Chapter 4
Findings and Analysis

4.1 Findings of objective 1

This section contains the outcome of the results of the questionnaire. The results of the variables are listed in the next paragraph with production chain components tabulated on the header row. Hence, the check mark represents the element of data required for the intersection of the related column and row.

Based on the response received from all SMEs, the following list of Decision Variables was compiled and used during the model design. Appendix 4 contains analysis of the answers.

Table 4-1 Questionnaire Recommended Variables

	Data Required					
Definition	**Wells and Flow Lines**	**Main Pipe lines**	**Separators and Gas Water Collection**	**Machines**	**Storage Stabilize and Loading**	**Demand**
Oil Production / Processing capacity	√	√	√		√	√
Wells allocations, allocations, lift model	√					
Separated gas			√	√		
Separators capacity for oil, water and gas			√			
Plant gas processing, capturing capacity			√	√	√	
Retention time			√			
Routine maintenance time			√	√	√	√
Mean time between Failures (MTBF)			√		√	
Mean time to repair (MTTR)			√		√	
Inspection time (off-production)	√		√			
Asset availability	√	√	√	√	√	√

Settings data needed	
Wells tests and Inflow Performance	Well flow rate (oil+ water+ gas+ condensate). including the capacity of transport lines
Capacity of Main Injection Facility	Total injection (capacity of all online water/gas injection module - the total of plant and pipelines)
Capacity of main water and gas wells	Well capacity of all online injection strings in the field- production injection ratios (water and gas)
Crude stabilization	Sulphur and gas residuals to flaring while oil passes crude storage tanks
Gas stripping and sweetening units	Capacities and volumes of gas and removed water and impurities (other gases)
Capacity of all injections	Total injection oil equivalent is: Water injection equivalent equal (water injection + gas injection divided by gas to oil factor)
Flow rates of service lines (oil, gas and water)	Flow rate in pipe fluid (oil+ water+ gas)

The collected results from on-line and paper are attached in Appendix 4. The consensus is that all the questions earned consensus approval except when modeling was in question. The modeling is debatable and the subjects have various views of how to address objective number two.

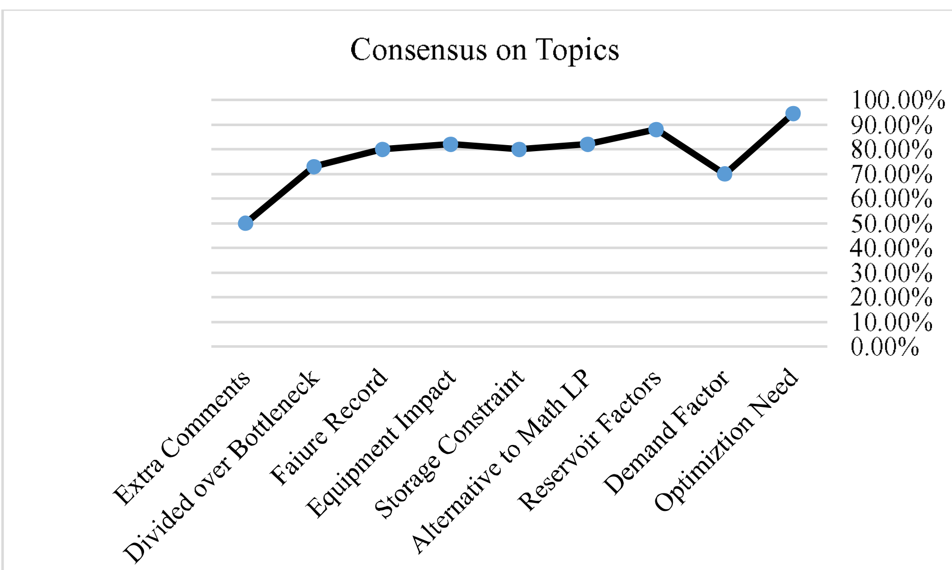


Figure 4-1 Consensus of the questionnaire

Feedback and suggestions from the subjects are listed in Table 4-2 with mitigations:

Table 4-2 Questionnaire analysis of comments

Subjects' Suggestions	**Answer**
Pressure Readings are important for the model	Pressure models are used normally in the PVT simulators. The facilities model optimization relies on flow rates which are directly correlated with pressure and temperature changes.
Include risk based inspection planning as an alternative to fixed interval planning	This is a very important topic. It qualifies for future research due to the technicalities involved in asset fitness for service and remnant life assessments.
Most wells stay in a steady state for a long time	True if the well is standalone. In a production network, the dynamic nature of the field activities affects inflow performance and causes production fluctuation.
Simulate CO_2 injection	Future study; based on suitability of strategy to overtake the water flooding since the CO_2 option is restricted to certain fields
Include manpower as a resource constraint	Manpower will continue to be a key factor regardless of the emerging real time and smart field technology. Manpower validity is for maintenance in general which is bundled with the vessel availability.
Account for predictive failures	Predictive and probability of failure are part of the risk modeling which is qualified for future work
Include stimulation events plans	Future models can be expanded to include all fields' events including project work and asset betterment
Water unloading scenario for Gas wells	It can be assessed if it is done without a shutdown. Otherwise, it can be

