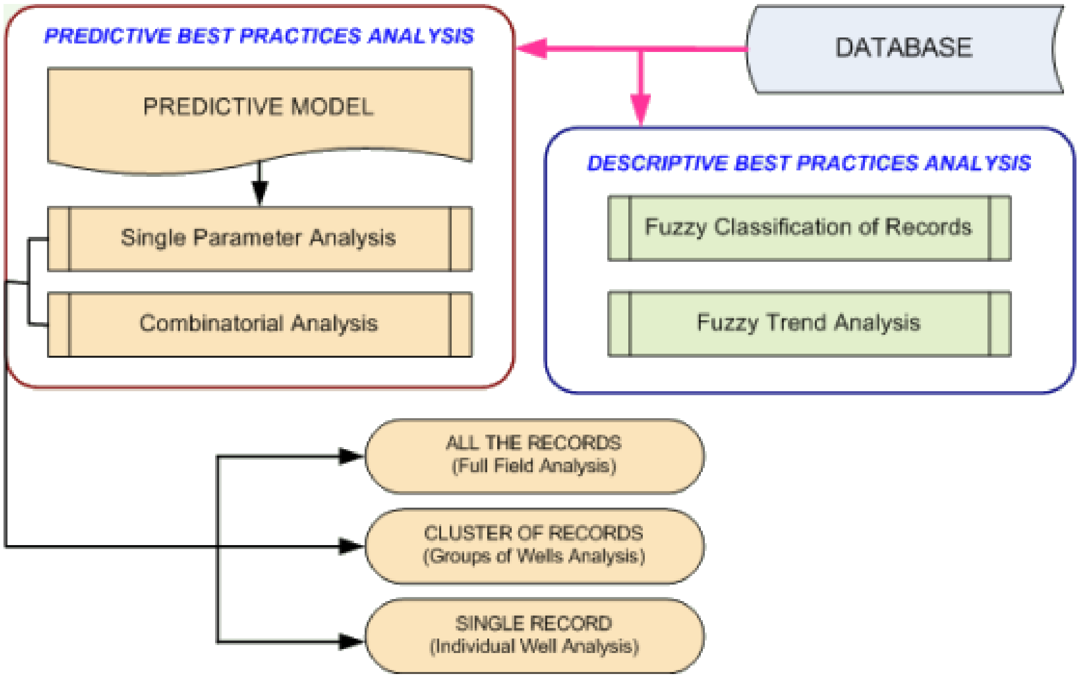

Figure 1. Intelligent Best Practices Flow Chart.

Table 1. Parameters in the database that were used during the "Best Practices" analysis.

No.	Parameter
1	Number of formations present in the well
2	Number of formations stimulated
3	Number of formations with hydraulic fracturing
4	Number of formations with acid jobs
5	Total perforated pay thickness
6	Date of First Stimulation
7	Main Fracturing Fluid - Water
8	Main Fracturing Fluid - Oil
9	Main Fracturing Fluid - Acid
10	Main Fracturing Fluid - Other
11	Total Shots per foot of perforated pay
12	Total Fluid amount (Mgal) per foot of perforated pay
13	Total Proppant amount (Mlbs) per foot of perforated pay
14	Total Proppant Concentration (lbs/gal/ft)
15	Average Injection rate per foot of perforated pay
16	Date of First Production
17	Best 3 months of production
18	Initial Flow Rate – Decline Curve Analysis
19	Initial Decline Rate – Decline Curve Analysis

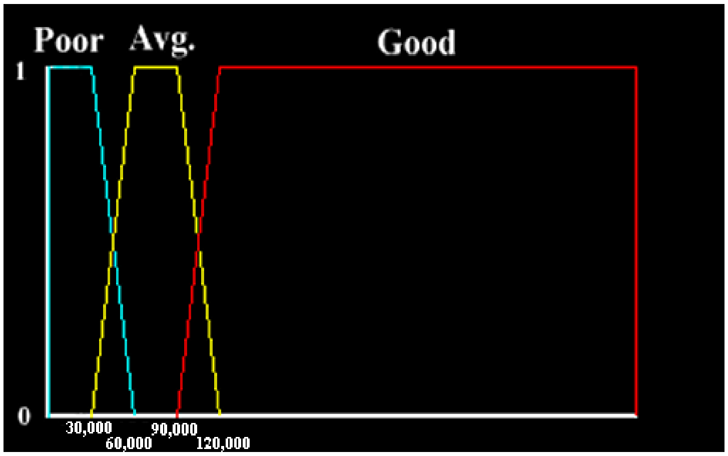

Figure 2. The "30 Year EUR" Productivity Fuzzy sets for wells in the Golden Trend Field.

