**URTeC: 2693211**

# Improving Well Designs and Completion Strategies Utilizing Multivariate Analysis

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 **DOI 10.15530/urtec-2017-2693211**

This paper was prepared for presentation at the Unconventional Resources Technology Conference held in Austin, Texas, USA, 24-26 July 2017.



## Abstract

Multivariate Analytics (MVA) is a powerful tool to assess the individual impact of geologic, completion, and well design variables on horizontal well production. This paper focuses on the MVA predictive models of 6-month oil production and the workflows applied to normalize geological variation when evaluating various drilling and completion designs.

Horizontal well and completion designs implemented throughout the Midland Basin continue to evolve, as technical knowledge and insights improve. With the availability of a large well-ordered dataset it is possible to analyze the impact of discrete variables on production. Due to basin-wide variation in geology, burial history, thermal diagenesis, and horizontal targeting, it is critical to normalize these effects in order to understand the impact of discrete drilling and completion variables on production. Laredo Petroleum has developed a rigorous, repeatable process to do so utilizing MVA.

Well design variations such as horizontal inclination, dog-leg severity, wellbore azimuth, and build-rate in the curve can also impact the ultimate production of a well. MVA results indicate modest production uplift is possible through modification of well designs, which can also reduce the amount of directional drilling adjustments required.
Completion design is another key contributor to well performance: Important variables including fluid type, water volume, sand volume, cluster spacing and pump rate are incorporated into the MVA workflow. Proprietary and publically available completion and microseismic data sets are used to assess the variation in stimulated fracture networks, which can be correlated to completion design and 6-month oil production. One of the results from this analysis is the positive correlation of increased proppant volumes with higher 6-month oil production.

Utilizing MVA workflows, Laredo has developed a repeatable process to normalize local and regional variability of geology drivers, such as vertical and lateral facies variability and diagenesis in order to leverage large data sets and assist in operational decisions. This MVA workflow has yielded critical insights into understanding drivers of well performance and designing future completion and well package tests.

## Introduction

During the evaluation of an unconventional asset, a range of horizontal testing is performed in order to determine the optimal well design and development strategy. Differentiating between highest and lowest performance outliers above the 90$^{th}$ percentile and below the 10$^{th}$ percentile is generally more straightforward, but the reasoning for the variation within the 10$^{th}$ to 90$^{th}$ percentile range may be more difficult to determine using traditional data bivariate analysis (Courtier, 2016). In the Wolfcamp play of the Midland Basin, a range of completion types and well designs provide a robust data set for evaluation in this study. In order to understand the primary drivers of well performance, the variation in target zone, rock quality, spacing, well design, and completion type must be quantified. Laredo's methodology for determining the net impact of each of these variables is through the utilization of multivariate analytics, referred to in this paper as “models”, consisting of a robust workflow to analyze large data sets. This workflow has previously been described by (Wicker et. al 2016 and Wicker et. al 2017).

In order to quantify the impact of each change in design between well locations, the model is broken down into groups which isolate into models of well design, spacing, completions, and reservoir quality. Models are run independently to determine the dominant drivers for each group in order to combine these variables in a cumulative oil model. To ensure that the relationships are consistent between models the highest-ranked significance variables are carried to subsequent models.

Due to the proprietary nature of the analysis, the significance of each variable within the modeling must be held confidential. However, general trends and workflow are demonstrated through the course of this paper. The variables are listed based on the model from which they originated Well Design Model (WDM), Spacing Impact Model (SIM), and Completion Impact Model (CIM).

**Model Setup and Constraints**

The focus of this paper is the impact of well design, spacing, and completion components on production. All models are run with and without geological normalization to understand the sensitivity of the geology on the solution. The result requires geological normalization in order to be statistically valid, but the trends and degree of uplift associated with the variables does not change between models. This repeatability between individual models helps to validate the stability of the models. All variables are evaluated for collinearity and data outlier analysis prior to running the models. All solutions are created based on bias solution, which limits the model to the variations that exist in data and will not forecast uplifts or modification of a variable that has not already gone through testing. This limits the potential of creating false positives. Each model is limited to one variable per 10 horizontals modeled to ensure validity of relationships in analysis. The importance of these practices are outlined in Wicker et. al. 2017 and Courtier et. al 2016. The models are updated as new horizontals have sufficient production data in order to provide a blind test population. This provides a ground truth of the trends and the degree of significance of variables seen in modeling.

