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Optimization of Well Sidetrack under Uncertainty using Response Surface and Decision Support. I. Primary Recovery Mechanism

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Abstract: ***The Optimal sidetrack time (tR-OPT) has been estimated for uncertainty of the probability of success (POS) of the sidetrack operation, reservoir properties and economics for a reservoir under primary recovery mechanism. The case studies worked on in literature considered in this study are for those for primary recovery in which production profiles were represented by empirical and analytical models. However, not all recovery can be adequately replicated by these analytical models. Hence, the need to apply proxy models not just to predict cumulative production but net-present-value (NPV).***

In this study the analysis of a decision tree with several branches is carried out to maximize NPV that is evaluated under the influence of production stoppage due to the sidetrack into another non-communicating upper zone with uncertainty of reservoir properties. The optimal sidetrack time adds a severe non-linearity in the response of the resulting proxy model and expected monetary value (EMV), the objective function. Multi -objective functions of proxy models over time-intervals for highly time impacted terminal branches, known as split design was applied to evaluate when to conduct a well sidetrack operation under risk and uncertainty in order to resolve severe non-linearity of the NPV solved by a standard optimization algorithm in a spreadsheet. The Predicted values of optimal sidetrack time by the developed workflow was relatively reasonable and highly satisfactory in comparison with simulation results and that of empirical and analytical models. Though, further performance improvement is possible, the constraint on computational time for multi-objective optimization must be weighed against the desired result. Monte Carlo implementation on EMV based on uncertainty of reservoir properties and varying POS acknowledges the fact that for favourable POS, that is values approaching 1.0, tR-OPT clustered at early production life with a spike and the later for unfavourable values.

Keywords: Experimental Design, multi-objective optimization, decision analysis, sidetrack, net-present-value.

I. INTRODUCTION

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This paper is the first in the series of dealing with the optimization of a well sidetrack using design of experiments and decision tree. Lerche & Mudford (2001) concluded in their analysis of optimizing sidetrack time that waiting till Zone B exhausted its production did not maximize Net Present Value (NPV). Hence the need to optimize the time to sidetrack into the upper Zone A. Ajibola et al. (2015) also attempted the use of proxy models but failed to get a perfect fit of the proxy model and Simulation model which caused the lack of optimization of sidetrack time. To carry out an efficient optimization study, there is the analysis of risk and uncertainty analysis. Uncertainty is usually analyzed by experimental design (ED or DOE), response surface, Monte Carlo simulation, multiple realization tree, Bayesian rule and a new method called integrated mismatch which incorporates the quality of history match to reserves prediction and then quantification of uncertainty. The methods are essentially statistical (Dejean & Blanc, 1999) and ED has proved to be a de facto tool.

Garb (1988) discussed and defined risks and uncertainties associated with reserves estimation and reservoir producibility, and grouped these into: technical, economic and political. ED offers the opportunity to study technical uncertainties by reducing the time consumed by fluid flow simulators (Jourdan & Zabalza-Mezghani, 2004; Prada & Cunha, 2008; Murtha et al., 2009). Field applications are focused on evaluation of sensitivity, candidate selection amongst projects, expressing views of risk and uncertainty, and explicit consideration of possible outcomes for decision making. Specific applications are SAGD performance (Prada & Cunha, 2008), enhanced oil recovery performance (Shook et al., 2014), value of smart wells (Esmaiel et al., 2005) and well-count optimization (Narahara et al. 2004) by either optimizing net present value (NPV) or cumulative oil produced. Detailed procedures for application of ED can be found in Dejean & Blanc (1999) and Prada & Cunha (2008). Use of ED comes along with inherent challenges of representing each computer simulation run as a physical experimental run (Egeland et al., 1992). Of importance is the lack of the resulting proxy model capturing the complexities of fluid flow in porous media and flow model under well and group controls (Murtha et al., 2009; Amorim & Moczydlower, 2007).

These leads to the next issue which may be the crux of the problem. That is the issue of non-linearity or curvature of the dependent variable. This is clearly stated and/or deduced from the works of Li et al. (2011), Yeten et al. (2005), Dejean & Blanc (1999) and de Amorim & Moczydlower (2007).

Increase in the data set is a solution for non-linearity (Lawal, 2009). This signifies increasing the level of factors in the experimental design that are culpable as identified. Other issues are handling of discrete independent variables (Li et al., 2011; Yeten et al., 2005) and non-conformity of proxy models due to mathematical and physical inconsistencies as noted by Lawal (2009). The main issue about curvature or non-linearity may be the production stoppage due to sidetrack into a new upper zone.

Genetic algorithm has gained wide application for non-linear optimization and likewise integrated with DOE in different forms in solving problems (Panjalizadeh et al., 2014; Ghassemzadeh & Charkhi, 2016; Naderi & Khamehehi, 2016; Artun et al., 2011). Despite this fact, this study goes on in adapting a standard optimization algorithm in a spreadsheet through multi-objective functions and proxy models over time-intervals in appropriately evaluating when to conduct a well sidetrack operation under risk and uncertainty. The adopted workflow is simple, robust and easily executed on a spreadsheet for optimization and uncertainty analysis.

Analysis of the technical risk involved in sidetrack operations as embedded in probability of success (POS) was previously investigated for primary recovery mechanism by Lerche & Mudford (2001). The objective was simply to compute time of sidetrack operation under risk based on NPV and production prediction based on analytical equations. Optimisation of expected monetary value, a product of NPV and probability was the objection function.