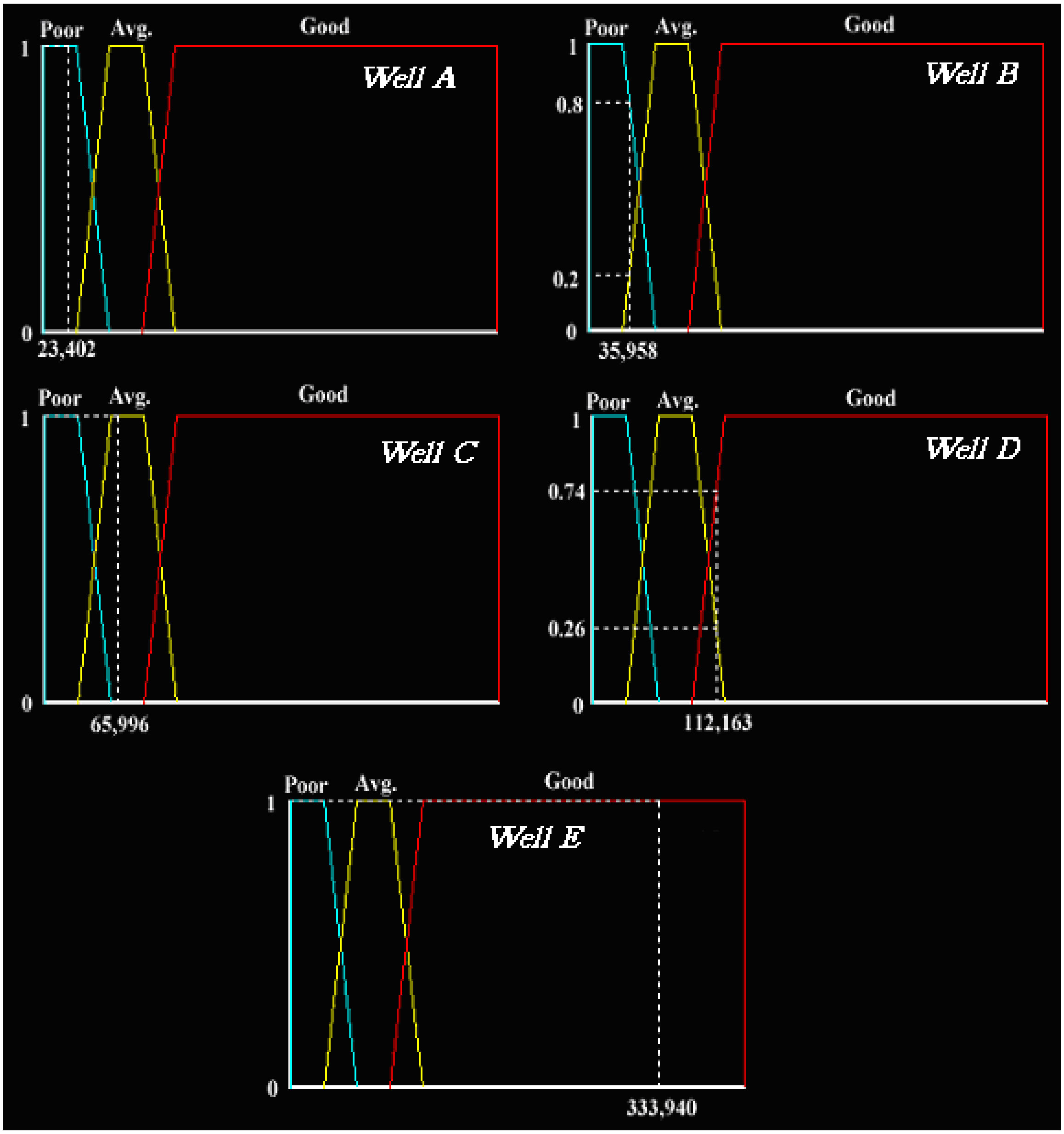

Figure 3. Classification of wells in the database using Fuzzy sets.

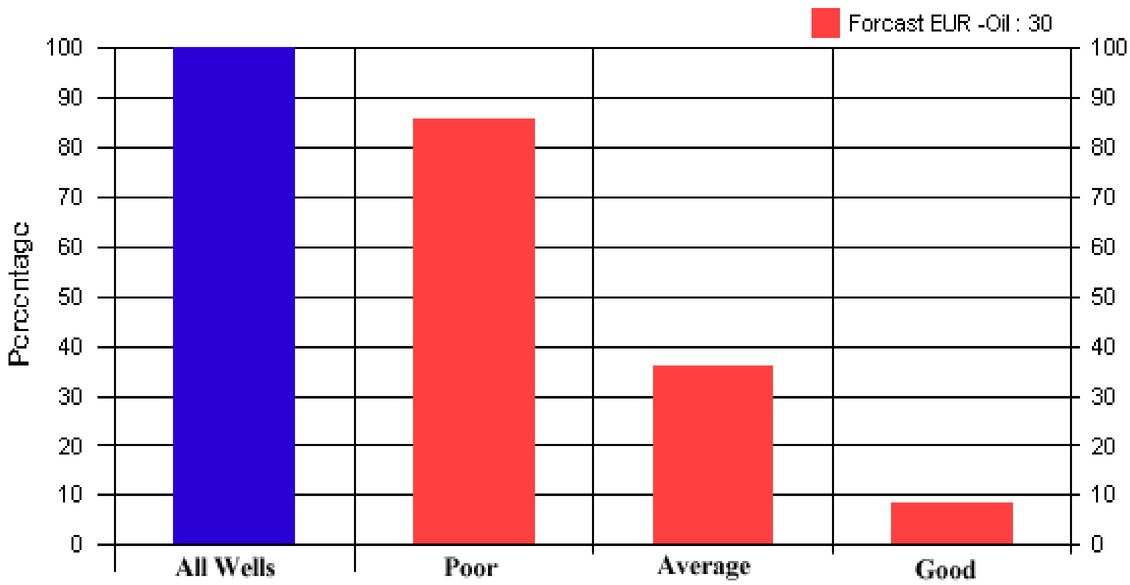

Figure 4. Distribution of the wells based on 30 Year EUR.