**Well Design Model**

The Well Design Model incorporates geographical information, lateral length, and directional plans of the wells. The goal of the Well Design Model is to understand if location, well layout, or flow back procedure have a dominant effect on production. The Well Design Model utilizes the information from 97 wells for calibration to analyze relationships with 6-month cumulative oil production within the Laredo acreage position. The properties that are analyzed include X and Y coordinates, flow back strategy, lateral length, shut-in time prior to flow back, and information on the directional path of the well. In total, 49 distinct variables are analyzed in the model.

Completed lateral length is defined as the distance between the first and last perforation in the horizontal. The directional path information is condensed to average data associated with dog leg severity, TVD change from heel to toe, azimuth, and average inclination of the lateral. The location information is calculated based on the center of the lateral and is displayed as X and Y coordinates. The shut-in time is quantified as the number of days between the end of the completions and the start of the flow back. The result of the Well Design Model shows a correlation coefficient of 0.752 between predicted and actual production (Figure 1).

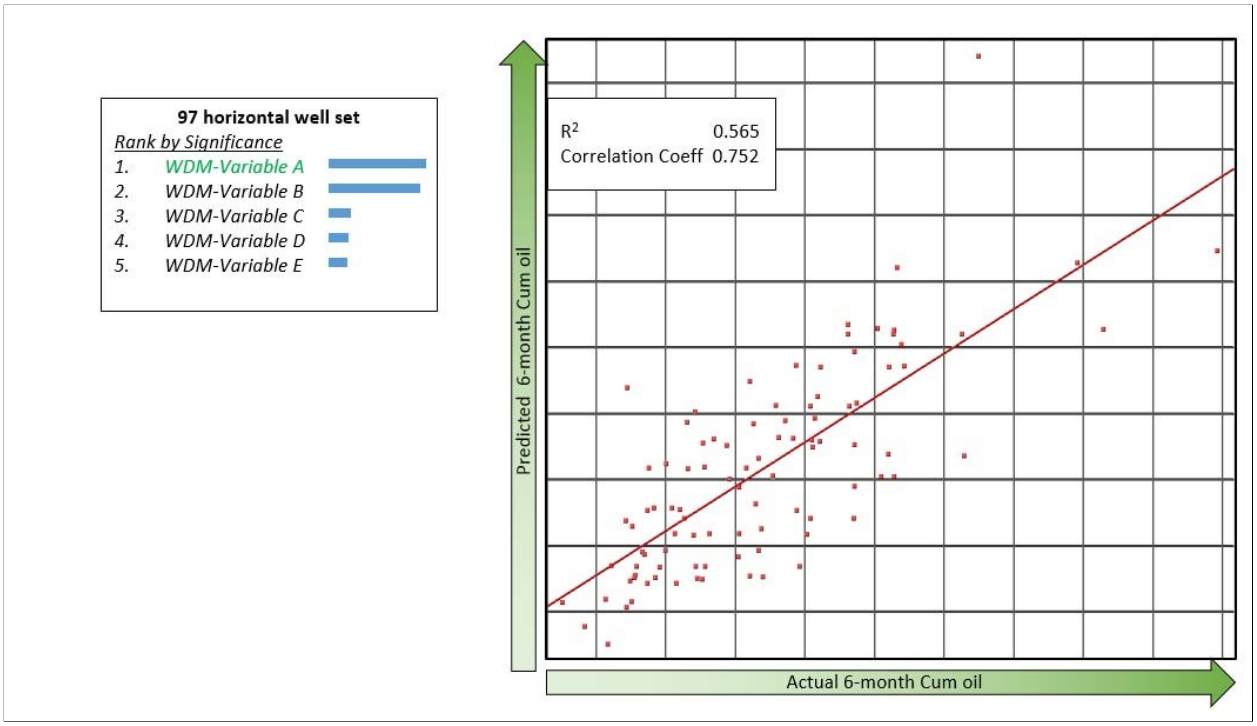


Figure 1: Results of Well Design Model showing capability to predict well performance.