	accommodated under well work-over due to the need for a shut-down to unload the condensate water
Include real time readings of flow meters	Real time in general can add value for day-to-day operational activities in handling alarms and trips in central control rooms
Apply (Program Evaluation Review Technique - PERT)	This tool is useful for the planning of projects. However, it needs more investigation for fitness for use in modeling
Include carbonate formations effects and other constraints	Reservoir simulation and geo chemistry are not addressed in this research
Inflow and nodal analysis	Nodal analysis is subject to specialized simulator
Choke size simulation	Choke size is a result of the well model which is subject to the well modeling simulator
Include reservoir and fluid properties	The reservoir and fluid properties are subject to reservoir simulation modeling
Include demand, price and market impact	The study will include demand and market. Price impact is not included in this research and qualifies for another research
Key information from distributed control systems to be included in the model	DCS is part of the digital oil field studies. These models serve the day to day operational activities
Resources, constraints, boats, rigs, etc.	Rigs as main constraints are included as a resource in the model. Mobile crews are not used as constraints due to high availability
Include pressure model to handle steady state	Pressure model is handled very well in the specialized simulators for PVT thermodynamics
Lost time shall consider non-technical elements such as	Many lost time elements are embedded in this research under the well shut-in data mining

resources, logistics, weather etc.	due to its importance from the planning constraints including operational, weather and logistics.
The most important thing is to clearly identify the levers which are key contributors in a production model and to see the bigger picture, and then take an “integrated approach" to ensure maximization of value by identifying synergies and opportunities to enhance operating efficiency, thereby reducing unit operating costs.	One outcome of this research is the analysis of the actual well productivity which is a key to profit and efficiency. Key cost elements (i.e. lost production opportunity has financial relevance and is part of this research) are indirectly addressed through effective planning and accurate production reporting.

The manually collected surveys are 67 and online collected responses are 24. The analysis of the questionnaire is in appendix 4.

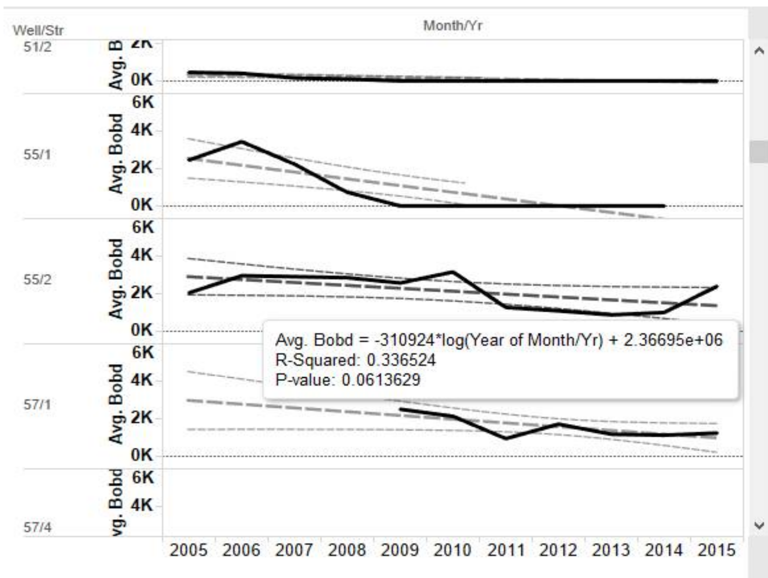
The variables related to flow, PVT (pressure, volume, and temperature), tubing size, tubing performance, formation size, choke valve settings, permeability, porosity and well characteristics are subject to special purpose simulators (e.g. PVTi and Eclipse 300[6] (Schlumberger, Abingdon Technology Center Training, 2005)). Operational variables such as process flow model, assets capacities, functions, processing capabilities, allowable rates, allocations, maintenance programs (workover or stimulation work), fluids' ratios, PVT results, asset efficiency or availability and operational shut-ins are of interest to this research. This research conducts analysis of the surface data and describes the well performance beyond the well testing by studying the overall system performance, what is the impact on the production data, and what are the set goals by running scenarios of what needs to be done to enhance the effective production capacity.

[6] Schlumberger solutions for simulation

4.2 Findings of objective 2 - Wells trends

Two main goals are handled to meet this objective. Goal number one is to collect the data related to the decision variables of objective 1. Data is addressed through data collection for the required variables to be used in the simulation modelling after analysis and extrapolation. The analysis aims at configuring the simulator with the field parameters as data trends, PDF or constraints.

The production data is used to produce the trend models and plot production trends for all wells' strings from a specified zone. The graphs and formulas are used to configure the simulation model are attached in appendices 1 and 2.



Caption
The trend of average of production BOPD for Month/Yr Year broken down by Well/Str.

Figure 4-2 Well production trend formula (sample)

(Figure 4-2 Well production trend formula (sample)) represents a sample of the production analysis report highlight of one well model formula, correlation factor R and P-value. The well graphs are attached in appendix 1.

The production values of the wells in model number 2 are analyzed for trend and formulas. Field model number 2 has portrayed a trend of periodicity for some wells which is a result of repeated timely workovers.

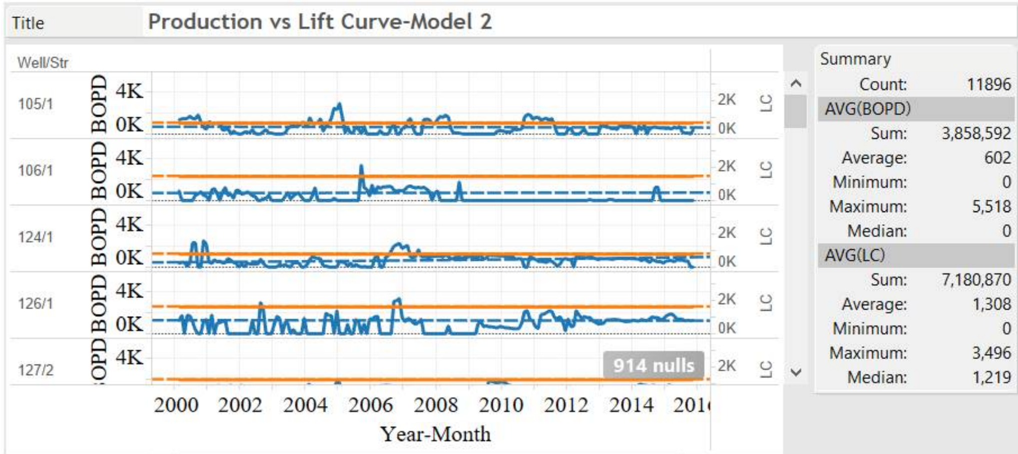


Figure 4-3- Sample of production trend in model 2

This is an expected trend where the curve amplitude grows after maintenance or stimulation. However, the trends were produced based on the P-value. A PDF model is used when no trend can be predicted. A sample of the results of the simulation model is depicted in (Figure 4-3- Sample of production trend in model 2). The full graphs and models are attached in appendices 1 and 3.