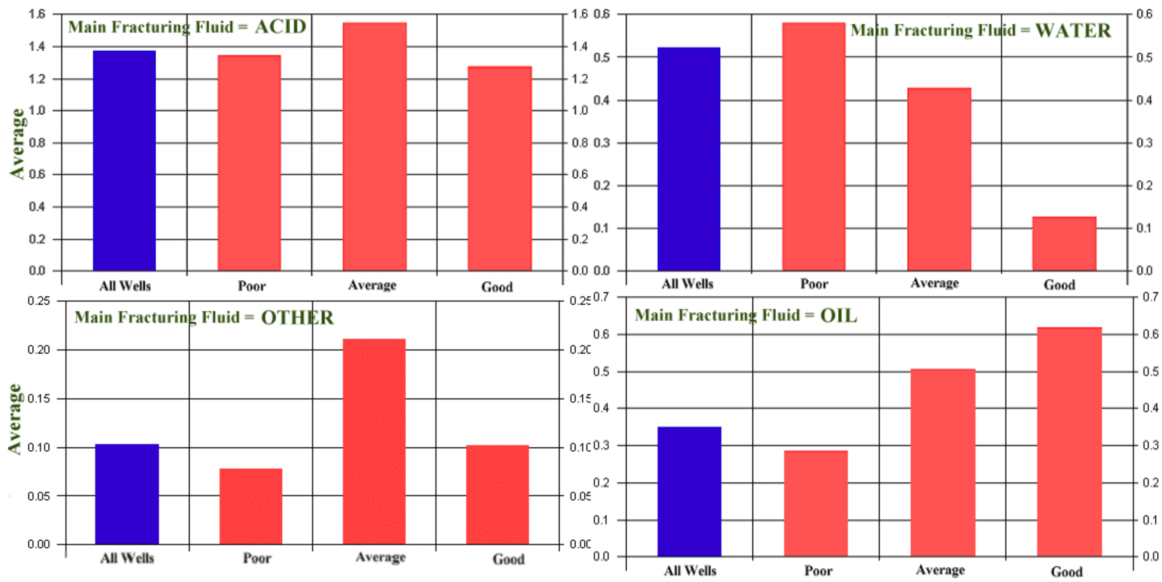

Figure 5. Distribution of the average value of Main Fracturing Fluids in wells of different quality.

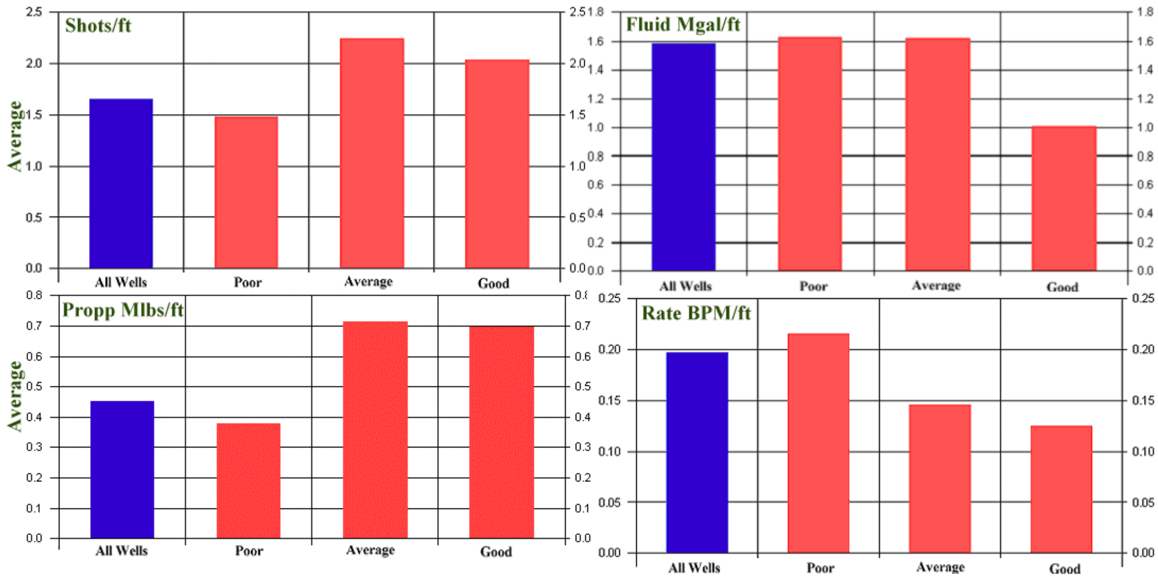

Figure 6. Distribution of the average value of completion parameters in wells of different quality.

Table 2. Parameters used during the neural network modeling process.