The highest-ranked significance driver in the Well Design Model is WDM-Variable A, which indicates a positive linear increase in predicted oil with increase in the variable with no indication of degradation. WDM-Variable B and WDM-Variable C are expressed as higher order solutions that are related to the vintage of wells. The WDM-Variable C ranks 4th in significance and shows decreased performance the larger the calculated values. Examples of solutions of the variables are shown in Figure 2 which include shut-in time and the average well trajectory. The shut-in time indicates a negative performance with longer time. The average well inclination indicates that the best performance is associated with wells that have a flatter trajectory.

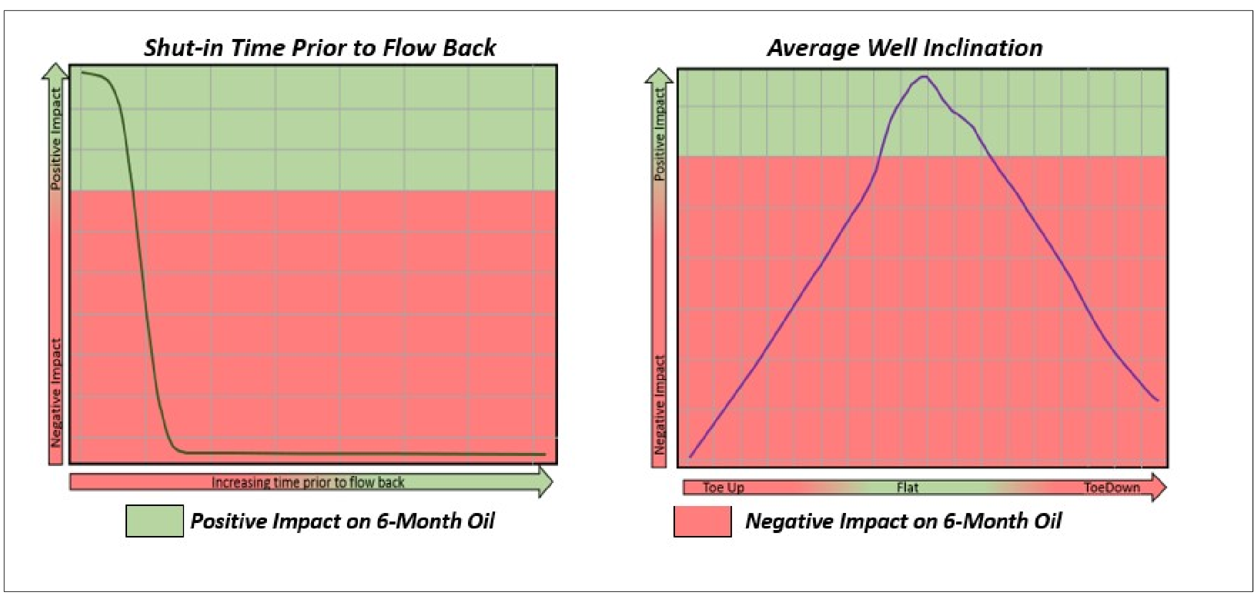


Figure 2: Impact of days prior to flow back and average well inclination on predicted oil volume.

While we cannot change the in situ rocks and fluids, specific variables that Laredo can influence include completed lateral length, well inclination, and, to a degree, shut-in time prior to flow back. Due to the lower impact, shut-in time and well inclination are not required for a combination model to predict cumulative oil production. However, these variables are relatively low cost modifications to well design and procedures which require minimum modifications to optimize. The optimization of well inclination provides a secondary benefit in decreasing the amount of directional changes and time sliding during drilling which yields a high average penetration rate in the horizontal section of the wells.