The problem was formulated as a decision analysis issue (Fig. 1) on the bases of ongoing production from Zone-B (Fig. 2) and subsequently sidetracking (recompletion) into Zone-A at a particular time that was optimally determined. POS of the sidetrack originates from the perceived success of continuous production of zone B (P_B), the zone initially under exploitation and that of successful sidetrack (P_A) leading to production from Zone-A. Challenges affecting sidetrack success are poor reservoir quality and pressure depletion of Zone-A due to a number of reasons (Ajibola et al., 2015), and poor quality of reservoir characterisation. In addition to these are technical failures from the drilling operation. These may not lead to the outright failure of production but significantly reduced or low production that is not commercial due to inexpensive well intervention and operational cost.

The NPV of each branch of the decision tree shall be evaluated in this study by proxy models with uncertainties of reservoir rock property of Zone-A as an input into the EMV. Optimisation of the objection function, EMV, shall be used to obtain the risked sidetrack/recompletion at different combinations of the uncertainties of POS. As stated before, prior study by Ajibola et al. (2015) highlighted the incapability of the proxy model to capture non-linearity/curvature. This issue shall be fully addressed in this study. Though, analytical prediction models do not show this trend, but there are limits to the replication of reservoir performance hence the need for resolving the use of ED to quantify the risk of sidetrack/recompletion time.

I. Numerical Simulation Model of the Synthetic Oilfield

The model considered for this study is for a primary recovery under water drive mechanism as the main drive. A single well consisting of parent bore is perforated in a zone (layer), and a secondary (sidetrack leg) open to flow at another zone and specific time.

2.1 Model for Primary Recovery under Water Drive Mechanism for the two layers.

The model is a modification of the SPE-1 comparative solution (Odeh, 1981) but suited for oil-water two-phase flow and aquifer support instead of gas injection and oil-gas two-phase flow. Structure, rock and fluid properties and other are given in Tables 1 and 2, while relative permeability curves are presented in Fig. 3. Layer 1 (L1) is termed as Zone-A and Layer 3 (L3), Zone-B. Layer 2 is essential a shale break with Net-to-Gross of 0. Rock properties for Zone-A are uncertain with respect to porosity, permeability, thickness and initial reservoir pressure.

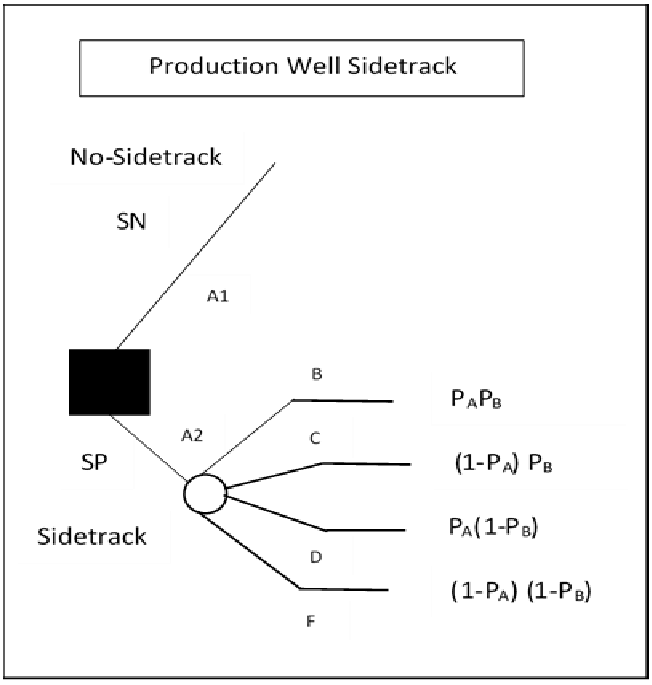


Figure 1: Decision tree diagram for production well sidetrack/recompletion (primary recovery mechanism) Lerche & Mudford (2001).

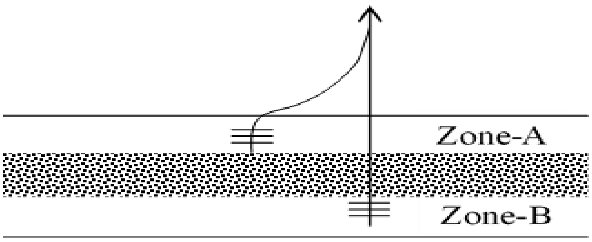


Figure 2 Well configuration for primary recovery mechanism

These are further discussed under experimental design setup in the next section. Maximum oil production and water-cut for control are 3000stb/d and 0.85 for production from Zone-A and 20000stb/d and 0.85 for Zone-B.

Production well is located at the centre of the reservoir block system and perforated at Zone-A and Zone-B respectively.