Qi
Di
Latitude
Longitude
Sub - RRQI
RRQI
Shots / ft
Date of first stimulation
MF - Water
MF - Oil
MF - Acid
MF - Other
Porppant Concentration (lb/gal/ft)
Ave. Inj. Rate (BMP/ft)

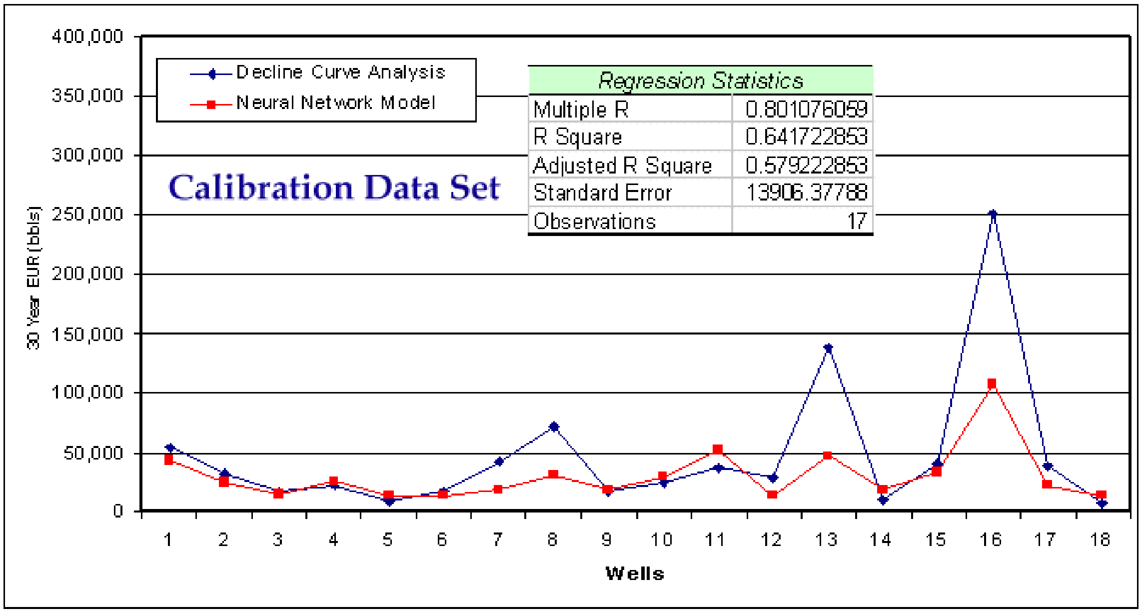

Figure 7. Actual and predicted 30 year EUR of the calibration data set.

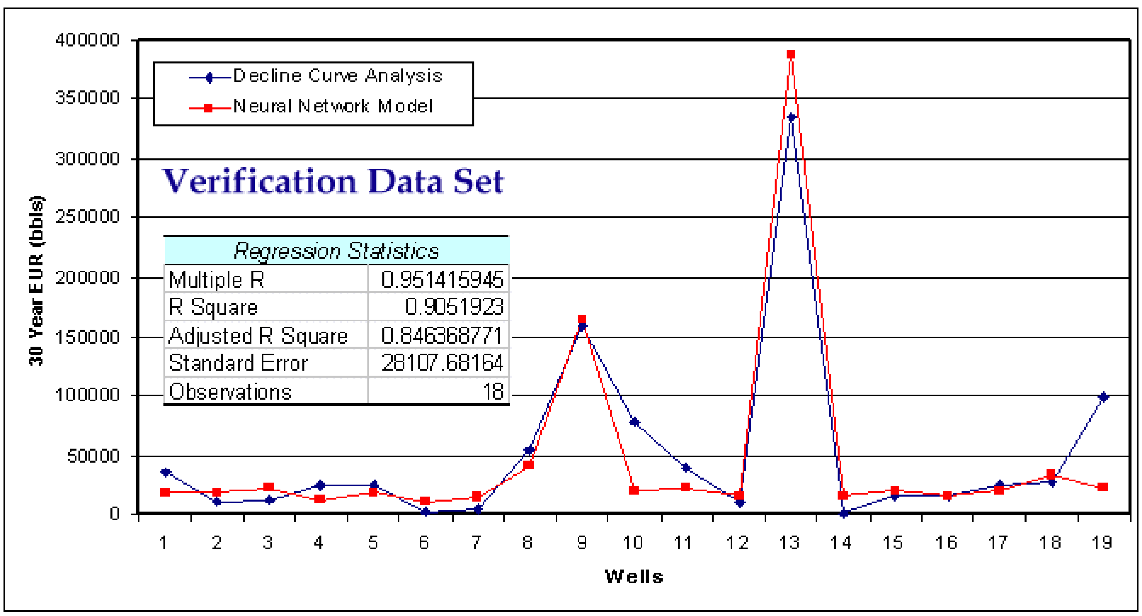

Figure 8. Actual and predicted 30 year EUR of the verification data set.

Table 3. Full field analysis Recommendation Matrix for best hydraulic fracturing practices in the Golden Trend.

	Parameter	Single Parameter Analysis			Combinatorial Analysis		Recommendations
		Percent of Population	Dominant Trend	Change in Value	Distribution	Dominant Trend	
Main Fluid	Water	Majority	Increasing	Moderate	Skewed	Use Little	Use Not Recommended
Main Fluid	Oil	All	Incressing	High	Skewed	Use A Lot	Use Recommended
Main Fluid	Acid	Majority	Decreasing	High	Skewed	Use Little	Use Not Recommended
Main Fluid	Other	Majority	Increasing	Low	Skewed	Use Little	Use Not Recommended
	Shot/ft	All	Decreasing	High	Skewed	Use Little	Use Small Numbers
	Prop Conc. (lbs/gal/ft)	All	Increasing	High	Skewed	Use A Lot	Use Large Amounts
	Rate (BPM/ft)	All	Decreasing	High	Skewed	Use Little	Use Low Rates