**Spacing Impact Model**

The Spacing Impact Model is designed to assess the impact of well spacing within and between individual landing points at typical development spacing configurations, for both existing legacy producing wells (parent wells) and for new wells that directly offset legacy wells (child wells). Spacing parameters are calculated at the center of the lateral and are represented as tangent, vertical, and lateral distances which includes horizontal spacing between laterals, distance from an existing well, and vertical distance to wells in other zones. Additional variables for the analysis are timing between existing and new drill, number of existing offsets, and number of new wells between the analysis well and an existing horizontal. All variables are calculated using 187 horizontals within Laredo acreage.

With the combination of the highest-ranked significance variable from the Well Design Model, a correlation coefficient of 0.795 and absolute error 12.7% is developed. The accuracy of the prediction is shown in Figure 3. The increase in accuracy is related to better quantification of the variability controlling well performance. The spacing variables that had the highest-ranked significance are the tangent lengths of each property compared to the vertical or lateral separations.

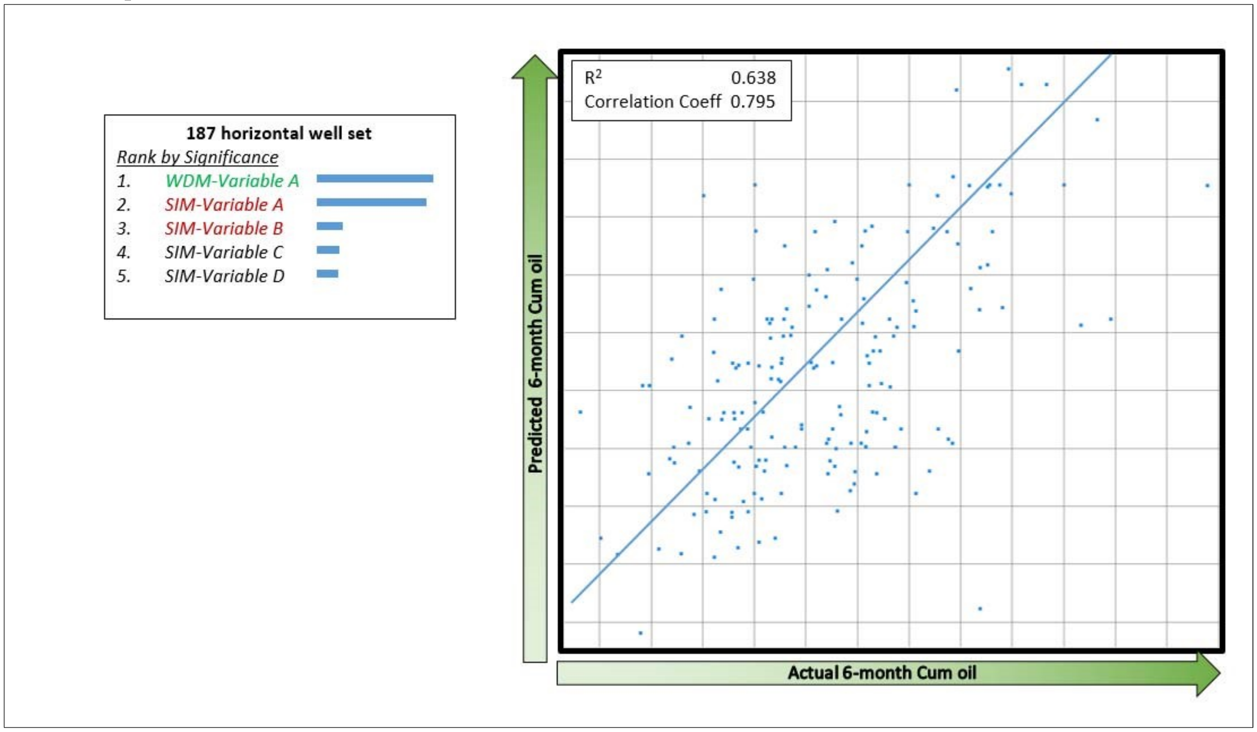


Figure 3: Results of Well Spacing Model showing capability to predict well performance.

