A New Methodology for the Identification of Best Practices in the Oil & Gas Industry, Using Intelligent Systems

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ABSTRACT

In this paper the theory and methodology of "Intelligent Best Practices Analysis" is presented. The methodology is then applied 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. Completion and stimulation practices can be further itemized as completion type such as open hole versus cased hole with perforations and the type and amount of fluids and proppants that is used during the stimulation and the rate at which they are pumped into the formation.

Detail stimulation data from more than 230 wells in the Golden Trend operated by three independent operators were collected and analyzed using this methodology. The study

was performed both for gas and oil bearing formations. The Best Practices Analysis pointed out that in the carbonate formations of the Golden Trend that are primarily gas producing, acid fracs are much more effective than acid jobs (where no proppant is pumped into the formation). For the clastic formations in the Golden Trend, from which both oil and gas are produced, the Best Practices Analysis showed that most effective fluids were those with a diesel oil base. Furthermore the analysis concluded that the formations in the Golden Trend respond best to frac jobs with proppant concentration of 1 lb/mgal/ft or higher that are injected at rates up to 1 gal/min/ft.

INTRODUCTION

Identification of best practices in the oil and gas operations is gaining unprecedented momentum. This is partly due to the realities of the new economy that ties the success of oil and gas companies to their performance in the stock market. 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 making decisions.

The new methodology is named "Intelligent Best Practices Analysis". It incorporates a hybrid form of intelligent systems that includes artificial neural networks, genetic algorithms and fuzzy logic 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.

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) that is introduced in this article 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.

INTELLIGENT BEST PRACTICES ANALYSIS

Inspired by state-of-the-art in data mining technology, Intelligent Best Practices Analysis (IBPA) is a combination of two sets of analysis, namely the "Descriptive Analysis" and the "Predictive Analysis". During a complete Intelligent Best Practices Analysis both of these analyses are performed and the results are tabulated in order for the final recommendations to be made. Descriptive analysis can quickly identify and show any apparent patterns that exist in the database. Predictive analysis takes the problem to a new level by developing a comprehensive solution space from the existing database. The new solution space makes it possible to interpolate between existing practices and go into areas that have not yet actually been explored, but are logical extensions of the existing practices.

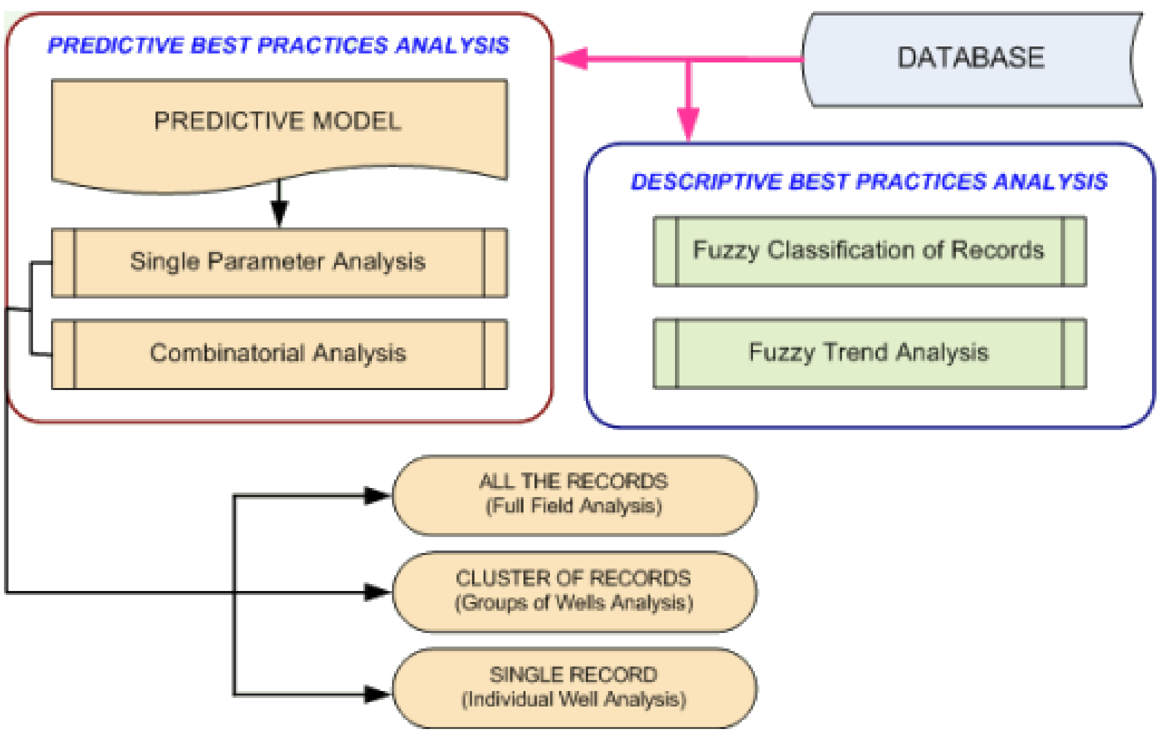

Figure 1. Schematic diagram of the Intelligent Best Practices Analysis.

First step in the analysis is identification of a process outcome. The process outcome is a dependent variable in the database that is used in order to measure the degree of success in a process. For example “five-year cumulative production” would be a reasonable outcome for identifying the best practices in a production related process, “rate of penetration” would be an appropriate variable for identifying the best practices in a drilling process, and “return on investment” would be an appropriate variable for identifying the best practices in a project evaluation process.

DESCRIPTIVE BEST PRACTICES ANALYSIS

Descriptive Best Practices Analysis tries to find and display patterns that exist in the database using a fuzzy averaging technique that has been developed for this methodology. Descriptive analysis does not manipulate the data in any shape or form. It simply presents data in a new light that makes detection of existing trends and patterns possible. This is performed in two steps. First the process output (the dependent variable) is classified using fuzzy set theory [1]. For example when “five-year cumulative production” is used as the process outcome a well can be classified as poor, average or good. If “rate of penetration” is used as the process outcome a record in the database can be classified as slow, moderate or fast. If “return on investment” is used as the process outcome the ROI of a project in the database can be classified as low, average or high. This is a conceptual categorization process and is a function of company’s economics and may be different from one company to another.

Upon completion of this step all the records in the database are classified using fuzzy membership functions that have been defined. For example the well shown in Figure 2, with a certain “five-year cumulative production,” say 7.5 MMSCF, would have a membership of 0.23 in fuzzy set of good wells and a membership of 0.77 in fuzzy set of average wells. Therefore each well, or record, will entirely belong to one of the fuzzy sets (membership function equal to 1) or belong to more than one fuzzy set, while belonging to each set to a degree. Therefore, the single parameter in the dataset (the process outcome) is now substituted with three parameters. The well in Figure 2 that used to be represented by the number 7.5 in the column “5 Year Cum, MMSCF” now is represented by three numbers 0.00, 0.77, and 0.23 in the columns “Poor Well”, “Average Well”, and “Good Well”, respectively.

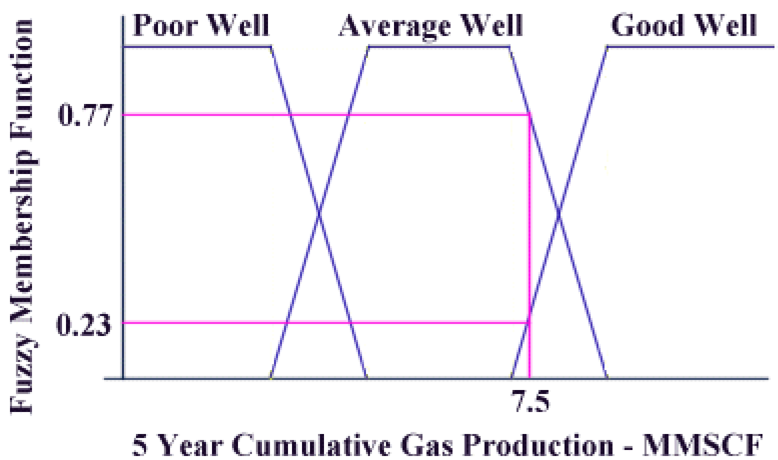

Figure 2. Fuzzy classification of a particular well (record) in the database.

At this point each of the parameters in the database (the independent variables) can be analyzed in order to see if a trend or pattern can be identified. This is achieved using a fuzzy averaging technique for each fuzzy set as shown in Equation 1, and then plotting them in the form of a bar chart.

$$\frac{\sum_{i=1}^{n} x_n \mu_n}{\sum_{i=1}^{n} \mu_n} \qquad \text{(Eq. 1)}$$

In the above equation ***n*** is the number of records that have membership function in a particular fuzzy set. ***x*** is the value of the parameter that is being analyzed in each of the records and μ is the membership function of the record in the particular fuzzy set. For example if for a hypothetical database we use the above averaging technique for a parameter with obvious results, say permeability, the result will be as shown in Figure 3.

In Figure 3 while the average value of permeability for all of the wells in the database is about 0.09 md, poor wells have an average permeability of 0.04 md, average wells have an average permeability of 0.13 md and good wells an average permeability of 0.33 md. This of course is an obvious trend and very well expected, since it is a well known physical phenomenon that better well (that produce higher amounts of hydrocarbon and have high 5 year cum) are those drilled in parts of the reservoir with high permeability. But for other parameters that are not necessarily so obvious, this kind of visualization of data can reveal important information as will be demonstrated in the later sections.

This analysis is performed for all the parameters (independent variables) in the database. Some parameters show clear patterns while others do not. Those parameters that do show clear patterns should be noted while others are to be further studied.