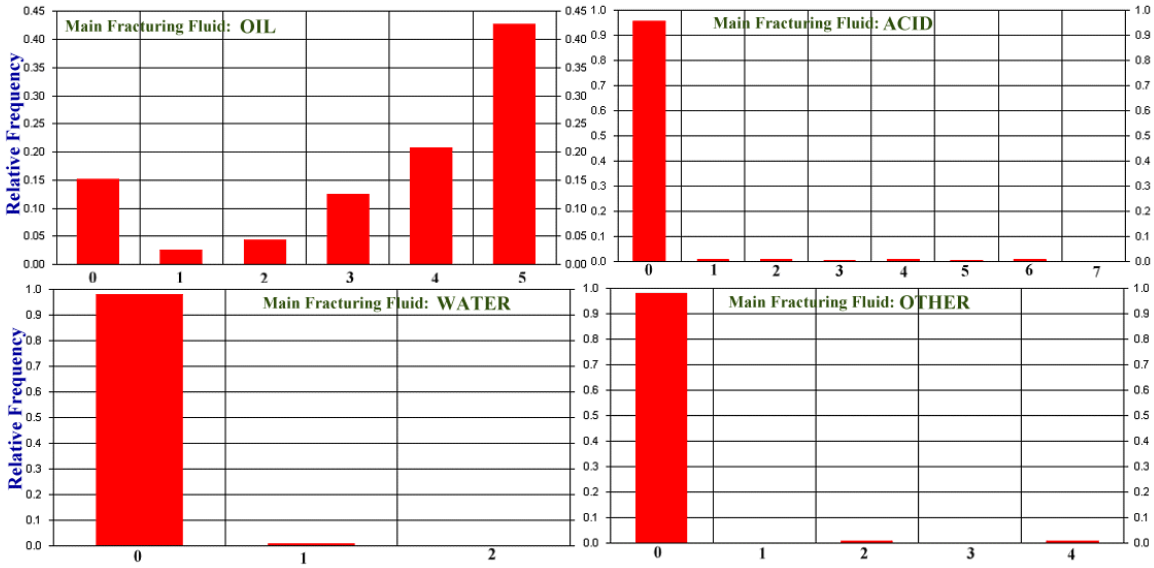

Figure 9. Full Field Combinatorial Analysis, results for main fracturing fluids.

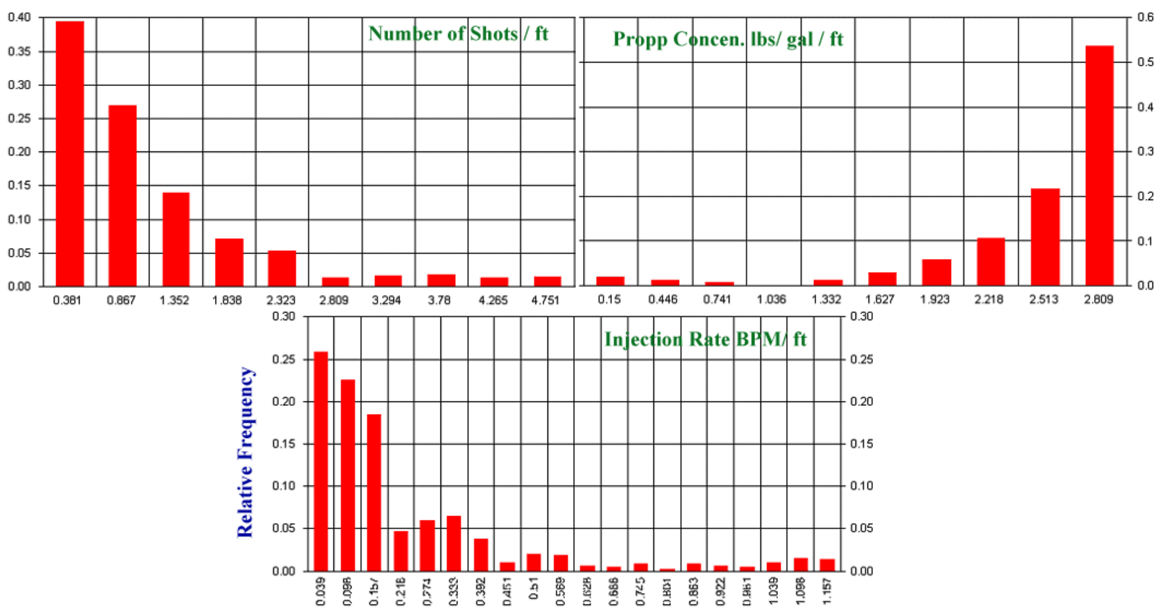

Figure 10. Full Field Combinatorial Analysis, results for other hydraulic fracturing parameters.