Modeling indicates that SIM-Variable A is the highest ranked spacing measurement and displays a non-linear relationship with the prediction of cumulative oil production. SIM-Variable B is the 2nd most significant spacing property and 3rd highest ranked when including WDM-Variable A, followed by SIM-Variable C and SIM-Variable D. Due to the high significance SIM-Variable A and SIM-Variable B were selected for use in combined models. Examples of the impact transforms are shown in Figure 4.

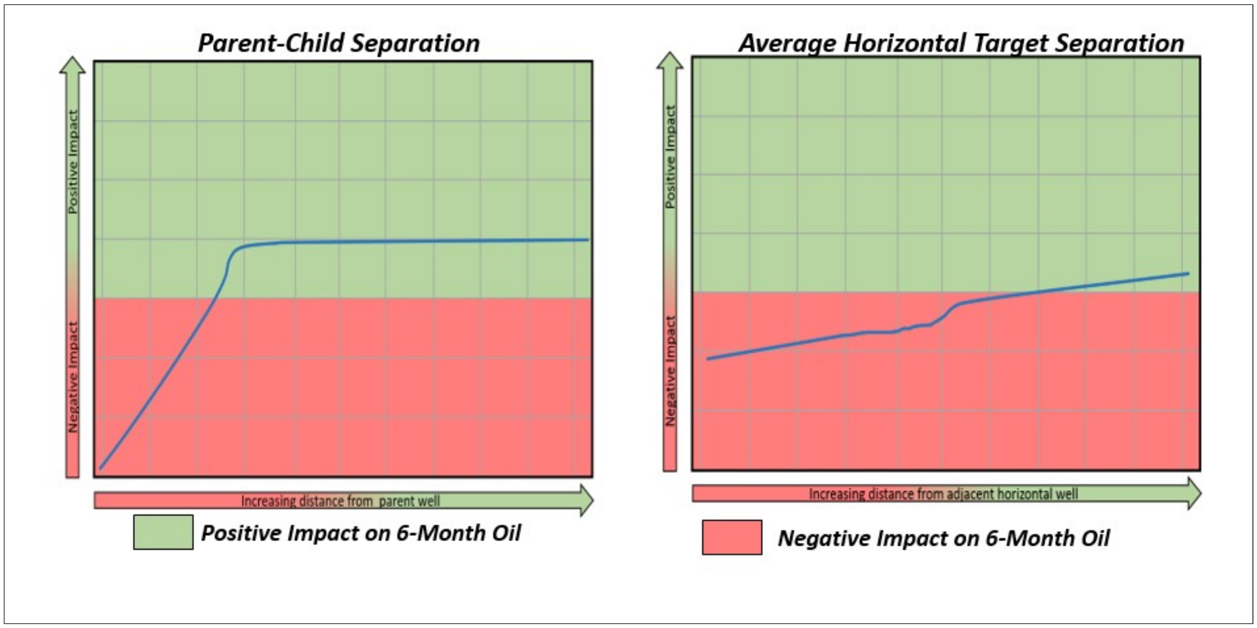


Figure 4: Impact of spacing component on predicted production volumes.

**Completion Impact Model**

The Completion Impact Model utilized information from 160 wells within the Laredo acreage position and is designed to assess the impact of completion design on production. Previously defined principal variables from the Well Design Model and Spacing Impact Model have been carried over into the Completion Impact Model along with geological normalization to provide an integrated model. Newly added completion variables include total sand pumped per foot, volume of water, fluid type, type of proppant, number of perforation clusters, shots per cluster, cluster spacing, a proprietary completion methodology, and pump rate. All variables are calculated at the stage-level and then averaged for all the stages in a lateral.

The combination of the independent variables from collinearity and the highest-ranked significance variables from the previous models resulted in a correlation coefficient 0.834 with an absolute error of 9%. The increase in the accuracy of the model is the result of incorporating the highest-significance drivers that control the variability in production including the proprietary methodology of normalization of geological variation. The accuracy of the prediction and the significance of each of the variables are shown in Figure 5. As with previous models, WDM-Variable A has the highest control on the prediction of 6-month cumulative oil production, with the CIM-Variable A factor being the second highest. CIM- Variable B is the third highest rank significance variable that represents the dominant test variable identified in future testing.