PREDICTIVE BEST PRACTICES ANALYSIS

The main idea behind the predictive analysis is to fill the gaps in the solution space in order to make a comprehensive analysis possible. Imagine a continuous hyper - dimensional surface that is full of hills and valleys. If this surface covers the space of all possible solutions, then records in the database are discrete points on this surface. Goal of predictive analysis is first, to develop a predictive model that can accurately approximate this solution space, and second, 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.

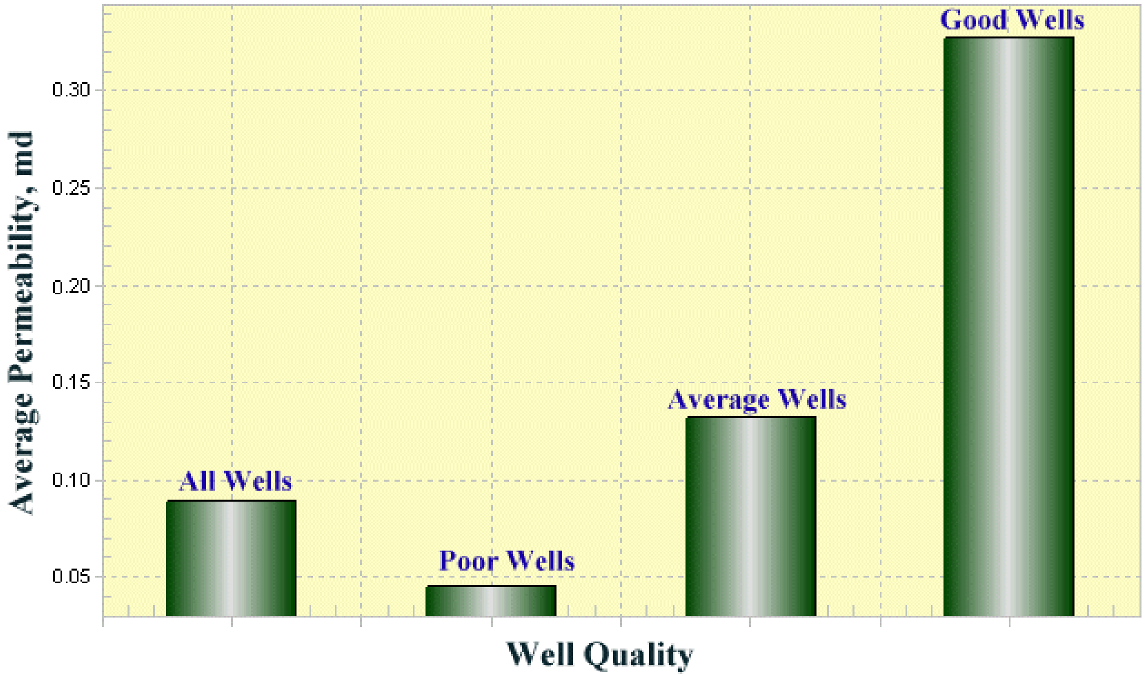

Figure 3. Fuzzy averaging of all the wells (records) in the database.

PREDICTIVE MODEL BUILDING

The first step in the predictive best practices analysis is to build a representative, predictive model. The models must be validated using part of the database (randomly selected) as blind data. It has been our experience that artificial neural networks [2], as universal function approximators, are the best tool for building complex, non-linear, predictive models. Selection of input parameters that will be used during the model building process is of immense importance. Model output is dictated by the nature of the process that is being analyzed. It would be the same process output that was mentioned in the Descriptive Analysis. The predictive model building is the most important step in the predictive best practices analysis process. This is due to the fact that all other steps that will be discussed rely on the accuracy of the predictive model.

SINGLE PARAMETER ANALYSIS

Single parameter analysis is the first step after a predictive model has been built. During this process we study the effect of a single parameter on the process behavior. We perform this analysis by following these steps:

1. Select a parameter that is to be analyzed.
2. Identify its minimum and maximum value in the database.
3. Calculate the range of the parameter by subtracting the minimum from the maximum.
4. Calculate an increment by dividing the range calculated in step 3 by say, 100.
5. Starting from the minimum value for the parameter, run the predictive model 100 times, each time incrementing the value of the parameter by the increment calculated in step 4. Perform this step while all other parameters are held at their original value.

Upon completion of these steps we will end up with 100 runs of the model for each record in the database. If each record in the database is representing a well, then this analysis is performed for each of the wells in the field. If the values of the process outcome (model output) are plotted against the parameter being analyzed, the resulting plot will show the sensitivity of the process to a particular parameter.

Figure 4 is an example of a single parameter analysis performed for a particular well (a record in the database). It shows that as the overall quality of the reservoir gets worse (identified by a higher RRQI value) the predicted 30 year EUR for the well reduces. Of course such analysis should be performed for the parameters that are being studied for the best practices analysis rather than parameters such as reservoir quality that are an uncontrollable parameter. The parameters of interest for such analysis would be those with non-obvious outcomes, so the results of the analysis could shed light on issues being considered. In the above example the consistent behavior of the model on a known parameter such as RRQI can increase our confidence on the model integrity and the fact that it respects the physics of the problem although it was not spelled out during the process of model building.

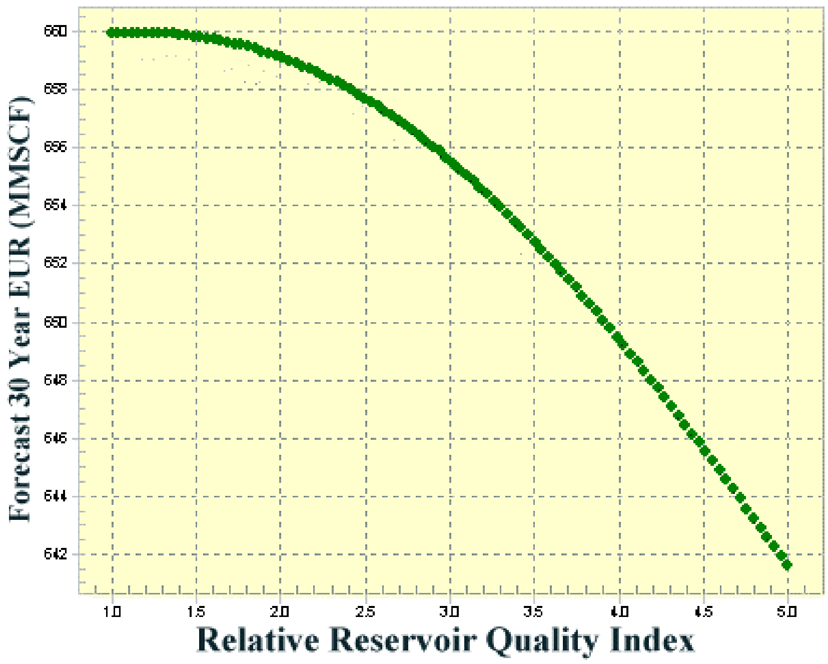

Figure 4. Sensitivity of Forecasted 30 Year EUR to Relative Reservoir Quality Index (RRQI) for a well in the database. RRQI is lower for the better parts of the reservoir.

The next step in this analysis is to summarize the results for each parameter being studied. This is accomplished by performing a trend analysis. For example, upon performing the above analysis on each record (each well), as shown in Figure 4, some information (statistics) about the shape of the curve is recorded. The curve would be either a straight line with decreasing or increasing trend, or it will be a curvature that can be approximated with a second or third order polynomial. In the latter case more information on the curvature needs to be recoded. For example is the curvature convex or concave. In either of the cases mentioned the minimum or the maximum value that the curve is also recorded. In other words all the necessary information and statistics should be recorded that would help to recreate the curve.

Once all this information has been recorded for each of the curves (each record or well in the database), then it should be summarized. An example of the final result of such analysis is shown in Table 1.

	No Case	Percentage	Shape Type	Trend	Range
1	9	4	Half Parab	Ascending	4918.47
2	215	96	Half Parab	Ascending	7762.42
	No. Case=	224			
	Descend % =	0			
	Descend Range =				
	Ascend % =	100			
	Ascend Range =	7648.66			

Table 1. Results of trend analysis for a particular parameter during "Single Parameter Analysis".

In the above table all the records in the database have generated similar trend (ascending) for a particular parameter. The dominating average range of the model output is also indicated. This dominating average range is compared with the universal range of the output in the database and is labeled as low, moderate or high. Results of this trend analysis for each of the parameters being studied is recorded for use in the final stage of the best practices analysis. The final stage of the study is the Recommendation Matrix that will be covered in a future section.

MULTIPLE PARAMETERS OR COMBINATORIAL ANALYSIS

As the number of parameters being studied in a multiple-parameter (combinatorial) analysis increases we no longer can picture the resulting solution surface. So what should we do in order to analyze the effect of multiple parameters on the process outcome? The answer is genetic optimization [3] of the solution using the predictive model. Why optimization? Because we are looking for the “Best Practices” which in essence is the ultimate outcome of process optimization. Best Practices by definition are those that provide best (optimum) results, in other words, practices that result in “Best” (optimum) outcomes.

Therefore in order to perform combinatorial analysis we follow these steps:

1. Identify the parameters that we are going to optimize in order to perform our analysis. It is advised that the parameters that we select have the following two characteristics:
    a. Be controllable. This simply means that the parameters should be those that can be controlled. For example when identifying best practices for hydraulic fracturing in a field, porosity of the reservoir is not a controllable parameter while the type of fluid being used for the job is a controllable parameter.
    b. Be independent. If there are dependency between parameters that are being optimized, then one must define those dependencies and code them into the optimization process, otherwise the result might not be meaningful.
2. Define any rules or constraints that should be imposed on the solutions while performing the optimization. As an example, a rule may state that only one of several available fluids can be used as the injection fluid and not a combination of several fluids.