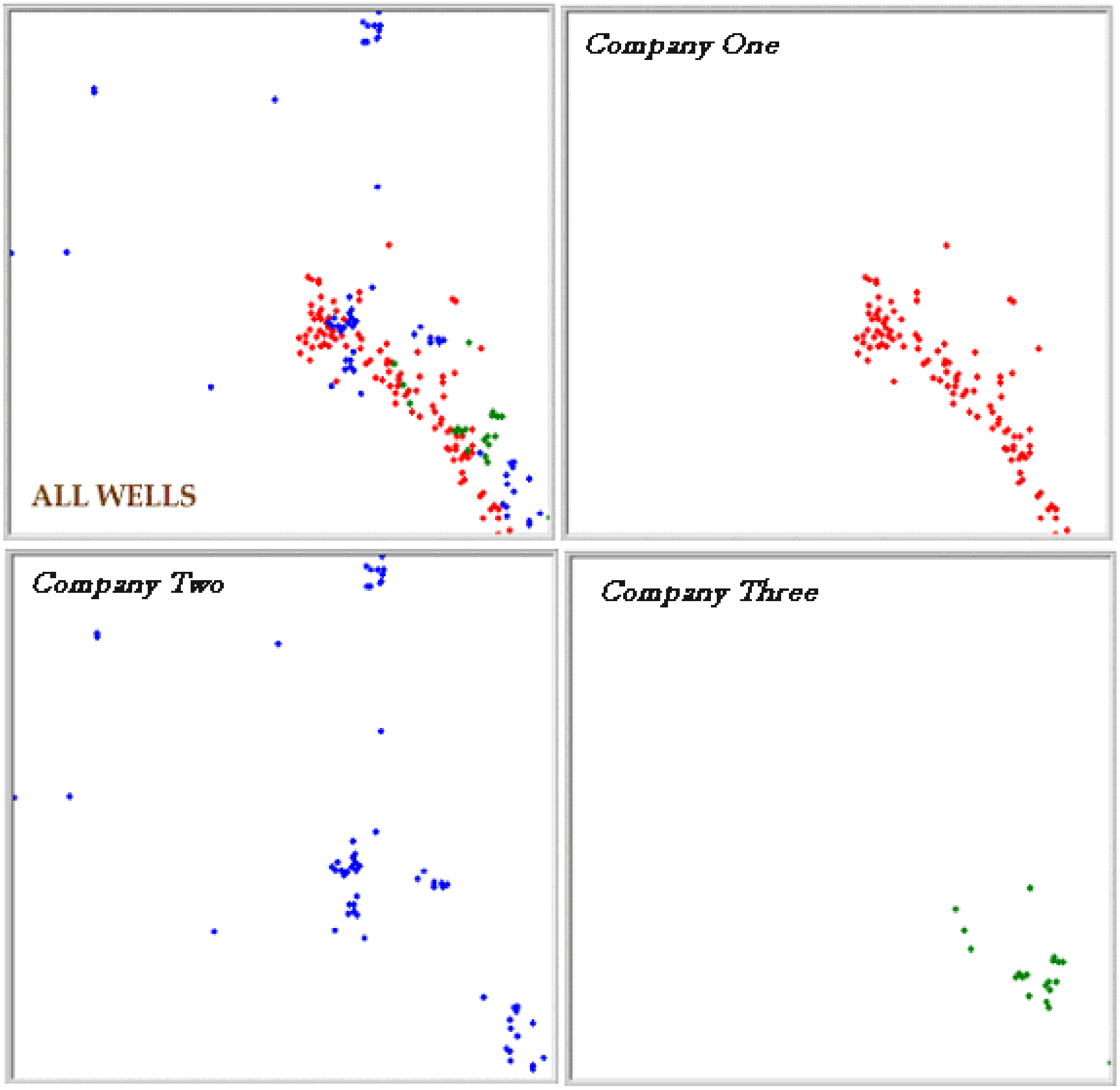

Figure 11. Wells in the database identified by the operating companies.

Table 4. Summary of the groups of wells analysis for Company One.

	Company One						
	Parameter	Single Parameter Analysis			Combinatorial Analysis		Recommendations
		Percent of Population	Dominant Trend	Change in Value	Distribution	Dominant Trend	
Main Fluid	Water	Majority	Decreasing	High	Skewed	Use Little	Use Not Recommended
Main Fluid	Oil	All	Incressing	High	Skewed	Use A Lot	Use Recommended
Main Fluid	Acid	All	Decreasing	High	Skewed	Use Little	Use Not Recommended
Main Fluid	Other	Majority	Increasing	Low	Skewed	Use Little	Use Not Recommended
	Shot/t	All	Decreasing	High	Skewed	Use Little	Use Small Numbers
	Conc. (lbs/gal/ft)	All	Increasing	High	Skewed	Use A Lot	Use Large Amounts
	Rate (BPM/t)	All	Decreasing	High	Skewed	Use Little	Use Low Rates

Table 5. Summary of the groups of wells analysis for Company Two.

	Company Two						
	Parameter	Single Parameter Analysis			Combinatorial Analysis		Recommendations
		Percent of Population	Dominant Trend	Change in Value	Distribution	Dominant Trend	
Main Fluid	Water	Majority	Decreasing	Moderate	Skewed	Use Little	Use Not Recommended
Main Fluid	Oil	All	Incressing	High	Skewed	Use A Lot	Use Recommended
Main Fluid	Acid	All	Decreasing	Low	Skewed	Use Little	Use Not Recommended
Main Fluid	Other	Half & Half	Mix	Low / Low	Skewed	Use Little	Use Not Recommended
	Shot/t	All	Decreasing	High	Skewed	Use Little	Use Small Numbers
	Conc. (lbs/gal/ft)	All	Incressing	High	Skewed	Use A Lot	Use Large Amounts
	Rate (BPM/t)	All	Decreasing	High	Skewed	Use Little	Use Low Rates

Table 6. Summary of the groups of wells analysis for Company Three.