Table 1 Structure and reservoir rock and fluid properties

Dimension	20*20*3		
Reservoir Tops	8400ft		
Grid Size	Δx=500 ft	Δy=500 ft	
	Δz: Layer 1 20 - 40 ft	Δz: Layer 2 10ft	Δz: Layer 3 50ft
Porosity	Layer 1: 0.11 - 0.19	Layer 2: 0.05	Layer 3: 0.21
Permeability	Layer 1: 50 to 100mD	Layer 1: 50 to 100mD	Layer 1: 50 to 100mD
Rock Compressibility	1.106E-06 psi^{-1}		
Density (lb$_m$/ft^3)	Oil: 46.24	Water: 62.43	Gas: 0.0044
Initial Pressure	Layer 1: 3700 – 5900 Psi @ 8400ft	Layer 3: 4800Psi @ 8400ft	
Aquifer Size and Compressibility	Layer 1: 2.0E + 09 ft^3, 1.0E -05Psi^{-1}	Layer 3: 7.0E+09 ft^3, 1.0E-05 psi^{-1}	
Aquifer PI	Layer 1: 300 Psi/stb/d	Layer 3: 500 Psi/stb/d	
Aquifer Connection	x-face		

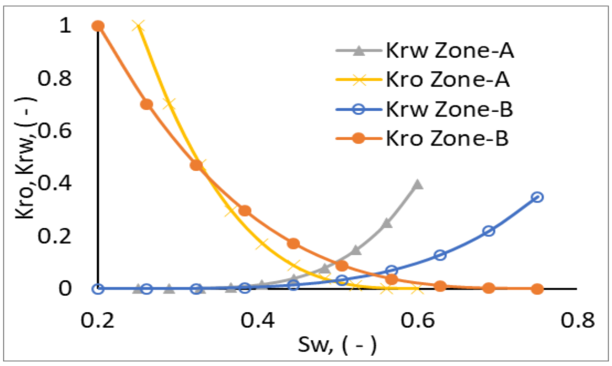


Figure 3 Relative permeability of Zone-A and Zone-B

II. OPTIMAL SIDETRACK TIME FROM OBJECTIVE FUNCTION

The objective function for this study is developed in this section. It entails the set-up of decision tree and corresponding expected monetary value for each case, generalized NPV model, ED and the objective function build-up. Finally, uncertainty analysis of optimal time by Monte Carlo simulation.

A. Decision Analysis Setup

The expected monetary value (EMV) for the recovery of sidetrack/recompletion for the production well (Fig. 1) is:

$$\begin{aligned} EMV_{sidetrack} &= E(Stk) \\ &= B \cdot P_{A,S}P_{B,S} + C(1-P_{A,S})P_{B,S} + D \cdot P_{A,S}(1-P_{B,S}) \\ &+ F(1-P_{A,S})(1-P_{B,S}) \end{aligned} \quad (1)$$

where B, C, D and F stands for the NPV of the terminal branches and $P_{A,S}$ and $P_{B,S}$ are the POS for production and sidetrack for Zone-A and Zone-B respectively.

B. NPV

The economic value of the field is evaluated by the equation:

$$NPV = \sum_{L=1}^{m}\sum_{t=1}^{n}(1+i)^{-t}\left(P_o q_{t,L} - C_{t,L} - I_{t,L}^{F} - I_{t,L}^{V}\right) \quad (2)$$

where m is number of layers; n, production years; L, layer number; t, time; i, discount rate; P_o, oil price; q, production rate; C, capital expenditure; I, operating expenditure *(F & V)* based on production F, fixed and V, variable.

Production from both layers are commingled and thus evaluated as a unit. Oil price, discount rate, capital expenditure and fixed operating cost are fixed. While variable operating cost depends on quantity of fluid produced and injected. Oil production from both layers is dependent on simulated rate obtained from a Black Oil simulator based on a synthetic oilfield.

The values for the economic parameters include; discount rate of 12.75%/year or 1.005%/month, oil price of $75/bbl, fixed operating expenditure of 0.25% while capital expenditure and variable operating expenditure is fixed at $5/bbl for production. Meanwhile, well drilling and completion for the production well are $16MM and $5MM for the main-bore and $8MM and $3.75MM for the sidetrack. This aligns with cost in the Niger Delta.

C. Experimental Design and Uncertainty Analysis Parameters

The uncertain parameters chosen for this study are porosity, permeability, reservoir pressure and thickness of layer for Zone-A in conjunction to these is sidetrack time. Exploitation of Zone-B is ongoing with the assumption of the zone already appraised and having high quality and quantity of data available due to the status of the well. Parameters given above are related to uncertainty associated with reserves estimate, reservoir quality, connectivity or depleted status as regards to pressure and appropriate time to schedule sidetrack with probable technical uncertainties.

These parameters are commonly applied for response surface modelling of reservoir performance as seen in Li et al. (2001), Yeten et al. (2005), Murtha et al. (2009), Narahara et al. (2004), Dejean & Blanc (1999), Prada & Cunha (2008), Esmaiel et al. (2005) and Amorim & Moczydlower (2007).

The standard procedure picks a number of likely parameters that would affect the objective of the study and screen the parameters prior to selecting those that are the so-called heavy-hitters for detailed analysis using response surface tools. Considering the issue of non-linearity reported and/or observed in previous studies, the tools considered in this study includes 3-level designs of Box-Behnken, Central Composite, D-Optimal and Taguchi.

Repetition of experiment was avoided since each run is repeatable with the exact same result. After careful consideration of these tools the focus to study non-linearity due to sidetrack-time as an independent parameter called for the use of central composite design and altering the point under investigation.

As well as carrying-out multiple designs with fixed range of uncertainty of permeability, porosity, pressure and layer-thickness with varying range of time intervals under consideration. However, this shall be achieved by studying the main effects plot to distinguish curvature and region of interest under similar trend for this purpose.

ED and response surface model shall be constructed for each branch of the decision tree. A dynamic reservoir model will be built for each terminal branch based on the combination of POS of Zone-A and Zone-B. This will be followed by a number of runs for each model with respect to the number of experimental runs generated by a commercial statistical tool which is subject to the ED or RSM design, number of factors and level.