3. Identify the number of population in each generation (number of solutions that will be used during the evolutionary process) and the number of generations that the solutions will be evolved to reach optimization.
4. Probability of genetic operations such as crossover, mutation, and inversion. These probability values will control the way each new generation is produced as a function of success and failure of the previous generation.
5. Identify convergence criterion. For example one convergence criterion can be that the best individual in the generation is not improving over several generations.
6. Perform genetic optimization.
7. Keep track of all the solutions in each generation. Select and save a certain number of top solutions from each generation.
8. Upon convergence, perform the following for each of the parameters that were involved in the optimization process:
    a. Use the top, say 10, solutions of each generation and record the values of the parameter being analyzed from each of these top solutions.
    b. Do the above step for all the generations.
    c. Do steps a, and b, for all the records (wells) in the database.
    d. Plot the frequency distribution for the values you have recorded for the parameter being analyzed.
    e. Analyze the trends that appears from the frequency distribution.

The process mentioned above uses the predictive neural model in order to identify the most appropriate value for each parameter that would result in optimum outcome and presents it in a graphical form in order to detect any apparent trends as the best practices.

Figure 5 is an example of such an analysis. In this figure it can be detected that, from a combinatorial analysis point of view, that the best practice for this particular field points toward low injection rates. The trend seems to be quite apparent.

Just like the Single Parameter Analysis, the results of Combinatorial Analysis are summarized in order to be used in the final stage that is the Recommendation Matrix. The summary will provide information on the nature of the distribution. For example the result of the Figure 5 is summarized by tow simple identifiers. The distribution is "skewed" and it is skewed toward the lower values that mean lower injection rates are preferred.

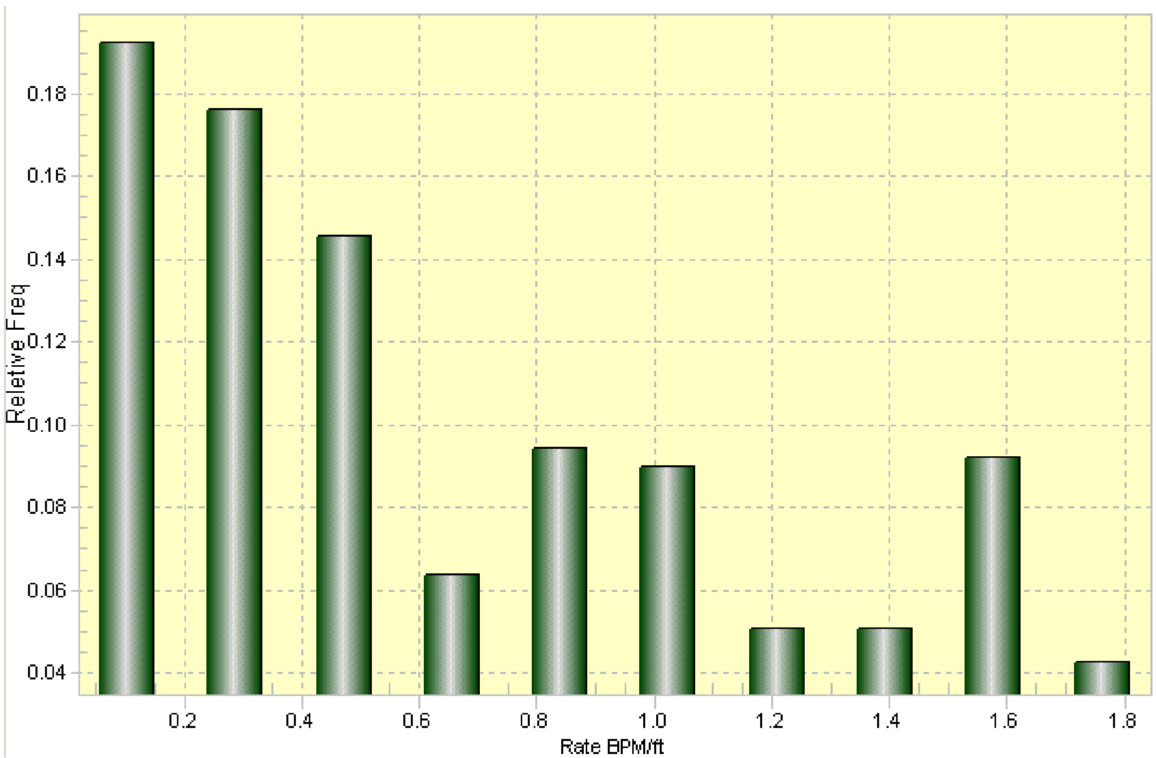

Figure 5. Frequency distribution of injection rates in BPM/ft for the top solutions during the optimization process.

Recommendation Matrix

Upon completion of the Single Parameter Analysis and the Combinatorial Analysis their results are summarized as mentioned in the previous two sections. The next and final step of the process is an attempt to combine the results from the above two analyses and make final decisions and recommendations on the Best Practices. If the results of the Single Parameter Analysis and the Combinatorial Analysis point to the same direction, for example a lower injection rate is preferable, then the recommendation on using low injection rates is made. If the results of the two analyses are conflicting, then the conclusion would be that the results are inconclusive.

SINGLE PARAMETER ANALYSIS	
PERCENT OF POPULATION	**MEANING**
ALL	More than 95% of records (wells) behave in a certain fasion
MAJORITY	More than 60% of records (wells) behave in a certain fasion
HALF & HALF	Between 45% to 55% of records (wells) behave in a certain fasion
DOMINANT TREND	
INCREASING	Use of this parameter causes an increase in process (model) outcome
DECREASING	Use of this parameter causes an decrease in process (model) outcome
MIX	Process (model) outcome is mixed (increase & decrease) for different records (wells)
CHANGE IN VALUE	
HIGH	The amount of increase in the process (model) outcome is high
LOW	The amount of increase in the process (model) outcome is low
MODERATE	The amount of increase in the process (model) outcome is moderate
COMBINATORIAL ANALYSIS	
DISTRIBUTION	
SKEWED	Probability Distribution Function for this parameter is skewed
NORMAL	Probability Distribution Function for this parameter is normal
UNIFORM	Probability Distribution Function for this parameter is uniform
DOMINANT TREND	
HIGH VALUES	Probability Distribution Function is skewed toward the high end of this parameter
AVERAGE VALUES	Probability Distribution Function has a normal behavior
LOW VALUES	Probability Distribution Function is skewed toward the low end of this parameter
NO TREND	The uniform Probability Distribution Function provides no trends for this parameter
RECOMMENDATIONS	
USE NOT RECOMMENDED	Try to avoid using this parameter
USE RECOMMENDED	Try using this parameter
INCONCLUSIVE	No recommendations can be made at this point for this parameter
USE LARGE VALUES	Higher values of this parameter is recommended
USE AVERAGE VALUES	Average values of this parameter is recommended
USE LOW VALUES	Lower values of this parameter is recommended

Table 2. Conventions for the Recommendation Matrix.

Table 2 shows the conventions used for each of the analyses and the recommendations. As you can see from this table the Single Parameter Analysis is characterized by three identifiers, namely the percentage of the population, the dominant trend, and the change in the value while the Combinatorial Analysis is characterized by two identifiers, namely the distribution and the dominant trend. Once the results of these two analyses are combined the recommendation can be one of the six that is identified in the table.

Therefore a typical Recommendation Matrix would look like the one shown in Table 3. In this Recommendation Matrix the Best Practice for fluid type in a particular field is shown. It is obvious form the results that for this particular field use of diesel oil as the main fracturing fluid is recommended based on the data from the well files.

Parameter	Single Parameter Analysis			Combinatorial Analysis		Recommendations
	Percent Population	Dominant Trend	Change in Value	Distribution	Dominant Trend	
Water	Majority	Decreasing	Low	Skewed	Low Values	Use Not Recommended
Oil	All	Increasing	Moderate	Skewed	High Values	Use Recommended
Acid	All	Increasing	Moderate	Skewed	Low Values	INCONCLUSIVE

Table 3. A typical Recommendation Matrix for fluid types in a hydraulic fracturing study.

The process that was covered in the last three sections, namely Single Parameter Analysis, Combinatorial Analysis and finally the Recommendation Matrix is performed more than one time. First it is performed for all the records in the database (all the wells in a field). Then the same process is performed for groups of records in the database (groups of wells). During this stage of the analysis the records in the database can be classified based on predetermined classes or a clustering routine can be used to classify the records. In the case where each record in the database represents a well in a field, then the classification of the records (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.

The last part of the analysis would be on individual records (wells). The relationship between these analyses is shown in Figure 6. This figure shows an inverted pyramid that increases in precision and decreases in averaging as one moves from the top of the pyramid (analyzing all the records in the database-full field analysis) to cluster of records (groups of wells) and finally to the single record (individual wells).