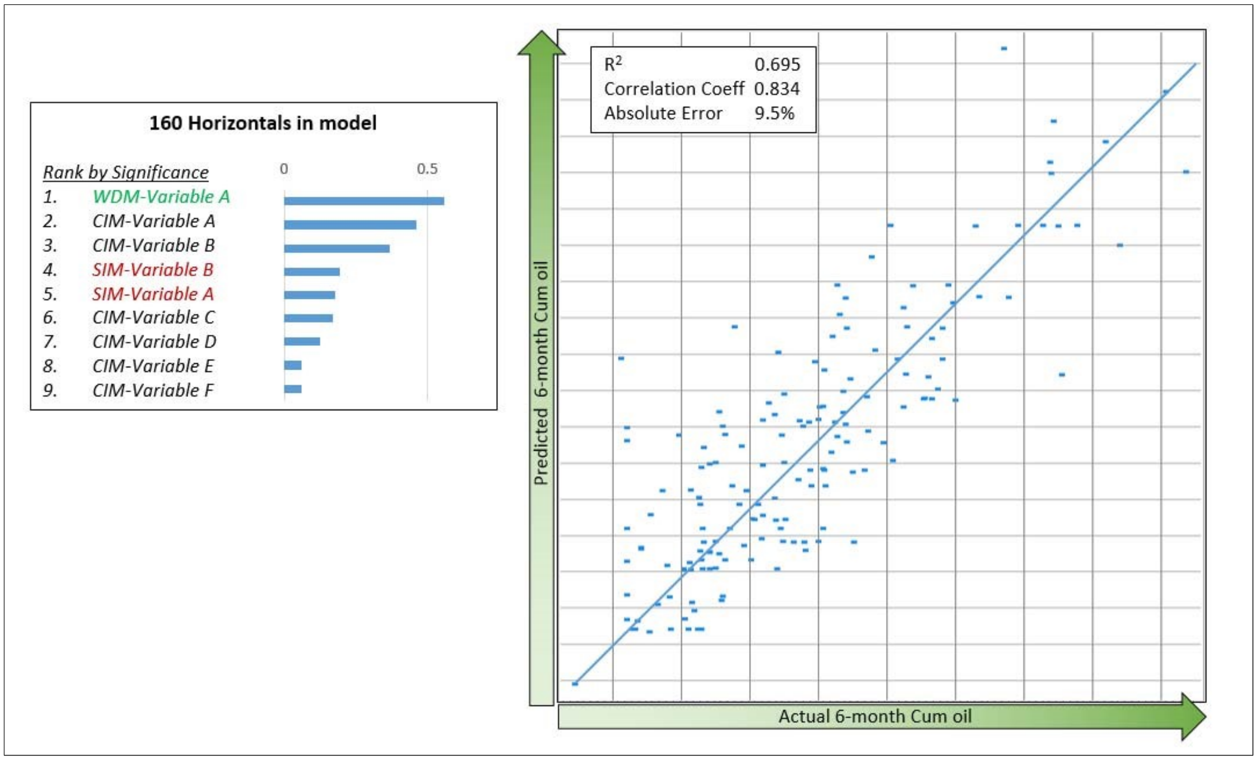


Figure 5: Results of combination with completion information showing capability to predict production volume.

Modeling indicates WDM-Variable A continues to have a positive linear trend. The geological potential variable has a steady improvement of production potential with increasing quality to a certain point when the impact plateaus, which is associated with higher well performance in this area driven by optimization of well design, completion, and spacing parameters. Increased volume of sand per foot indicates a linear improvement through the highest volumes tested to date. Spacing model variable trends are unchanged with the incorporation of new variables. Implementation of a proprietary completion method appears to be providing a positive impact on production. Examples of the Completion impact model transforms are shown in Figure 6.