D. Optimization Function

Objective function for optimization to obtain the optimal sidetrack time is based on equations (1) and (2) respectively. Where B, C, D and F stands for the NPV of the terminal branches. NPV is a proxy model. The proxy model is dependent on the number of experimental runs where the dynamic reservoir model outputs the independent parameters listed in Eq. (2). However, NPV of terminal branches "C" and "F" are specifically dependent on sidetrack time since no production from Zone-A and the uncertainties considered are only parameters of Zone-A. Hence a regression model is used to fit the response without the need for multiple experimental runs. A semblance of the optimization function is presented in Eq. (3), (4), (5) and (6) which represents the proxy and regressed models of NPV for terminal branches "B", "C", "D" and "F". On substituting these into Eq. (1), Eq. (7) is obtained.

$$B = \beta_0^B + \beta_1^B \phi + \beta_2^B h + \beta_3^B k + \beta_4^B t + \beta_5^B P + \cdots \tag{3}$$

$$C = \beta_0^C + \beta_1^C t + \beta_2^C t^2 + \beta_3^C t^3 + \cdots \tag{4}$$

$$D = \beta_0^D + \beta_1^D \phi + \beta_2^D h + \beta_3^D k + \beta_4^D t + \beta_5^D P + \cdots \tag{5}$$

$$F = \beta_0^F + \beta_1^F t + \beta_2^F t^2 + \beta_3^F t^3 + \cdots \tag{6}$$

$$\begin{aligned} E(Stk) = {} & (\beta_0^B + \beta_1^B \phi + \beta_2^B h + \beta_3^B k + \beta_4^B t + \beta_5^B P + \cdots) \cdot P_{A,S} P_{B,S} \\ & + (C\beta_0^C + \beta_1^C t + \beta_2^C t^2 + \beta_3^C t^3 + \cdots)(1 - P_{A,S}) P_{B,S} \\ & + (\beta_0^D + \beta_1^D \phi + \beta_2^D h + \beta_3^D k + \beta_4^D t + \beta_5^D P + \cdots) \cdot P_{A,S}(1 - P_{B,S}) \\ & + (\beta_0^F + \beta_1^F t + \beta_2^F t^2 + \beta_3^F t^3 + \cdots)(1 - P_{A,S})(1 - P_{B,S}) \end{aligned} \tag{7}$$

Eq. (7) is a representation of the objection function, subject to a time interval to give the optimal sidetrack time. The maximum EMV {E(Stk)} gives the time. While Eq. (8) is an ideal situation, Eq. (9) is suitable for cases of non-linearity of each proxy model that may be necessitated by the impact of time and production stoppage from the main productive zone as enumerated/stated earlier in the introductory section. So, Eq. (9) is for a case of different proxy model for each of the time intervals considered. Thereby translating to more experimental runs that would be conducted, but, with fairly reasonably accuracy of evaluating the optimal sidetrack-time as a reservoir management tool. These approach results in a simple multiple non-linear objective function optimization scheme. This is a robust procedure since the value of the functions at the time bounds are fairly similar.

$$\begin{aligned} t_{opt} = \max_{0 \le t \le t_n} \big[& (\beta_0^B + \beta_1^B \phi + \beta_2^B h + \beta_3^B k + \beta_4^B t + \beta_5^B P + \cdots) \cdot P_{A,S} P_{B,S} \\ & + (C\beta_0^C + \beta_1^C t + \beta_2^C t^2 + \beta_3^C t^3 + \cdots)(1 - P_{A,S}) P_{B,S} \\ & + (\beta_0^D + \beta_1^D \phi + \beta_2^D h + \beta_3^D k + \beta_4^D t + \beta_5^D P + \cdots) \cdot P_{A,S}(1 - P_{B,S}) \\ & + (\beta_0^F + \beta_1^F t + \beta_2^F t^2 + \beta_3^F t^3 + \cdots)(1 - P_{A,S})(1 - P_{B,S}) \big] \end{aligned} \tag{8}$$

$$t_{opt} = max \begin{cases} 0 \le t \le t_1 : [E(Stk)] \\ t_1 \le t \le t_2 : [E(Stk)] \\ t_2 \le t \le t_3 : [E(Stk)] \end{cases} \tag{9}$$

E. Monte Carlo Simulation

Optimal time computed by either Eq. (8) or (9) is for an instance of the uncertain parameters. Uncertainty analysis is carried out by Monte Carlo simulation with multiple runs based on uniform distribution of each parameter. Maximum number of runs is controlled by the stability of the mean NPV as computed from the proxy model.

III. RESULTS

The performance of the presented workflow of the primary recovery case with active edge are highlighted. This includes analysis of the proxy model by split design, application to optimal time computation based on the multi-objective function and uncertainty analysis of sidetrack time by Monte Carlo simulation. Results are hereby given.

A. ED and Proxy Model

Terminal branches "B", "C", "D" and "F" of Fig 1 for sidetrack through the production well are considered for the application of ED and presentation of NPV proxy models subject to uncertain parameters.