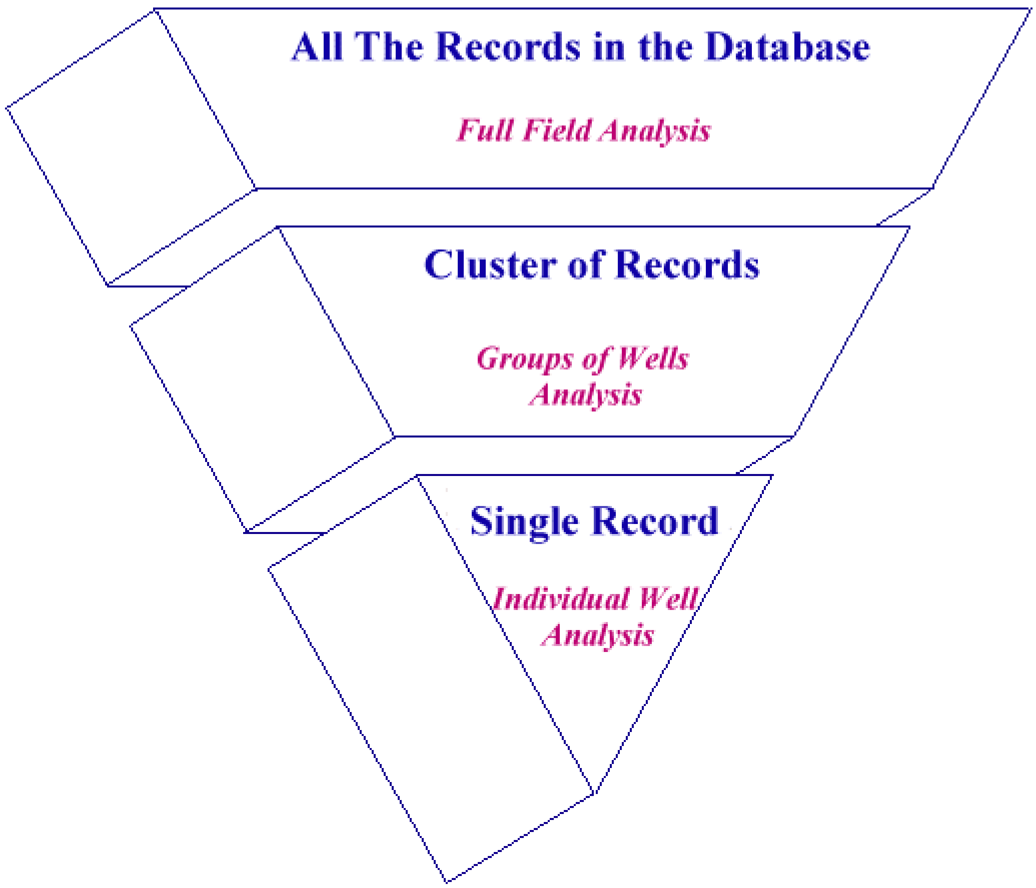

Figure 6. The relationship between different levels of the Intelligent Best Practices Analysis.

The best practices identified through the analysis of all the records (full field analysis when each record in the database represents a well) in the database are general and are applied to the majority of the records (wells). This majority of records (wells) are large enough in population to warrant the title of the "best practices" for entire database (field). On the other hand since many values had to be averaged in order to reach to the conclusions that are presented, the general nature of the practices must be stressed. This simply means that there are records in the database (wells in the field) that would not necessarily follow the general trends identified.

When the analysis is performed on a cluster of records (groups of wells) that are classified based on some reasonable criterion, the generality of the best practices decreases and the practices identified to be the best, become more specific to a certain group of records (wells) sharing certain similarities.

During the individual well analysis too much faith is banked on the predictive model that is statistical by nature. The predictive model, although developed using the state-of-the-art in the integrated intelligent systems, is ultimately a product of the data that is usually measured, collected, reported, and recorded by human subjects and therefore is not free of errors, even if we assume that it is statistically representative of all the variations that are present in reality.

An important issue that must be discussed at this point is the precision versus averaging issue and their contribution to the future decision making process. The precision of the analysis increases as it moves from full field scale to groups of wells and finally to individual wells. During the full field analysis maximum amount of averaging takes place as all the records (wells) are put into the same bag and we try to make general statements that has the highest degree of applicability. Once we move into the cluster of records (groups of wells) our statements are more precise and the law of averages applies to a lesser degree, but certain amount of averaging is still taking place. Finally the most precise of all the analysis would be the single record (individual well) analysis. During the single record (individual well) analysis we can change all the controllable parameters in any directions that we wish and examine the output before making our final decision. On the other hand, since the model used for the analysis is a non-deterministic and purely data-driven model, some may question the degree of its reliability for single record (individual well) analysis and prefer certain degree of averaging to take place in order to increase their confidence on the patterns being identified.

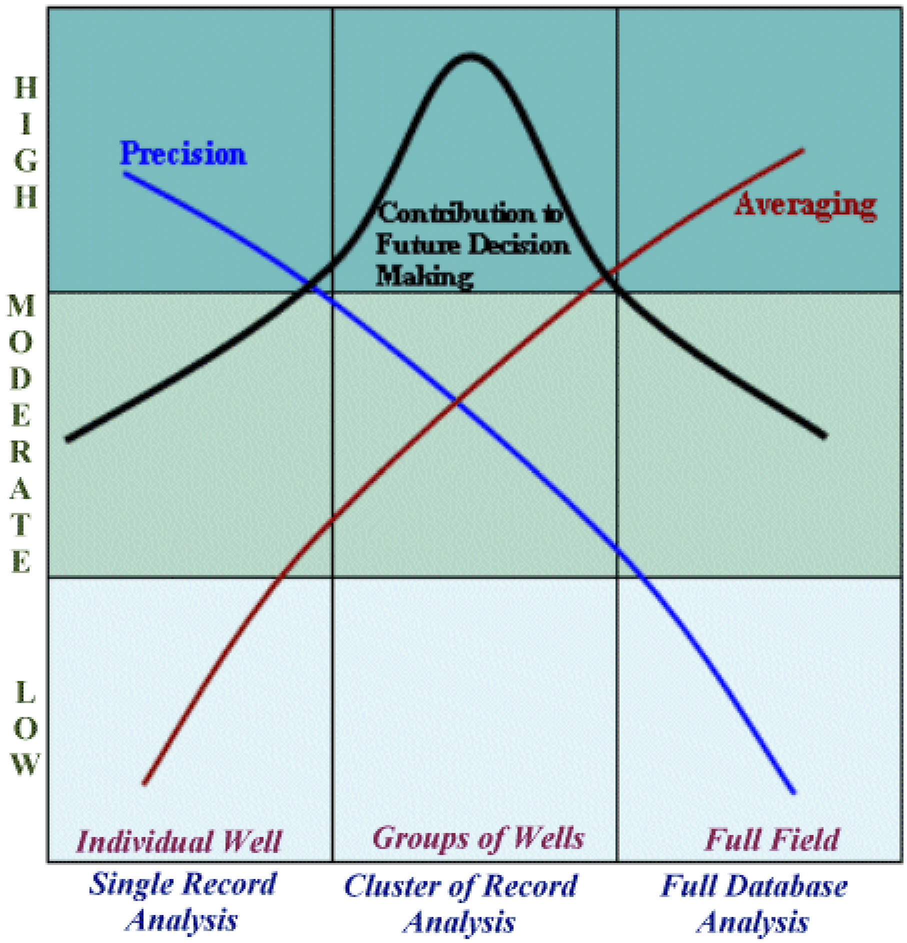

Figure 7. Schematic diagram showing the precision, averaging, and their contribution to the decision making process offered by Predictive Best Practices Analysis.

Figure 7 shows the degree of precision (such as high, moderate and low) offered by these analyses. It also shows the degree by which averaging is dominating each of these analyses. The precision of the analyses decrease as it moves from single record (individual well) analysis to entire database (full field) analysis. This trend is exactly opposite for the amount of averaging that is implemented in the processes. This figure shows that when it comes to decision making on the future wells (since it is the main reason for performing such analysis) both precision and averaging play an important role. Therefore, the “cluster of records (groups of wells analysis)” is probably the more important and reliable analysis as compared to the other two, when making future decisions.

APPLICATION TO THE GOLDEN TREND FIELDS

In the previous sections the principles of Intelligent Best Practices Analysis was covered in detail. In the next several sections 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 shows the type of information available in the database. Table 4 shows the list of parameters that will be analyzed during this study. This list of parameters is a function of the data availability in the data base. It shows the 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.

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

Table 4. Parameters in the database that were used during the "Best Practices" 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 8, 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. Furthermore, based on these classification, a well that produces less than 2.7 bbls/day (on average throughout 30 years of production) is a poor well and a well that produces more than 11 bbls/day (on average throughout 30 years of production) is a good well.

In order to clarify the classifications mentioned above please note the following example. In Figure 9 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.

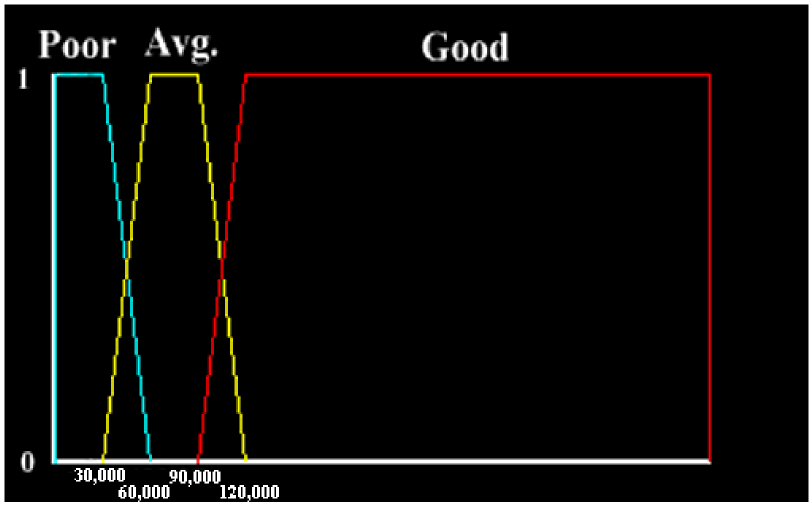

Figure 8. The "30 Year EUR" Productivity Fuzzy sets for wells in the Golden Trend Field.