4.3 Findings of objective 2 – Gaps of production plans and actuals

A correlation analysis was run for model no. 1 to obtain the correlation factor R. The analysis covered computed lift curve, allowable production limits and actual production covering a 5 year period prior the simulation.

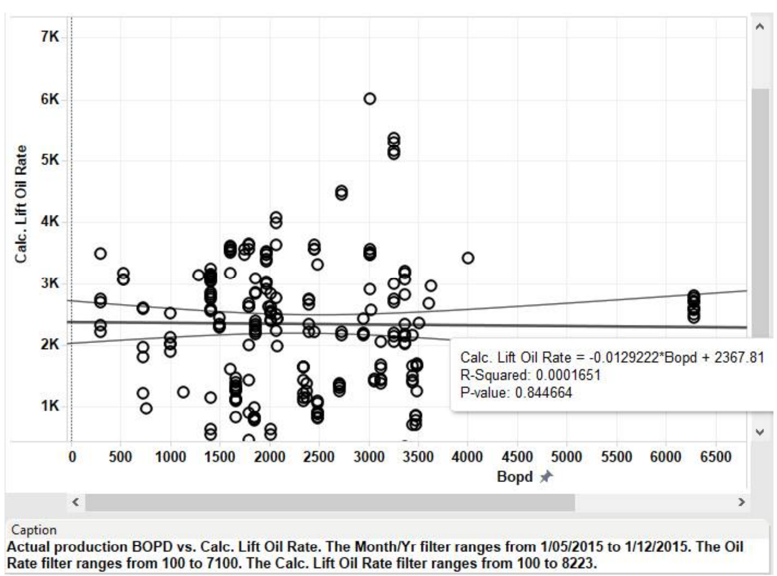
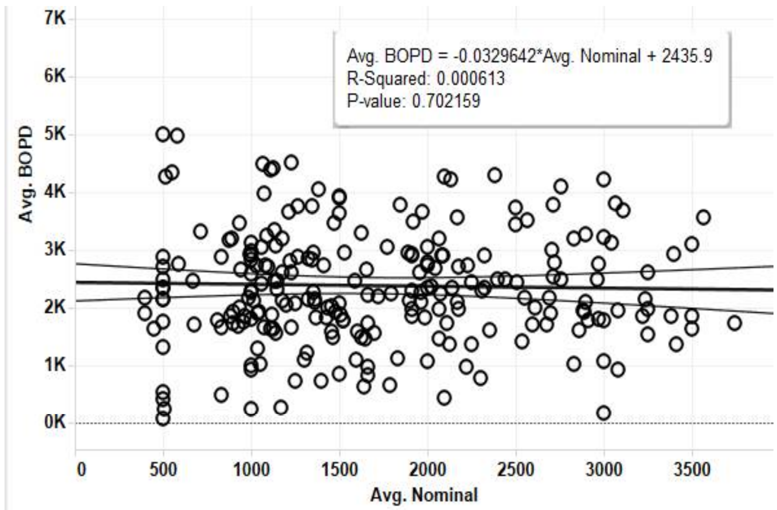


Figure 4-4 Correlation of computed lift curve and actual production-model 1

The production plot versus well lift curve values resulted with R-Square equal 0.0016 and the correlation factor R equal 0.04 showing poor correlation in the model and the hypothesis testing H0 of no correlation is accepted. Figure 4-4.

Five years of nominal allowable production rates are plotted against actual production in Figure 4-5.



Caption
Average of planned Nominal vs. actual BOPD. Details are shown for Well/Str.
R-square = 0.000613. R=0.0247.

Figure 4-5 Correlation of planned nominal and actual production – model 1

The R-square value of 0.000613 and R-Factor of 0.025 depicts the absence of correlation between allowable and actual production based on the (Figure 4-5 Correlation of planned nominal and actual production model 1). Hence the hypothesis testing H0 of no correlation is accepted.

The lift curve was evaluated at the well level and produced varying R-Square mostly below 0.3 and R value of below 0.5 as seen in one sample from the analysis report (Figure 4-6 Correlation well allowable and actual production). The full report is available in electronic format.