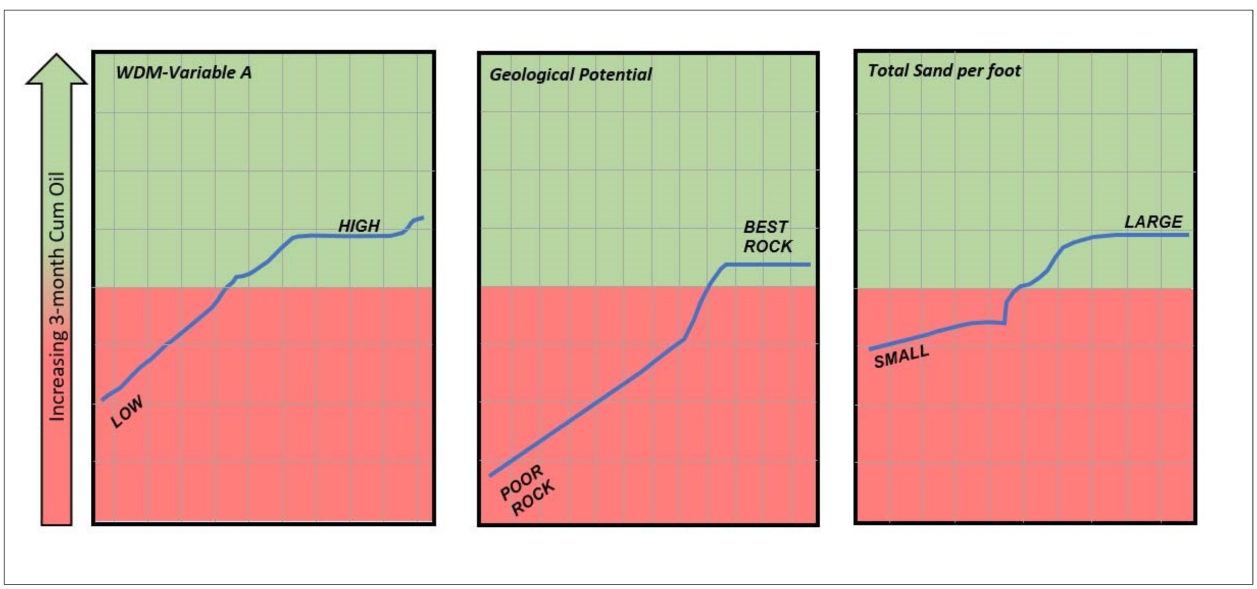


Figure 6: Examples of Completion Impact Model variables of concern on predicted production volumes.

The results of the Completion Impact Model warranted additional testing of higher sand volumes and additional cluster configuration. The analysis of data gathered during this testing and its impact are discussed in Trowbridge, 2017. The impact of these modifications in conjunction with Laredo's Earth model have shown a production uplift when implemented as discussed in Courtier, 2016 and Wicker, 2017. Additionally, the utilization of the proprietary completion technique has yielded a low cost uplift option that warrants future analysis and testing.

**Monte Carlo Analysis**

The development of integrated models allows for the creation of Monte Carlo simulations that can apply a volumetric uplift associated with the modification of a single variable. As an example completion length has significant variability across the data set, which prompted additional analysis to quantify the amount of impact and determine the validity of uplift at longer lateral lengths. In order to do this, the MVA solution from the combined model is written to each well with the appropriate information resulting in a population of 270 horizontals. The results from predicted versus actual values of 90-day production are binned using a histogram analysis into 500' lateral length groups and are plotted in Figure 7.