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 10 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.

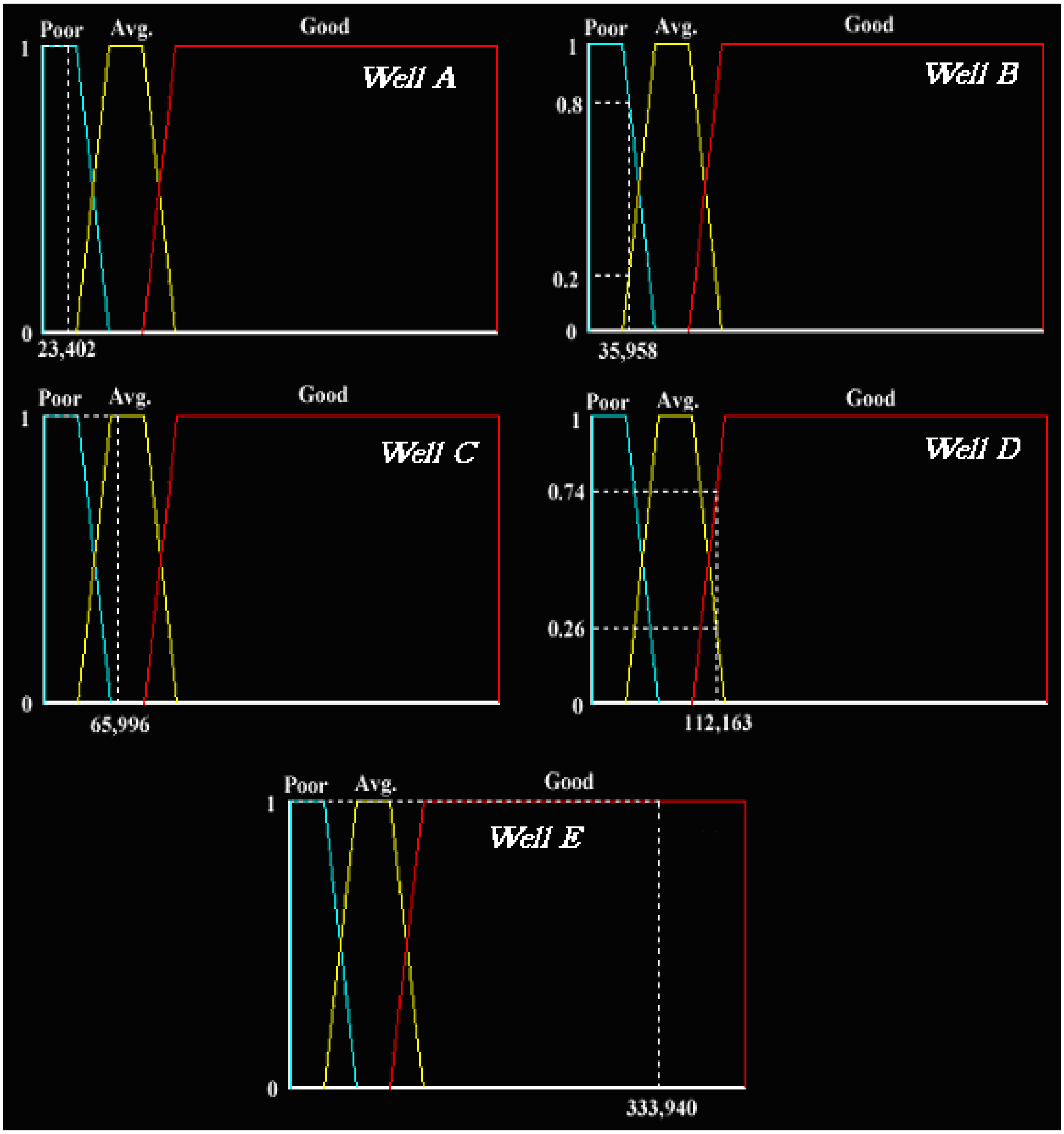

Figure 9. Classification of wells in the database using Fuzzy sets.

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. We calculate these fuzzy average values using Equation 1 presented in a previous section.

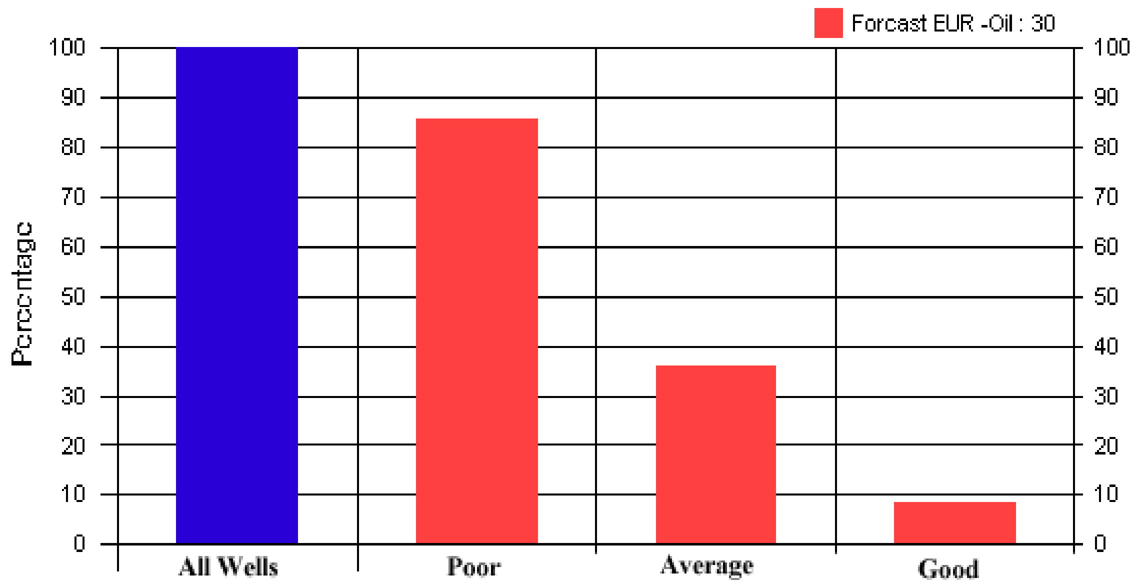

Figure 10. Distribution of the wells based on 30 Year EUR.

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".

Figures 11 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.

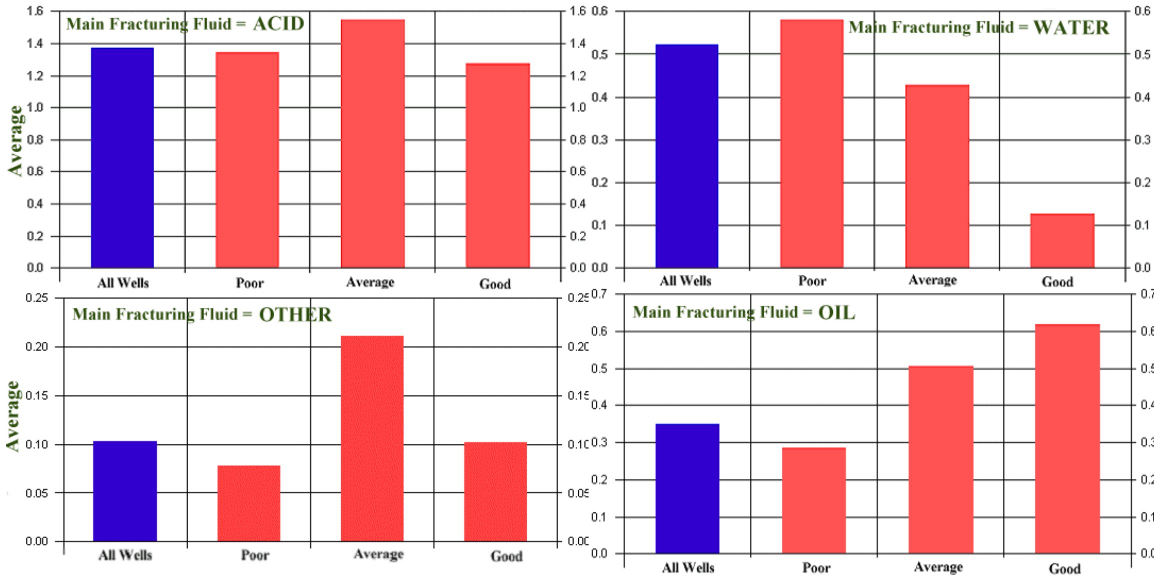

Figure 11. Distribution of the average value of Main Fracturing Fluids in wells of different quality.

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 12 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 12 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.