(i) Branch "B"

Table 2: Minimum, mid-point and Maximum points for ED

Factor	Minimum	Base	Maximum
Porosity	0.11	0.15	0.19
Permeability	50 md	75 md	100 md
Layer-thickness	20 ft	30 ft	40 ft
Reservoir Pressure	3700 Psi	4800 Psi	5900 Psi
Time	0yrs	8yrs	16yrs

Box-Behnken design is applied and 5 factors of 46 experimental runs were considered, namely; permeability, porosity, pressure, time and layer-thickness (see Table 2 above). Pressure was rather insignificant based on p-value greater than 0.05. Squared and interactive terms were likewise removed based on this. The resulting quadratic equation is Eq. (10).

$$NPV_B = 1091.3 + 453.9\phi + 0.867k + 4.546h + 11.75t + 0.3549t^2 - 26.59\phi t + 0.0235kh - 0.1000kt - 0.4020ht \quad (10)$$

where R-sq, R-sq(adj) and R-sq(pred) are given as 0.9820, 0.9775 and 0.9515 respectively. Residual analysis gave a normal plot, not observable trend and fairly straight-line trend. The main effect plot (Fig. 4) speaks volume of the impact of the factors and the non-linearity influence of time which is not severe.

The proxy model was validated by input of values for the factors within the upper and lower values of the ED. Values used for layer-thickness, permeability and porosity are 25 ft, 60 md and 0.16 respectively. Whereas the values of time are from 0 to 16 years with an interval of 2 years. Result of the test is presented in (Fig. 5) with a regression coefficient of 0.9351.

(ii) Branch “C”

No production from Zone-A, hence, the only independent parameter is time. Simulation runs were conducted for sidetrack at 0 to 16 years with an increment of 2 years making 8 runs. The regressed model is;

$$NPV_C = 1289.9 + 0.9885t - 0.0297t^2 \quad (11)$$

where R-sq is 0.9982.

(iii) Branch “D”

The same design as in Branch-B, but different random seed was applied. Eq. (12) is the proxy model and the main effect plot is as seen in Fig. 6. Time is observed to have a non-linear effect on the dependent variable and has the most impact on it. This is also obvious from the F-value from the ANOVA and the fact that the interaction parameter “k•h” has a p-value of 0.061 which is higher than 0.05 but was left as a significant parameter due to the known influence of the term on productivity.

$$NPV_D = -228.6 + 493.7\phi + 0.798k + 4.306h + 226.21t - 7.8819t^2 - 30.84\phi t + 0.0244kh - 0.0970kt - 0.3896ht \quad (12)$$

where R-sq, R-sq(adj) and R-sq(pred) are 0.9998, 0.9998 and 0.9996 respectively.

Non-linearity effect thus necessitates the application of Central Composite and D-Optimal design. The latter design was expanded to include 4-levels for time. Results obtained was likewise poor and the proxy models constitute only time as the only significant factor and so rendered not suitable for use.

Next, time as a factor was split into two segments to reduce the impact of non-linearity as in the reduction of interval for solving partial-differential-equations with finite-difference scheme. The problem is split into two Box-Behnken designs of time 0→□8 years and 8→□16 years and 4 factors (pressure removed) having 27 runs each. Choice of split is qualitative and based on the main effect plot.

NPV proxy model for split Box-Behnken design is presented by Eq. (13a-c). Main effect plots (Fig. 7a-b) shows the reduction of the non-linearity effect / curvature based on time and the pronounced influence of other factors for time interval 8→16 years. An attempt to combine the designs into 54 (27 + 27) experimental runs for regression analysis resulted in a model of only time as the significant factor and non-normal residual plot.

$$NPV_D = \begin{cases} 0 \le t \le 8: NPV_{D_{0-8}} \\ 8 \le t \le 16: NPV_{D_{8-16}} \end{cases} \quad (13a)$$

$$NPV_{D_{0-8}} = -162.1 + 1.63h + 0.433k + 86\phi + 337.68t - 20.554t^2 + 0.0399hk + 15.11h\phi - 0.5684ht - 0.1302kt - 47.2\phi t \quad (13b)$$

where R-sq, R-sq(adj) and R-sq(pred) are 0.9999, 0.9998 and 0.9997 respectively.

$$NPV_{D_{8-16}} = 702.4 + 2.659h + 1.069k + 177\phi + 59.26t - 0.00259k^2 - 1.3724t^2 + 0.01091hk + 5.78h\phi - 0.2175ht - 0.0498kt - 18.08\phi t \quad (13c)$$

where R-sq, R-sq (adj) and R-sq (pred) are 0.9984, 0.9972 and 0.9934 respectively.

On validation of the of proxy model for the 46 runs Box-Behnken (NPV-BB) design and split designs (NPV-BB T0-8 and NPV-BB T8-16), the latter is favourable with regression coefficient of 0.7246 and 0.998039 respectively as also observed in Fig. 8. Fig. 9 is a Box-Whisker plot of 21 cases of simulation result of NPV based on data given in Table 6. This clearly shows the need for the split design as accuracy of the proxy model required for different segment of time should be different and tailored as such to fit this observed trend. Time influence in other words diminishes and hence justifies the split model scenario as applied.