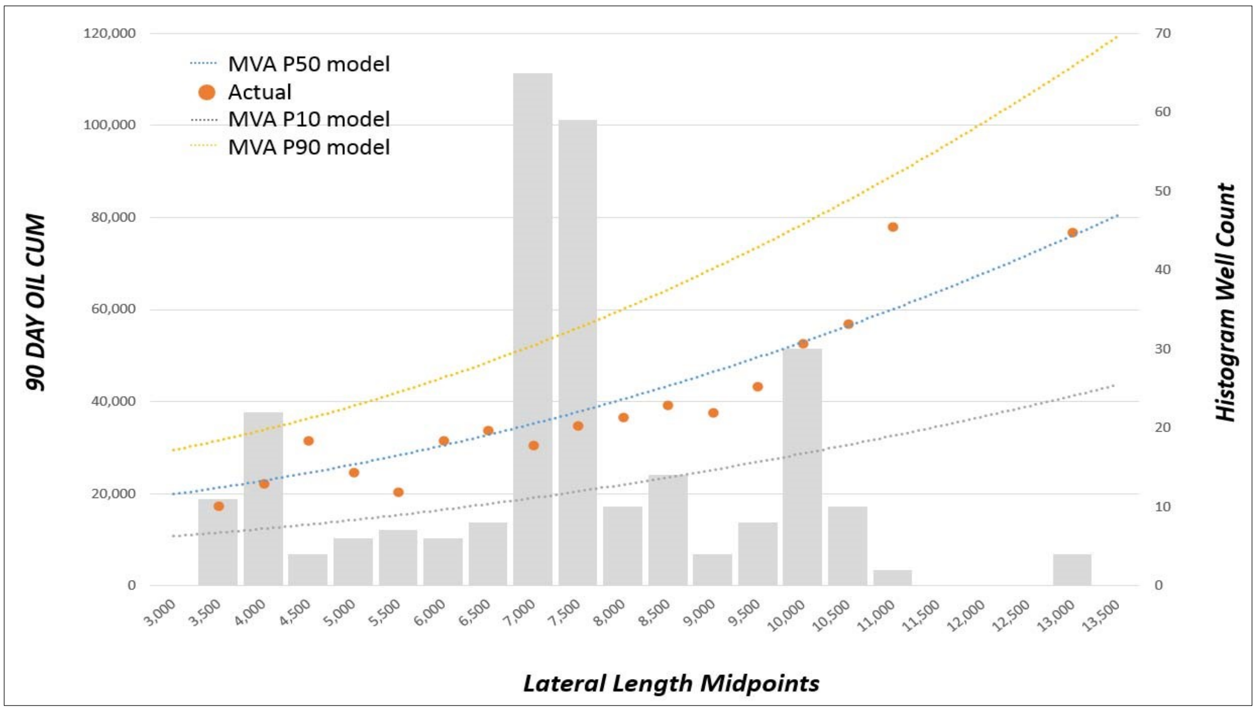


Figure 7: Impact of completed lateral length model compared to actual average well results binned by lateral length.

**Continuous Model Improvement & Knowledge Development**

The above MVA models are discussed successively in the order of which they were originally developed. Results from one MVA model can be leveraged and integrated progressively into the next model. The above approach demonstrates consistent repeatability in terms of both ranked significance of key variables in the overall MVA models and with individual highly ranked significance variables non-linear behavior with respect to production. Such consistency provides confidence in understanding which variables are controlling production and to what extent. This also allows accelerated learning and optimization via selecting specific future well and completion designs to maximize asset value during future development.

Setting aside time, resources and training to build high quality organized data sets and MVA organizational competencies over a number of years within Laredo has proved critically important for this approach to work successfully.

## Conclusions

Multivariate analytics provides a robust methodology to evaluate and determine the dominant controllers on the cumulative production of horizontal wells in local and asset-wide comparisons. This and similar workflows have been utilized by Laredo Petroleum extensively as documented in Curth, 2015, Courtier 2016, Wicker, 2016, Wicker, 2017, and Courtier, 2017 to evaluate datasets and identify optimization potential in completions, spacing, targeting, drilling, and production. With the modification of variables across the scope of a well's design, additional improvements at a varying cost can be achieved. In the analysis of the well design, completion, and spacing parameters, some low cost changes are identified such as average inclination of a horizontal, distance of separation between existing and packaged wells, and an implementation of a proprietary completion technology. Some of the identified variables require more cost benefit and risk analysis prior to implementation in the field. Through continual validation of modeling results and blind testing, the quantification can be determined with a high degree of certainty.

## Acknowledgements

This workflow was developed and vetted through the cooperation of several individuals and companies. The following deserve recognition for their efforts: Laredo staff, Drillinginfo, Transform, and Sean Carey. Without their support this process would not have been possible.

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