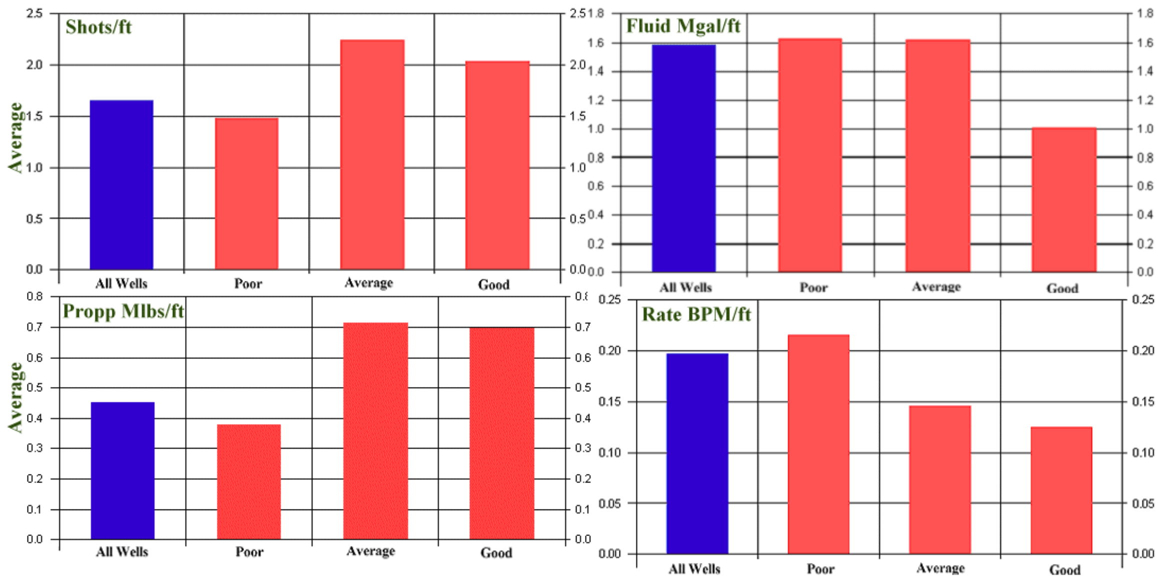

Figure 12. Distribution of the average value of completion parameters in wells of different quality.

Amount of proppant used during the hydraulic fracturing treatment according to Figure 12, 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 complete, let's look at the Predictive analysis. The next several sections will cover this analysis for oil production from the Golden Trend fields.

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 4 shows the list of the input parameters used in the neural network model.

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)

Table 4. Parameters used during the neural network modeling process.

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 and Di. 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 [4] 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.

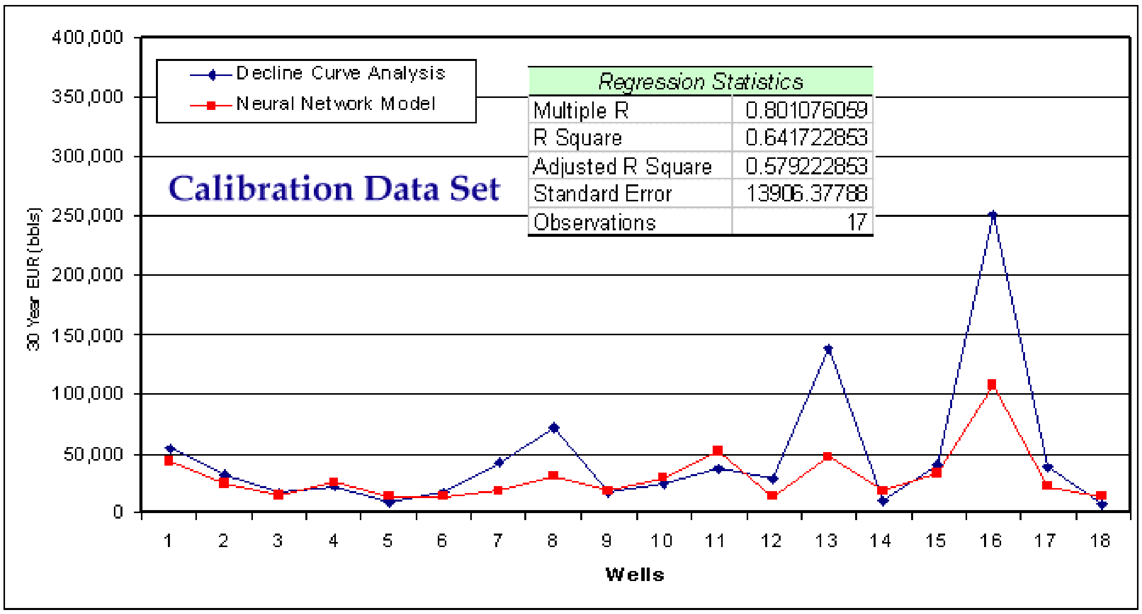

Figure 13. Actual and predicted 30 year EUR of the calibration data set.

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 13 and 14 show the results of the model performance on calibration and verification data sets.

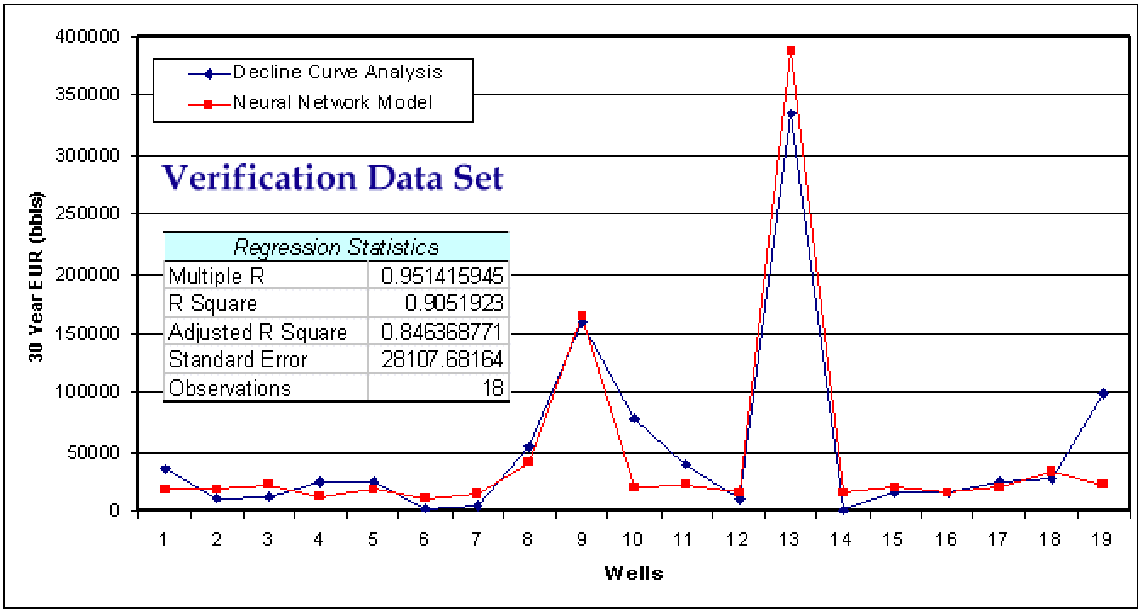

Figure 14. Actual and predicted 30 year EUR of the verification data set.

The R^2 for the training 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 5. This matrix combines the results of single parameter and combinatorial analysis and provides best practices recommendations.

	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

Table 5. Full field analysis Recommendation Matrix for best hydraulic fracturing practices in the Golden Trend.

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.

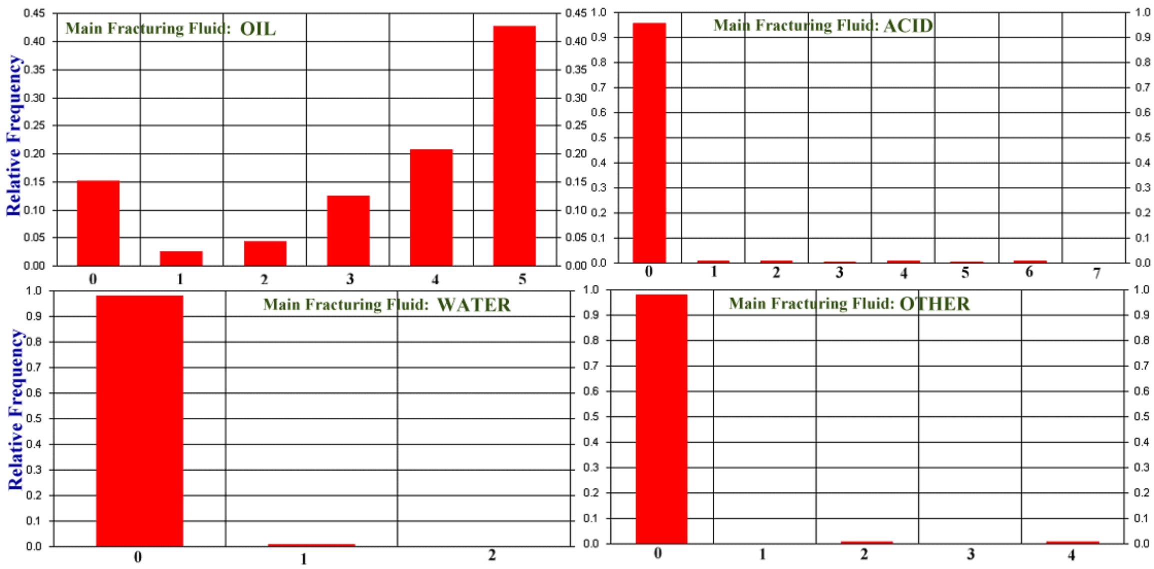

Figure 15. Full Field Combinatorial Analysis, results for main fracturing fluids.

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 15 and 16 shows the results of combinatorial analysis for full field analysis.