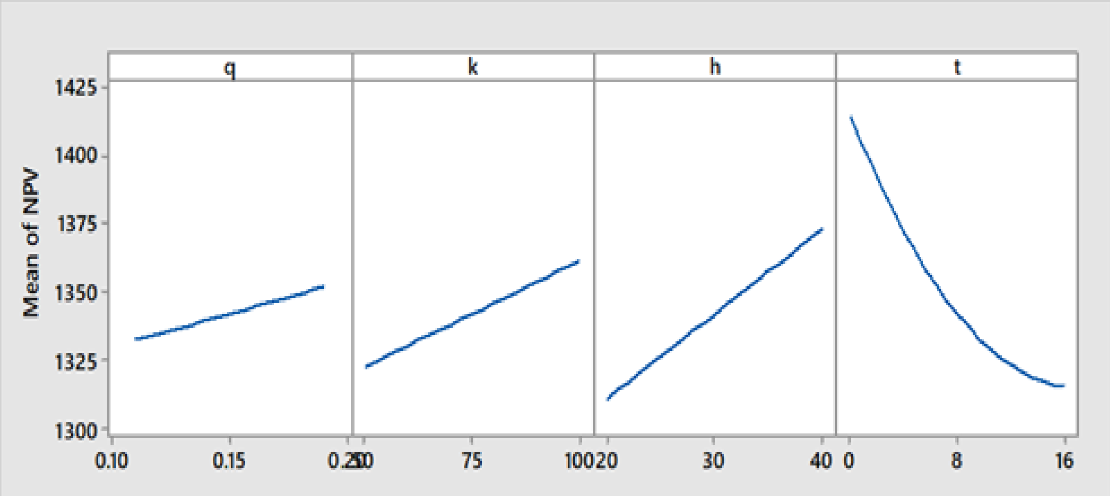


Fig. 4: Main effect plot – Branch “B”

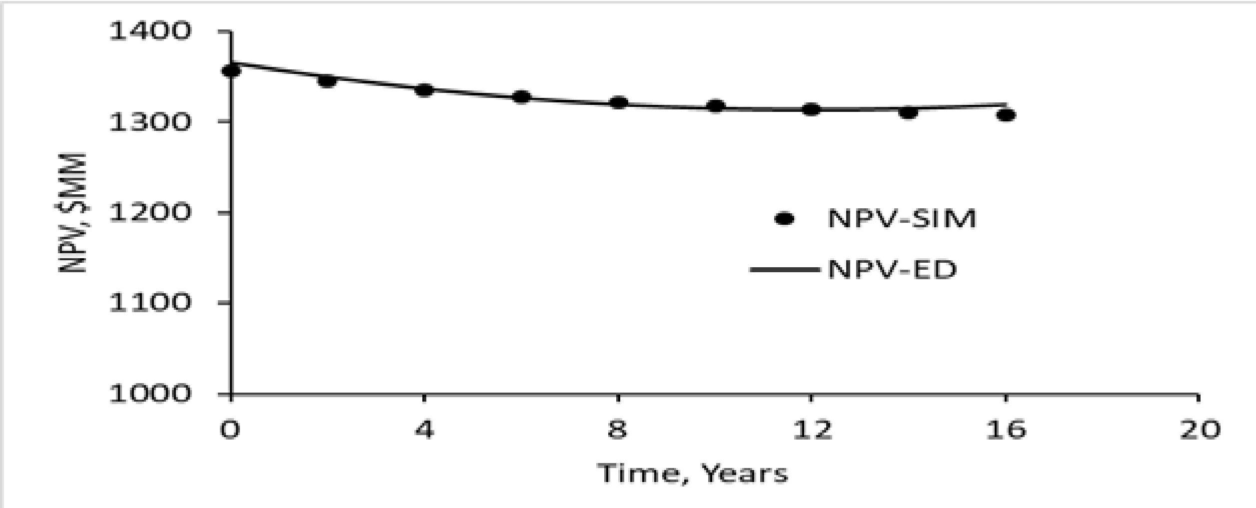


Fig. 5: Proxy model validation – Branch “B”

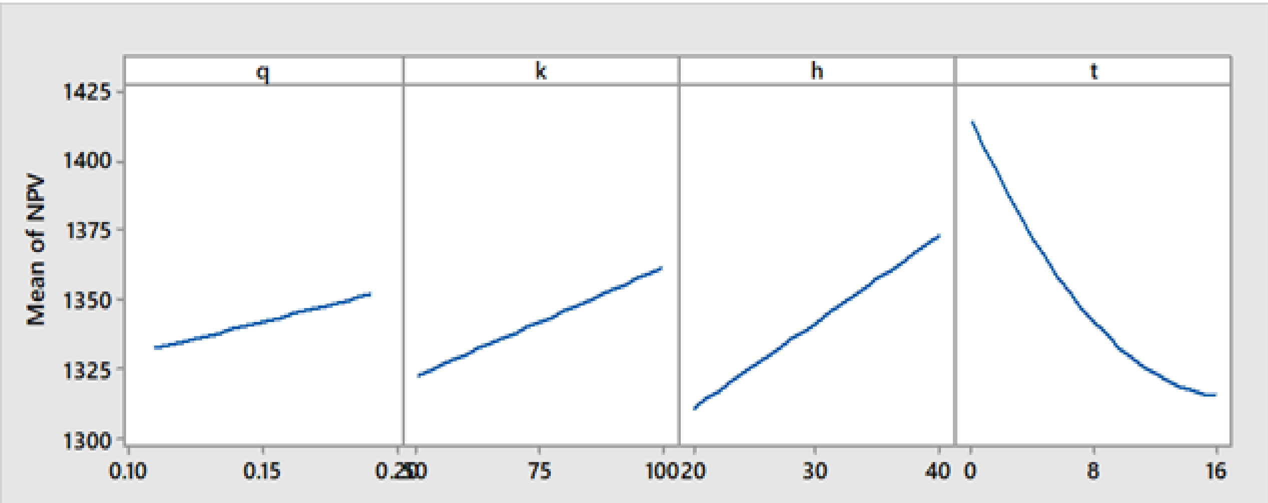


Fig.6: Main effect plot – Branch “D”