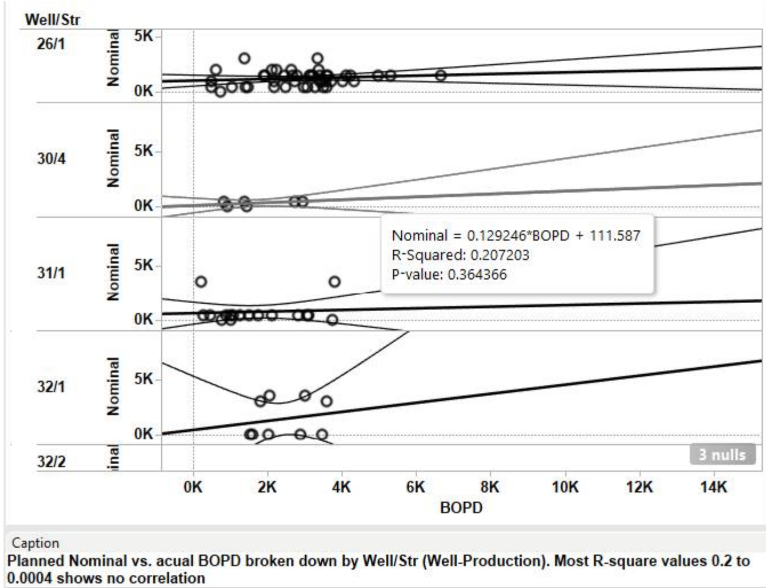


Figure 4-6 Correlation well allowable and actual production – model 1

The wells' nominal allowable production listed is in (Appendix 17 - Wells maintenance programs models 1 and 2) as defined by reservoir engineering. Lift curves are used to set the operational targets and flow assurance 1.2.5 (Production dynamics).

The result of plotting lift curve computations for expected production against actual production for the elapsed year produced an R-Square value of 0.1845 rendering a correlation factor of R=0.42.

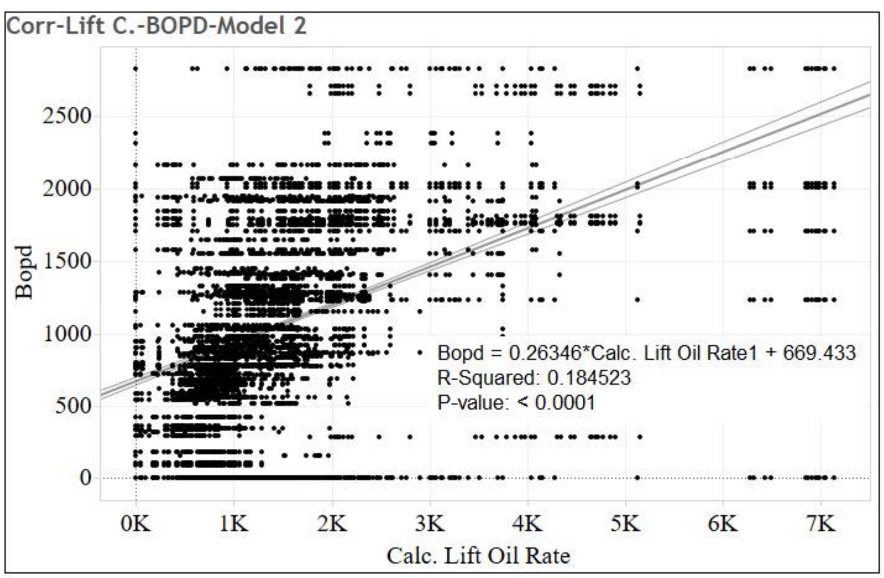


Figure 4-7 Calculated lift curve versus actual production-model 2

Therefore, the correlation between computed lift curve for model 2 shows poor relationship between the actual and the required optimization from the lift curve computations. (Figure 4-7 Calculated lift curve versus actual production-model 2). Hence the hypothesis testing H0 of no correlation is accepted.

The results of analysis of correlation between planned allowable limits and actual production values produced a regression factor R-square equal 0.197 and correlation R-factor equal 0.44 representing poor correlation. (Figure 4-8 Nominal allowable versus actual production - model 2).

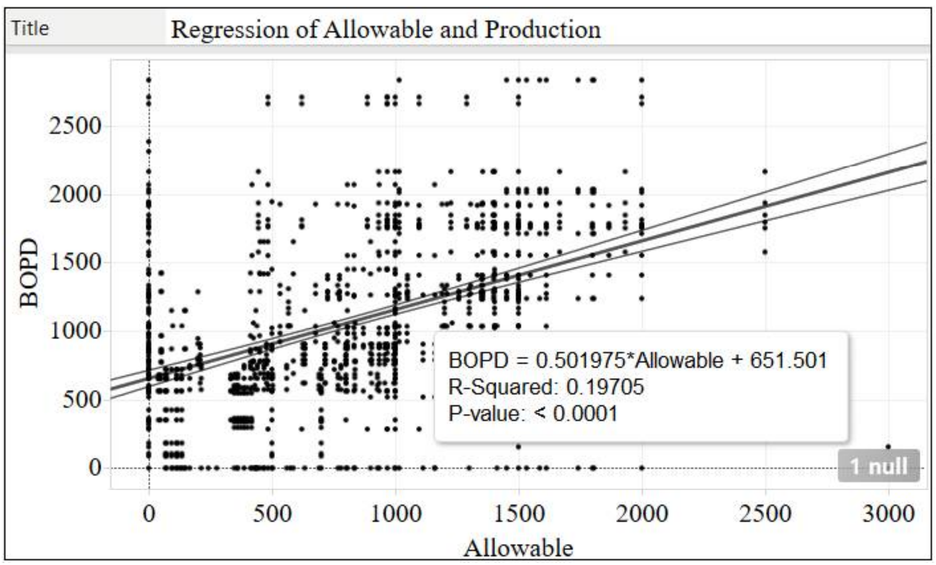


Figure 4-8 Nominal allowable versus actual production - model 2

4.4 Findings of objective 2 - Simulation models

Process diagrams in appendices 10, 11 and 12 (process diagram, simulation model 1 and model 2) are modeled in graphical representation. The models are built as described in appendix 12.

The demand trend is modeled in parallel to the oil loading for shipping. The results are produced in material units of MBOPD, MMSTCFD and MBWD.

4.4.1 Simulation run for validation of the model number 1

The model was run for one month for the subject reservoir and produced results compatible with the actual production. The model was configured to run using actual production values for comparison with known information. The graph in (Figure 4-9 Correlation of simulation model and actual results for validation) shows the correlation of production of the tested month and the simulated results.