	Company Three						
	Parameter	Single Parameter Analysis			Combinatorial Analysis		Recommendations
		Percent of Population	Dominant Trend	Change in Value	Distribution	Dominant Trend	
Main Fluid	Water	Majority	Decreasing	Low	Skewed	Use Little	Use Not Recommended
Main Fluid	Oil	All	Incressing	Moderate	Skewed	Use A Lot	Use Recommended
Main Fluid	Acid	All	Incressing	Moderate	Skewed	Use Little	Inconclusive
Main Fluid	Other	Majority	Increasing	Low	Skewed	Use Little	Use Not Recommended
	Shot/t	All	Decreasing	Low	Skewed	Use Little	Use Small Numbers
	Conc. (lbs/gal/ft)	All	Increasing	Moderate	Skewed	Use A Lot	Use Large Amounts
	Rate (BPM/t)	All	Decreasing	Low	Skewed	Use Little	Use Low Rates

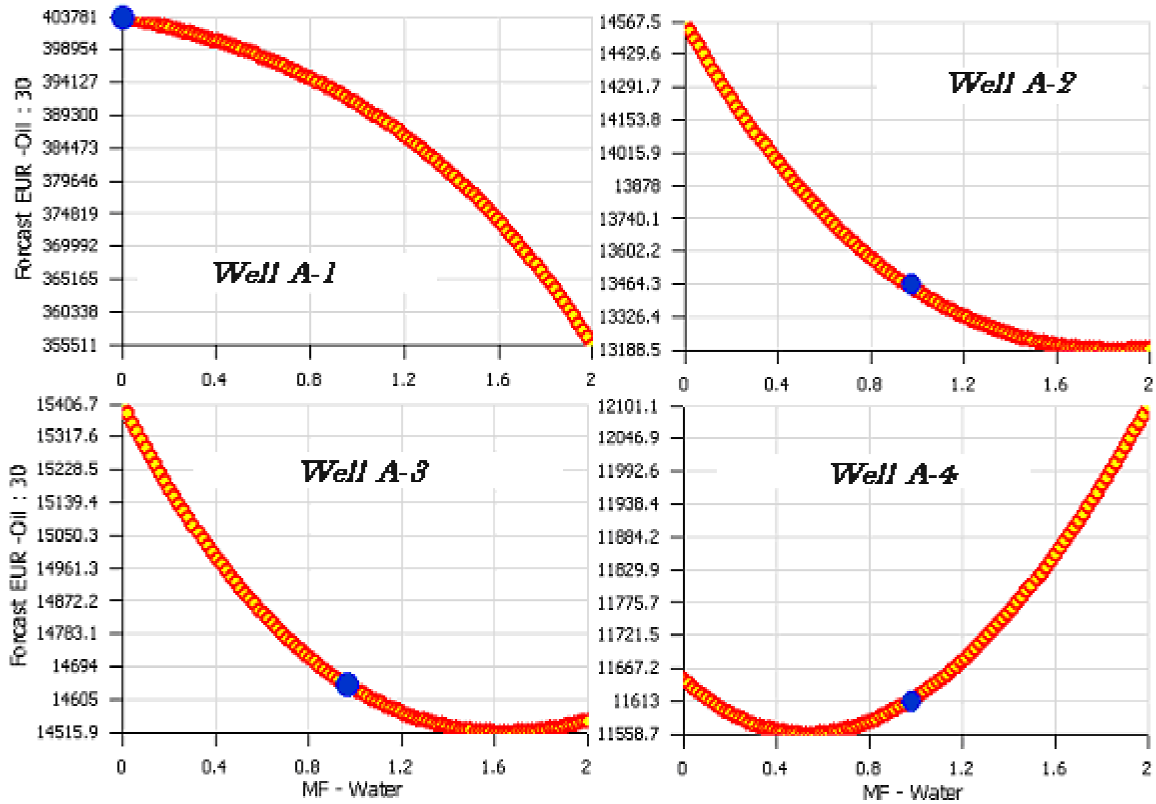

Figure 12. Sensitivity analysis for water as the main fracturing fluid for four wells in the database.

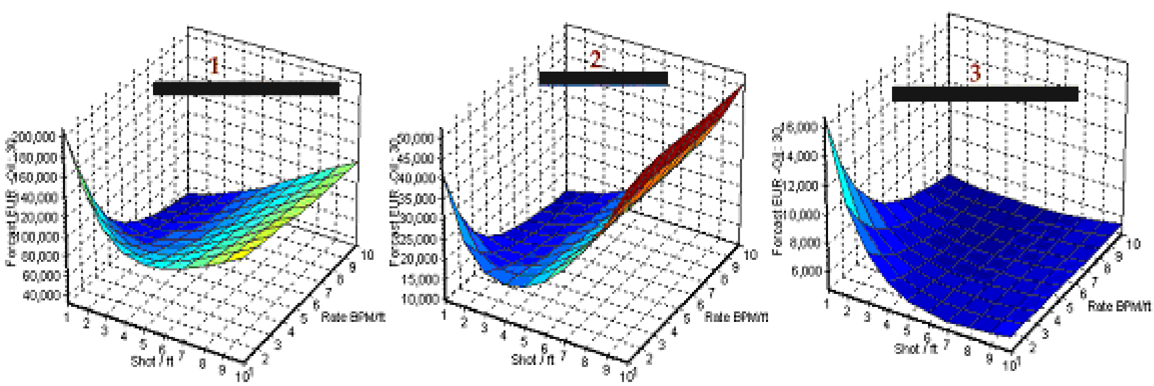

Figure 13. Sensitivity analysis for "Shot/ft" and "Rate" for three wells in the database.