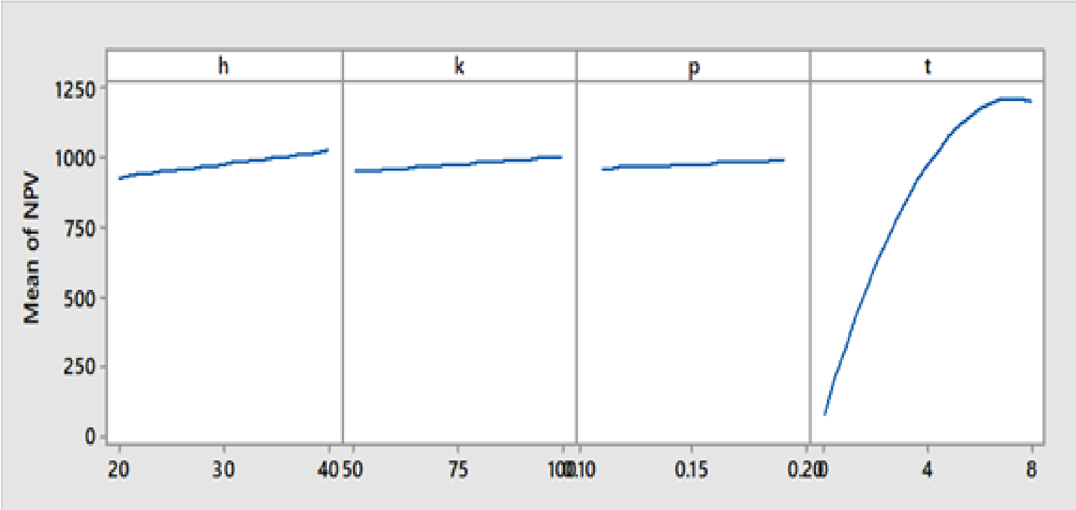


Fig. 7a: Main effect plot – Branch “D”, Time 0→□8 years

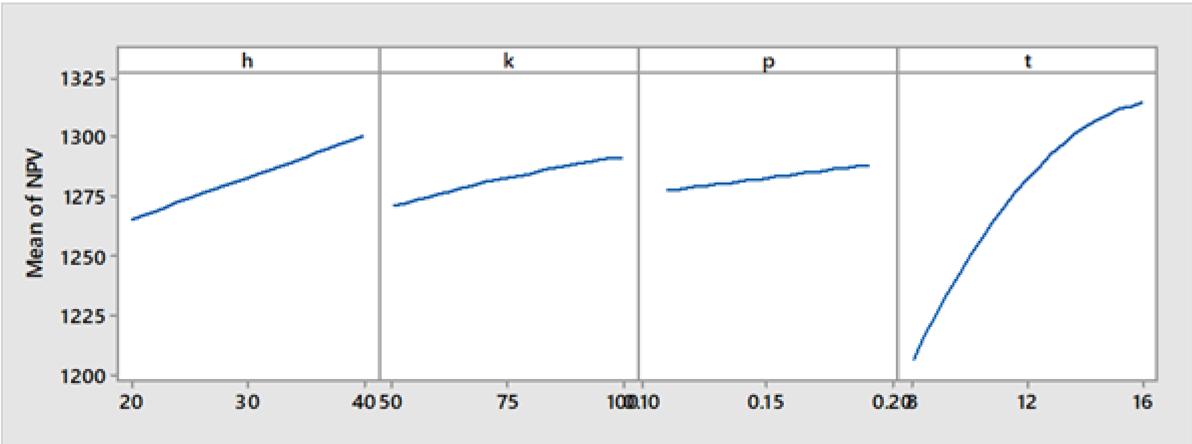


Fig. 7b: Main effect plot – Branch “D”, Time 8→□16 years

Table 6: Validation runs

Test	Layer-thickness, ft	Permeability, md	Porosity	Test	Layer-thickness, ft	Permeability, md	Porosity
1.	25	60	0.16	12.	37	75	0.15
2.	20	40	0.12	13.	26	93	0.11
3.	35	80	0.15	14.	38	62	0.11
4.	38	70	0.17	15.	22	54	0.16
5.	27	55	0.18	16.	22	59	0.11
6.	39	65	0.14	17.	33	54	0.11
7.	29	47	0.13	18.	21	97	0.18
8.	23	85	0.11	19.	35	98	0.16
9.	32	77	0.19	20.	38	95	0.16
10.	30	65	0.15	21.	21	80	0.12
11.	31	90	0.19				