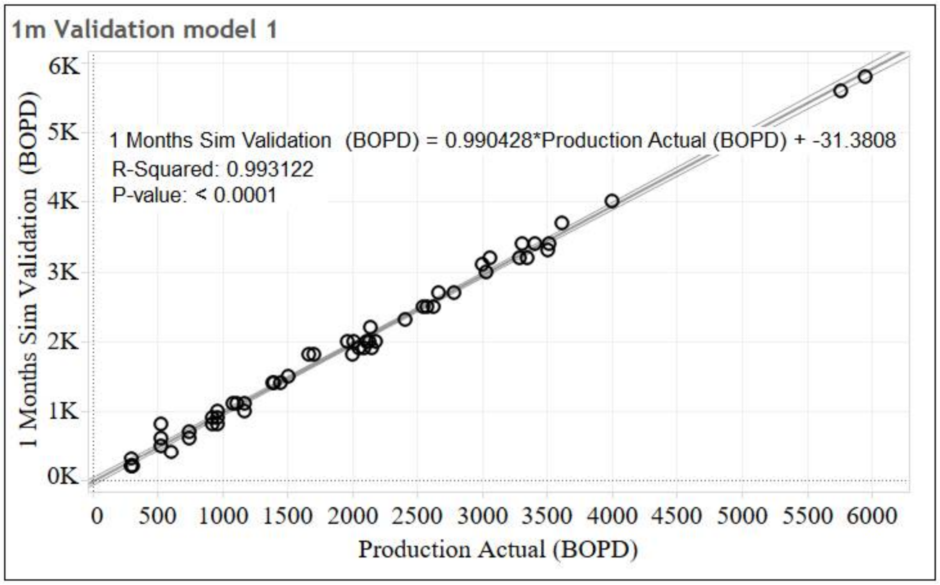


Figure 4-9 Correlation of simulation model and actual results for validation

Therefore, there is enough reason to reject the null hypothesis and consider the simulator as a valid model with calculated correlation factor R=0.996. The formula produced a linear model between the simulated production values and the settings which are based on the actual production. A linear trend model is computed for well production (BOPD) versus the well validation setting. The model is be significant at $p <= 0.05$.

Table 4-3 Correlation results

Equation 4-1 Production and simulation correlation	Y = 0.990428*X- 31.38008
Number of modeled observations:	54
Number of filtered observations:	5
Model degrees of freedom:	2
SSE (sum squared error):	590355
MSE (mean squared error):	11353
R-Squared:	0.993122
Standard error:	106.55
p-value (significance):	< 0.1

On the average, the validation model showed almost identical values to the actual production with a slight loss (3.1% for truncation) as a result of settings related to using hours as unit of time and a minimum production unit of 1k barrels. This is used in the estimated production correction factor that will follow.

4.4.2 Simulation forecast for six months – model number 1

The simulation was run for six months. The result of the simulated production forecast was run in correlation analysis with the latest month's production.

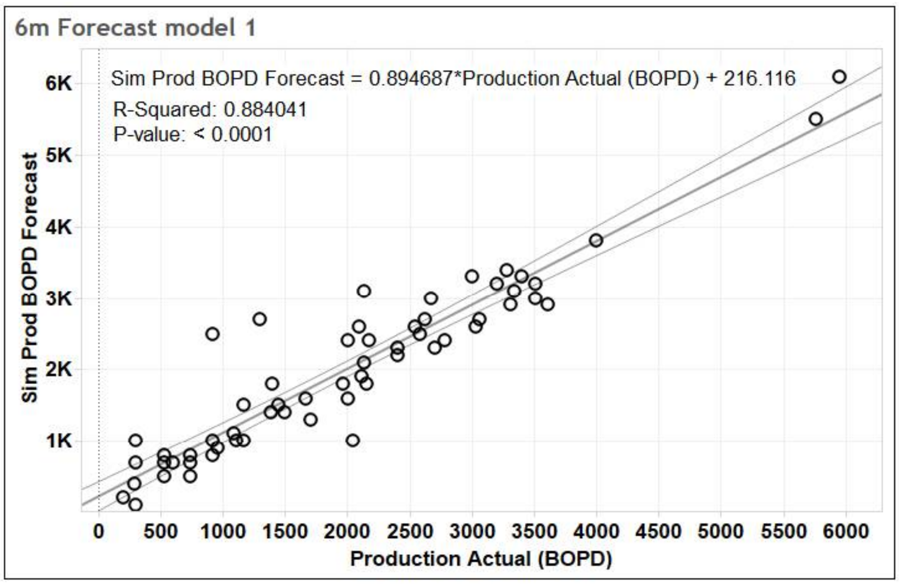


Figure 4-10 Six months forecast with target production of latest actual

The correlation results conclude that the R Square is 0.884 (R=0.938) which represents a high linearity between the simulated forecast and the previous period actuals rendering the null hypothesis H0 as unacceptable.

The produced volumes resulted with a (3.9%) difference. The difference is the measure of the expected decline and due to elapsed time. Therefore, when the predictions are very close to actuals, an organization can plan effective well priorities and consequently be in a better position to increase production through construction of new wells. This can be assessed quantitatively (e.g. annually add two new wells, two reworked) by evaluating development scenarios for sustaining production at the demand level – Section 5.2.

4.4.3 Simulation forecast for fourteen months - model number 1

The simulation was run for fourteen months and resulted with R-square of 0.636 and the correlation R factor equal 0.8. The overall production decline is 6.8% against the targeted rate (basis of production rate is the latest available actual).