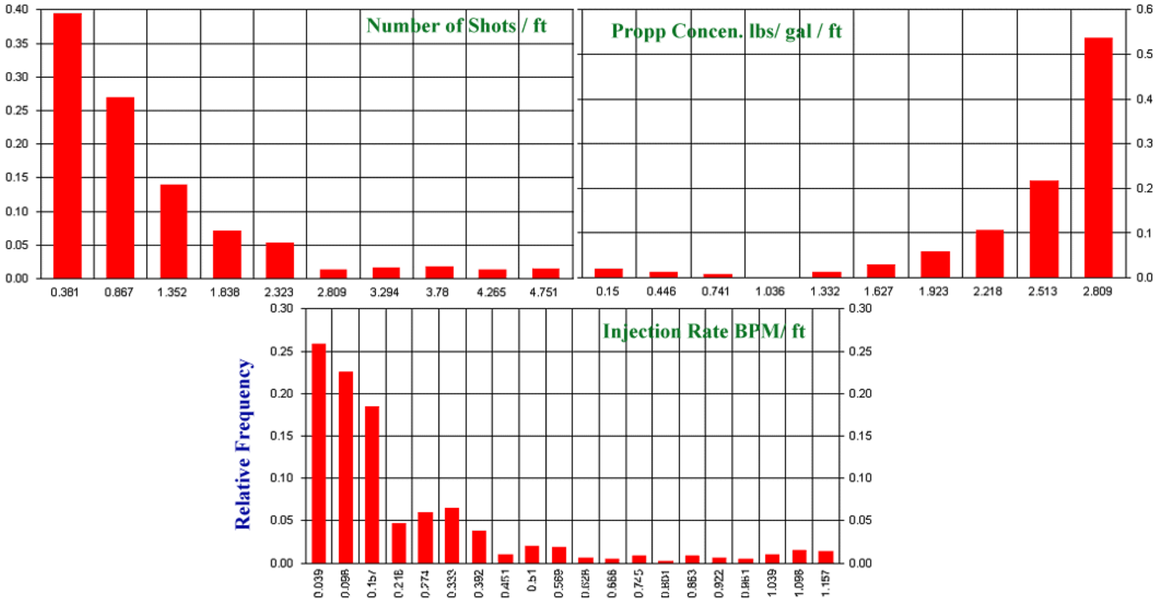

Figure 16. Full Field Combinatorial Analysis, results for other hydraulic fracturing parameters.

Groups Of Wells Analysis

The predictive best practices analysis based on groups of wells are covered in this section. As it was mentioned before many different grouping of the wells can be considered. For this study wells once were 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.

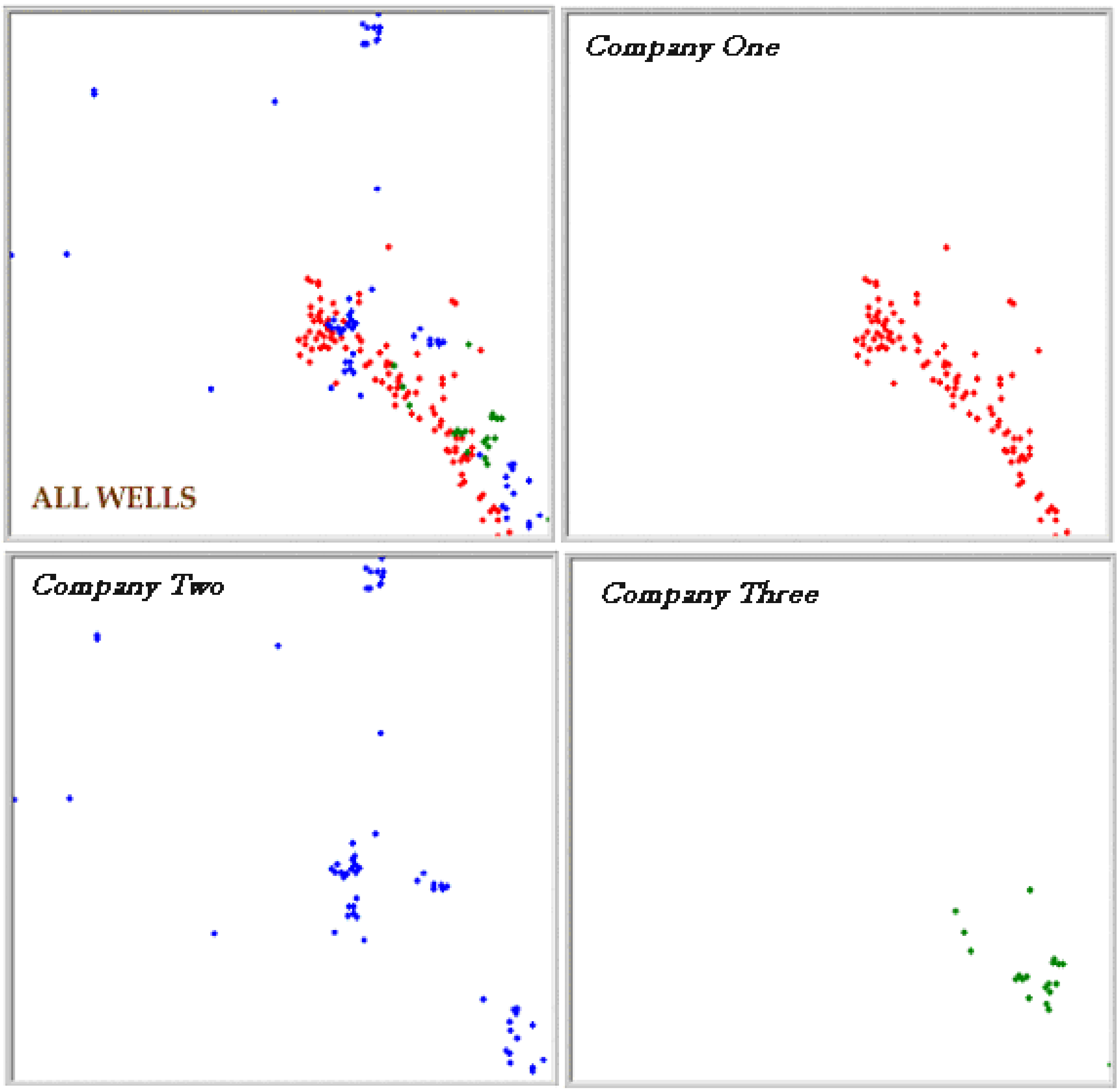

Figure 17. Wells in the database identified by the operating companies.

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 17 shows the location of the wells being operated by different companies in the Golden Trend. The Recommendation Matrix for each of the operators is shown in the Tables 6, 7, and 8. 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*.

	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/ft	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/ft)	All	Decreasing	High	Skewed	Use Little	Use Low Rates

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

Table 7 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*.

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/ft	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/ft)	All	Decreasing	High	Skewed	Use Little	Use Low Rates

Table 7. Summary of the groups of wells analysis for Company Two.

In Table 8, 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.

	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/ft	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/ft)	All	Decreasing	Low	Skewed	Use Little	Use Low Rates

Table 8. Summary of the groups of wells analysis Company Three.

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 WELLS 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 18 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.

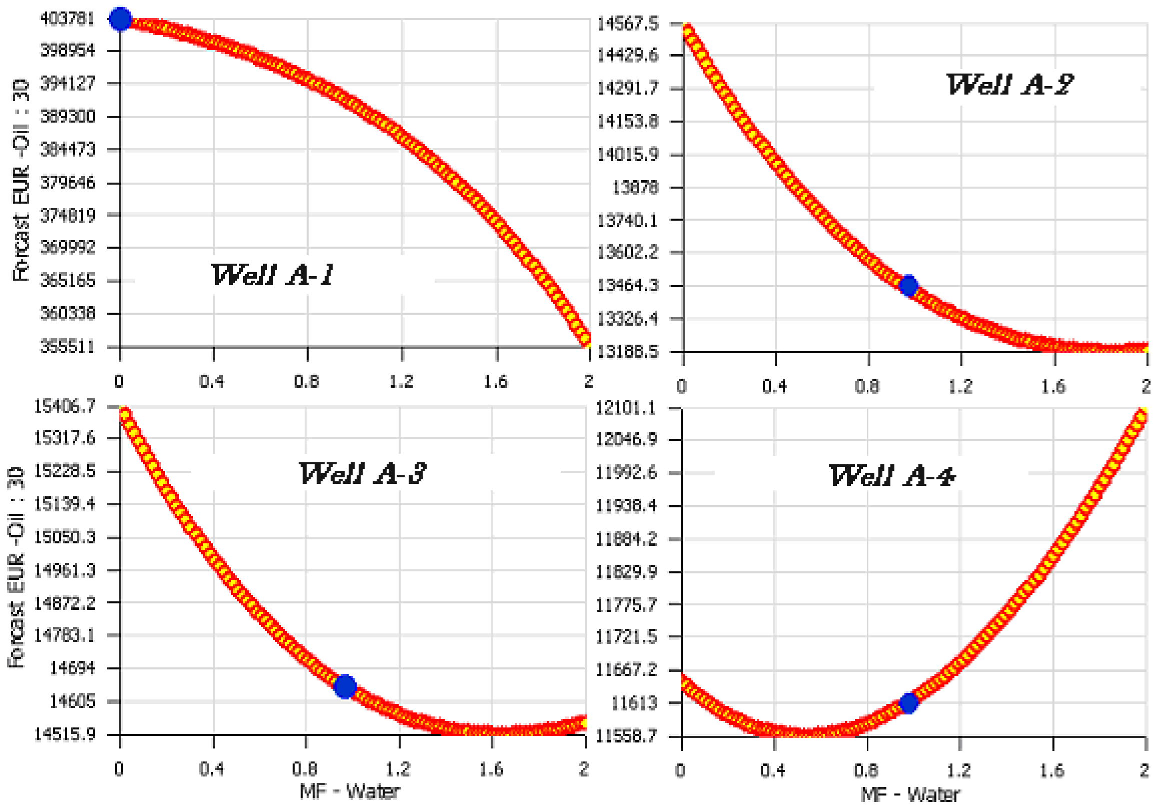

Figure 18. Sensitivity analysis for water as the main fracturing fluid for four wells in the database.

For example in Figure 18 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 18 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 18 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 19 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".