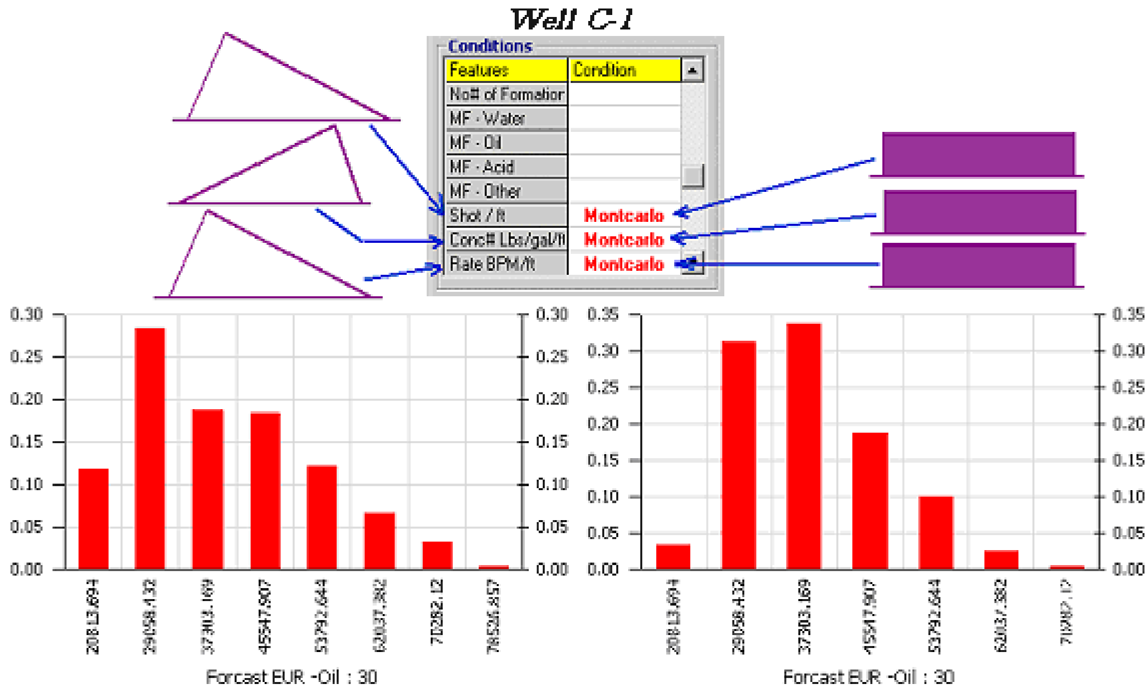

Figure 14. Combinatorial Analysis for *Well C-1* Operated by *Company One*.

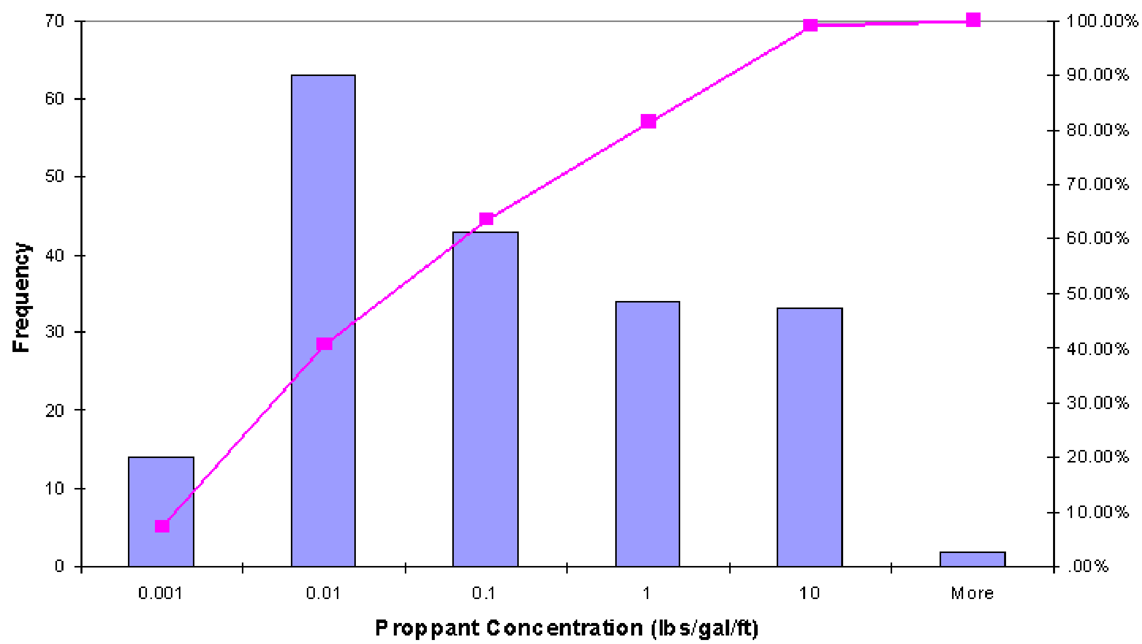

Figure 15. Logarithmic probability distribution function for Proppant Concentration.