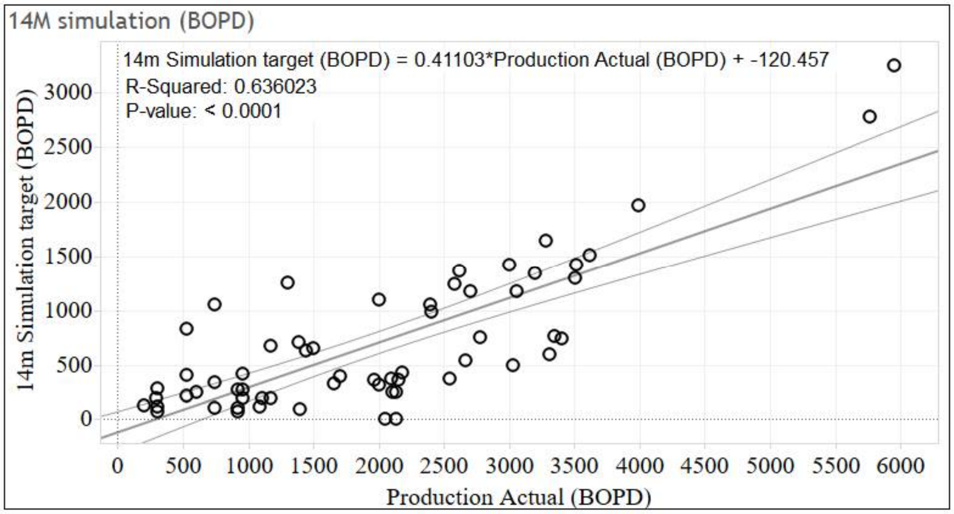


Figure 4-11 Correlation of simulation results of 14 months forecast

Table 4-4 Fourteen months simulation model statistics

Equation 4-2 Model formula	Y = 0.41103*X-120.457
Number of modeled observations:	75
Number of filtered observations:	0
Model degrees of freedom:	2
SSE (sum squared error):	9.24E+12
MSE (mean squared error):	1.54E+11
R-Squared:	0.636023
Standard error:	392369
p-value (significance):	< 0.1

A second scenario was run for model one by introducing two new wells and reworking two low producers. The simulation produced the correlation in (Figure 4-12 Correlation for simulated model results of 14 months - new wells).

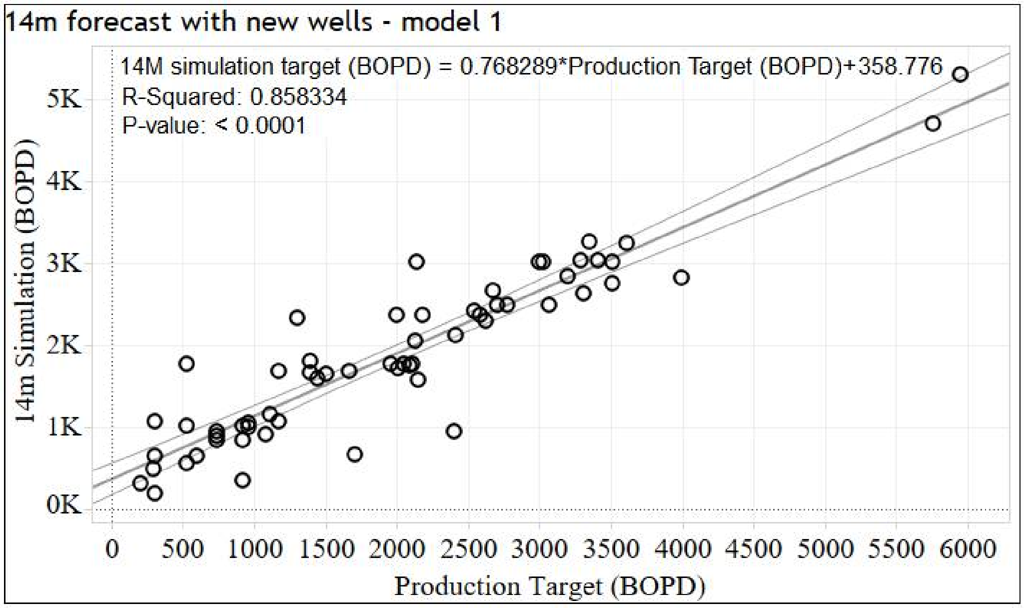


Figure 4-12 Correlation for simulated model results of 14 months - new wells

The above was produced after incorporating the measures of additional wells added to the production stream. The average workover of two wells and developing another two new wells (equivalent to four per month) produced R=0.926 correlation and a reduced the lost opportunity to 2.2%. Therefore the null hypothesis H0 is rejected.

A linear trend model is computed for Y given X on the time axis. The model is significant at $p <= 0.05$.

4.4.4 Simulation forecast for one month – model number 2

One month scenario was run and produced a production forecast with 2.2% difference from the targeted production. The correlation results of the simulation model are depicted in (Figure 4-13 Correlation model 2 for validation purpose – 1m). The analysis of R-square value (0.9806) produced a correlation equal 0.99 which constitutes a high correlated relationship rendering the model as acceptable and rejection of the null hypothesis H0.