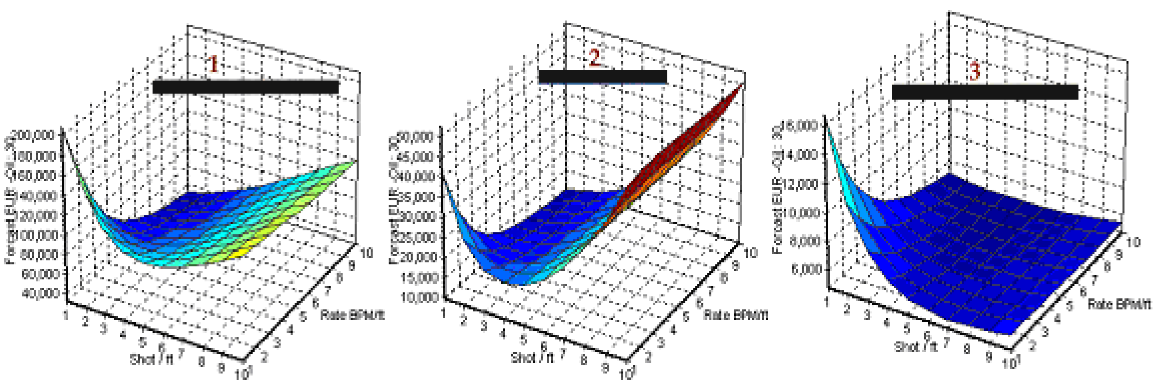

Figure 19. Sensitivity analysis for "Shot/ft" and "Rate" for three wells in the database.

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:

1. Identify the number of parameters that are going to be studied simultaneously.
2. Identify a probability distribution function for each of the parameters.
3. Identify the number of simulation runs that should take place.
4. 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 20 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.

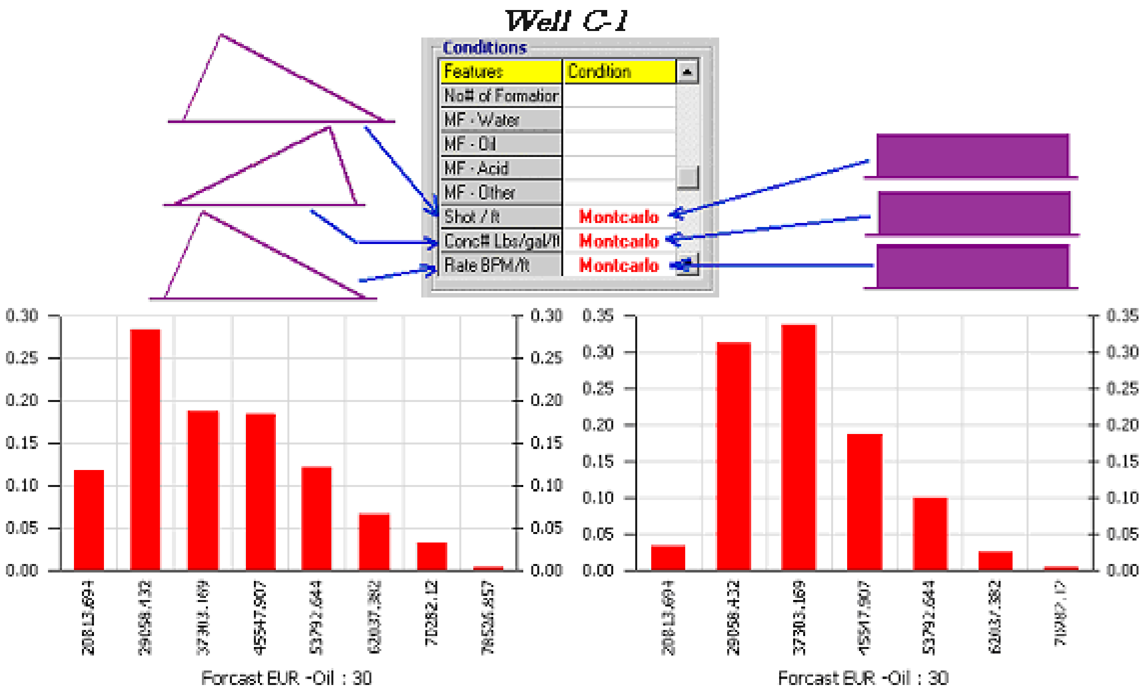

Figure 20. Combinatorial Analysis for *Well C-1* Operated by *Company One*.

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.

FINAL CONCLUSIONS & CLOSING REMARKS

A new and novel methodology for identification of Best Practices in oil and gas related operations have been developed. The new method, dubbed Intelligent Best Practices Analysis (IBPA), is developed based on hybrid intelligent systems that combine artificial neural networks, genetic algorithms and fuzzy logic to achieve it objectives. IBPA is a fully data driven, and therefore unbiased, analysis technique that can discover the best practices in any oil and gas operation and present them in the form of easy to understand rules. This Intelligent Best Practices Analysis (IBPA) is a two-step process that includes descriptive and predictive analysis. During the descriptive analysis wells (records) in the database are divided into several fuzzy sets and fuzzy-averages of several parameters are calculated to identify the trends that are present in the database. These trends and patterns usually provide a strong foundation for the best practices that are ultimately identified.

Predictive best practices analysis is a drill-down process that starts with all the records in the database (the full field analysis) and ends with individual records (individual well analysis). During the full field analysis the best practices based on all the records (wells) in the database are identified. Then records (wells) are divided into groups, based on different criteria, and each group is analyzed in order to 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 records (wells) and using the results of past two steps as a guide to enhance the productivity 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 will come online) that would not necessarily follow the identified trends as expected. This makes refining of the best practices by individual well 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 [5].

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 the Golden Trend. Figure 21 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 [6].

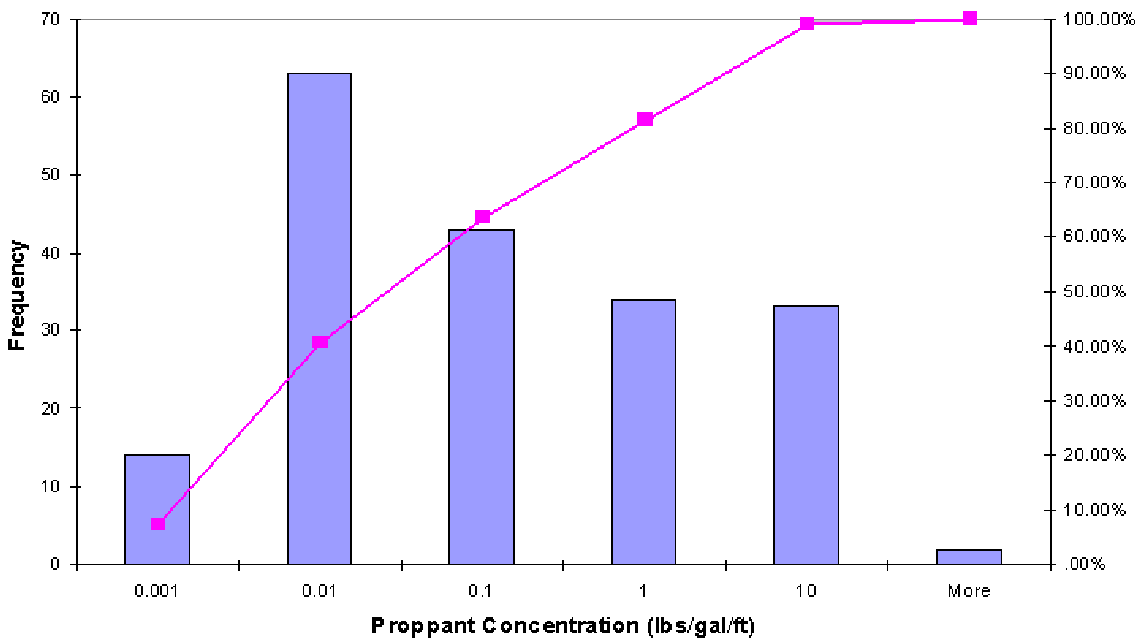

Figure 21. Logarithmic probability distribution function for Proppant Concentration.

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REFERENCES

1. Virtual Intelligence Applications in Petroleum Engineering: Part 3 – Fuzzy Logic. Mohaghegh, S.D., ***Journal of Petroleum Technology***, **Distinguished Author Series**, November 2000, pp 82-87.
2. Virtual Intelligence Applications in Petroleum Engineering: Part 1 – Artificial Neural Networks. Mohaghegh, S.D., ***Journal of Petroleum Technology***, **Distinguished Author Series**, September 2000, pp 64-73.
3. Virtual Intelligence Applications in Petroleum Engineering: Part 2 – Evolutionary Computing. Mohaghegh, S.D., ***Journal of Petroleum Technology***, **Distinguished Author Series**, October 2000, pp 40-46.
4. Identifying Successful Practices in Hydraulic Fracturing Using Intelligence Data Mining Tools; Application to the Codell Formation in the DJ Basin. Mohaghegh, S., Popa, A., Gaskari, R., Ameri, S., and Wolhart, S., *SPE 77597, Proceedings, 2002 SPE Annual Conference and Exhibition.* September 29-October 2, San Antonio, Texas.
5. Conversations with Dr. Mike Conway of Core Laboratories, Inc. June 2003.
6. Johnson, R. L., Dunn, K. P. Hopkins, C. W. and Conway, M. W. "The Pressure Dependence Ratio: A Bottomhole Treating Pressure Diagnostic Tool for Hydraulic Fracturing in Tight, Naturally Fractured Reservoirs," SPE 77916. Presented at SPE Asia Pacific Oil & Gas Conference & Exhibition held in Melbourne, Australia, 8-10 October 2002.