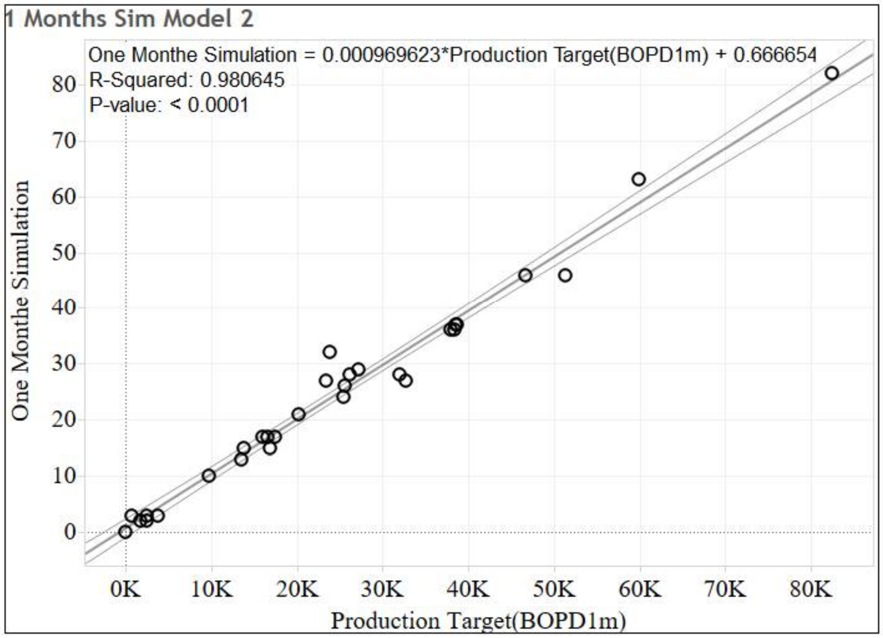


Figure 4-13 Correlation model 2 for validation purpose – 1m

4.4.5 Simulation forecast for twelve months – model number 2

A one year scenario was run and produced a production forecast with 5.7% difference from the targeted production. The correlation results of the simulation model are depicted in (Figure 4-14 Correlation of target production and simulated results- 12 m).

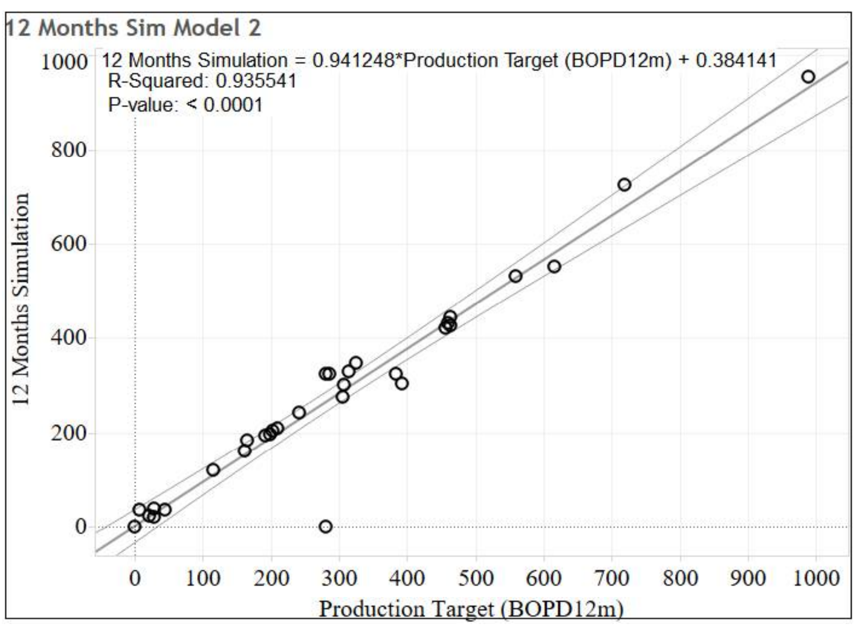


Figure 4-14 Correlation of target production and simulated results- 12 m

The correlation compares the relationship of the targeted production based on the latest month's available data and the forecasted results. The produced correlation R factor is 0.96 supports rejecting the null hypothesis H0. Hence there is a high correlation between the variables. In order to meet the committed targets, a new scenario with additional wells (new or reworked) was tested. This is done in the two year scenario in the next section.

4.4.6 Simulation forecast two years – model number 2

One scenario was run for 24 months and another one with additional wells. The unmodified model run for 24 months results produced a difference of 7.5% in production due to natural decline of the overall field performance.

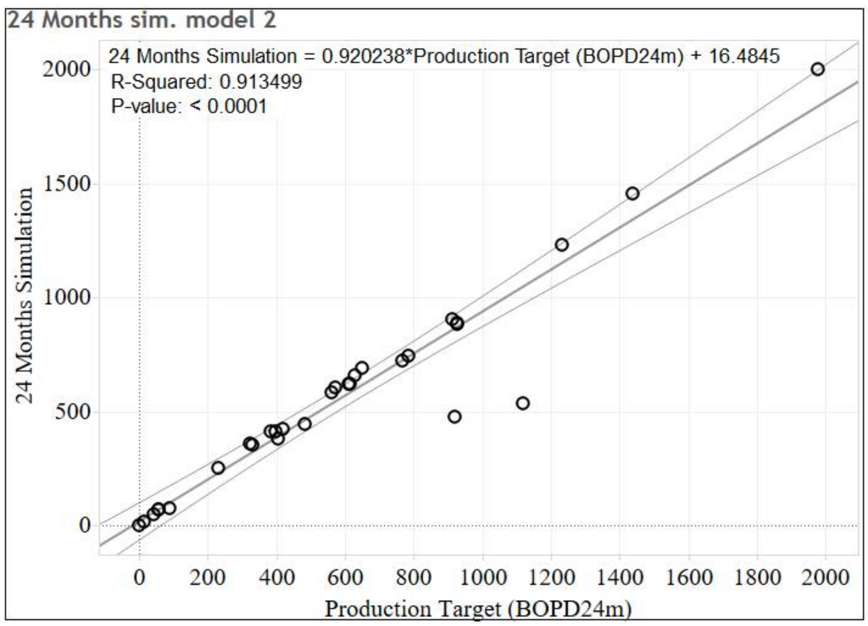


Figure 4-15 Correlation of target production and simulated results – 24 m

The curve produced a high correlation factor R=0.95 which supports rejecting the null hypothesis H0. (Figure 4-15 Correlation of target production and simulated results – 24 m)

The second scenario was run with 2 additional wells produced a 2.8% difference rendering improvement from the 7.5%. The two new wells (one new and one reworked) reduced the lost production opportunity to 2.8%. (Figure 4-16 Correlation of target production and simulation results 24 m - new wells).

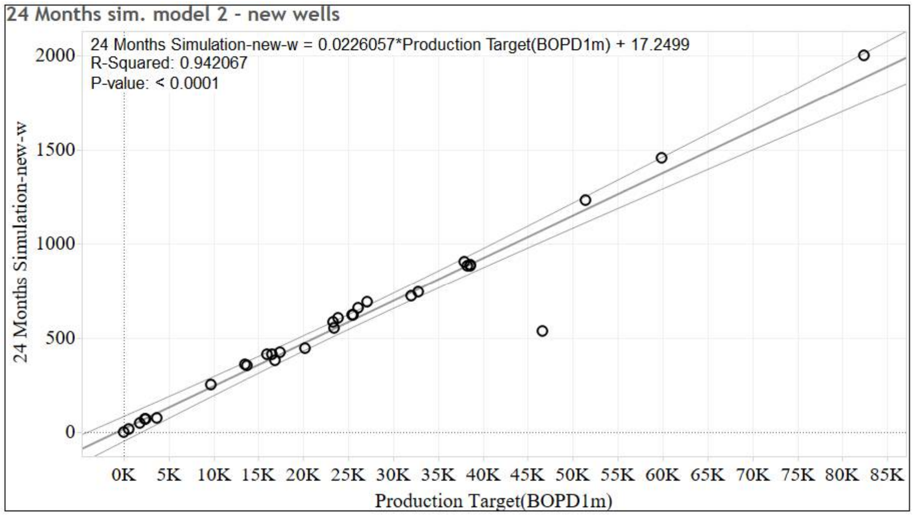


Figure 4-16 Correlation of target production and simulation results 24 m - new wells

The curve produced correlation R factors is 0.971 renders the rejection of H0. Hence, the new wells improved the production targets as well as the correlation between the model results and the targets. The results are in appendix 10.

4.5 Summary of simulation versus exiting model results

Table 4-5 briefs the simulation results for model 1 validation, one month forecast, six months forecast, fourteen months forecast with new wells and outages scenarios;

Table 4-5 Simulation summary results - model 1

Period	Target Oil (LC basis)[7]	AEC Oil	Simulation Model	Delta AEC[8]	Delta sim. Model	R Factor
Validation Model	3,302,806	3,798,227	3,194,000	15%	3.3%	0.99
Forecast 6 months	19,816,835	22,789,360	19,045,000	15%	3.9%	0.93
Forecast 14 months	44,918,159	51,655,883	41,830,000	15%	6.8%	0.79
Forecast 14 months (new wells)	44,918,159	51,655,883	44,403,000	15%	2.2%	0.92

[7] LC is the Lift Curve basis considering latest production readings

[8] AEC is the Automatic Effective Capacity in use by the Company

The result is summarized in (Table 4-5 Simulation summary results - model 1). The fourteen months scenario with two new and two revamped wells for model 1 reduced the lost production opportunity from 6.8% to 2.2%.

Model 2 exhibited an expected periodic production trend where the cycle is repeated after each well intervention. The simulation was run over 3 periods: one month, one year and 2 years with an additional run with the development scenario for a twelve months period. The results produced a linear difference due to the linear periodicity of the model. The findings are briefed in the Table 4-6:

Table 4-6 Simulation summary results - model 2

Period	Target Oil (LC)	AEC result	Sim. results	Delta AEC	Delta Sim.	R. Factor
One month	768,049	883,256	751,000	15%	2.2%	0.98
One year	9,216,588	10,599,076	8,687,000	15%	5.7%	0.96
Two years	18,433,176	21,198,152	17,038,000	15%	7.5%	0.955
Two years (1 new and 1 WO well)	18,433,176	21,198,152	17,897,000	15%	2.8%	0.971

4.6 Chapter conclusions

Objective number 1 results included the set of variables and a wide range of suggestions that represent the population perspective in addressing the problem. Chapter four presents the produced results, the well models, the correlation analysis and correlation between the existing lift curve model and the actual production. The chapter also includes the simulation model, the results of the simulation model runs using the production trends setting, the simulation validation and future scenarios. The results of the simulation are validated and compared with the results of the existing model with computations and explanations of the differences. The chapter contains the mathematical formulation (Appendix 2 - Well extrapolation model 1) and (Appendix 3 - Well extrapolation model 2) used for simulating future production, asset availability and probability distribution functions for events that have random patterns of occurrence. The chapter also describes how the simulation is representing the real world and the optimization through seamless scenarios of modifying the production strategies by adding, replacing or revamping assets. The findings of objective 1 and 2 are summarized with reference to details on the relevant appendices. The difference between capacity and actual production is a known challenge in the industry. The general consensus learned from the response is that the solution requires contributions by many stakeholders and continuous update. This makes objective 2 of the dynamic integrated simulation a very viable approach to integrate all the involved disciplines' efforts in one model to mitigate this challenge.

The use of the integrated process simulator with a data mining basis enhanced the correlation between planned production and simulation results from 0.75 to 0.965. The simulator is able to:

- Improve well maintenance and the stimulation program since the model provide dynamic and adequate forecasting
- Improve the correlation between plans and actuals
- Helps improve the sequencing of priority wells for the production or shut-in
- Trending makes predictions more visible to help planning well shut-in due to WOR or GOR.
- Quantify losses due to natural well decline