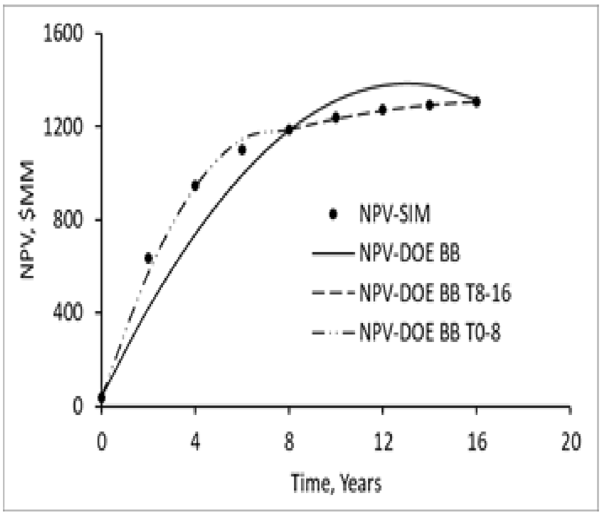


Figure 8: Proxy model validation – Branch-D

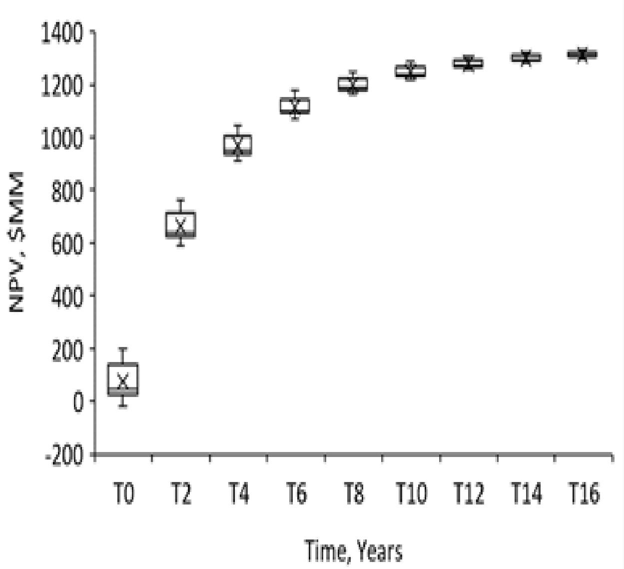


Figure 9: Box-Whisker plot of 21 runs for Branch-D based on simulation result

(iv) Branch "F"

Time is the only independent parameter since no production from Zone-A for this particular terminal branch. 8 simulations were conducted for the 0, 2, 4, 6, 8, 10, 12, 14 and 16 years. The regressed model is;

$$NPV_F = -29.196 + 406.38t - 60.547t^2 + 5.0384t^3 - 0.2186t^4 + 0.0038t^5 \quad (14)$$

where R-sq is 1.0.

B. Optimal Sidetrack/Recompletion Time

Presented in (Fig. 10) is a combined plot of the models for the terminal branches that make up the production well sidetrack for primary recovery. This was further applied in computing EMV (Fig. 11) and the resulting optimal time plot in Fig. 12. The match was perfect; however, the focal points of the optimal time was 0 and 16th year. Reason for the trend is the relatively low recoverable oil from Zone-A in comparison to Zone-B. Significant and considerable recovery from Zone-A would have tilted the status of optimal-time with respect to POS.

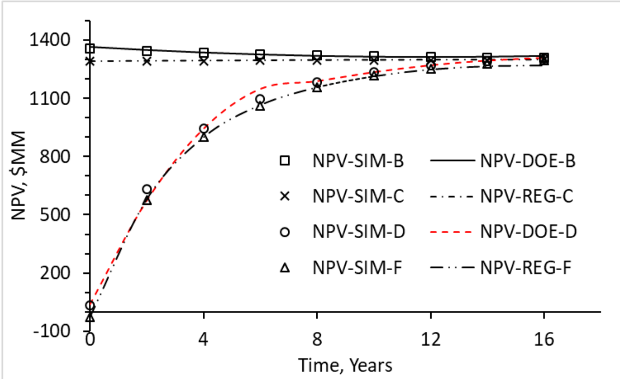


Fig. 10: NPV plot for comparison of simulation results and proxy and regression models of all terminal branches

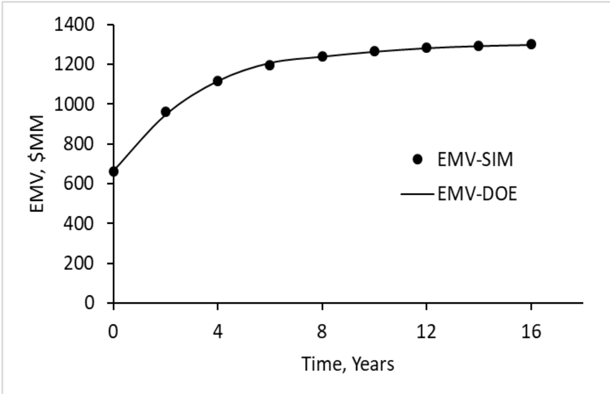
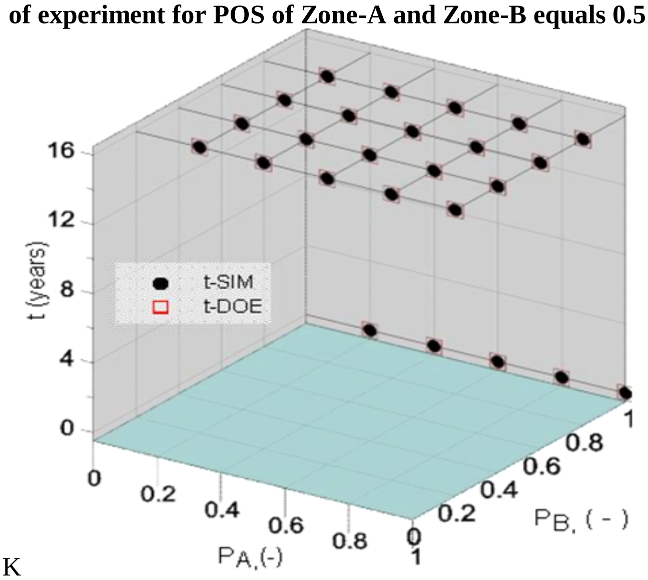


Fig. 11: EMV plot of comparison of simulation and design of experiment for POS of Zone-A and Zone-B equals 0.5



K

Fig. 12: Optimal Sidetrack-time plot of comparison of simulation and design of experiment for various combination of POS for Zone-A and Zone-B

C. Split Design Performance

Proxy models presented so far in this study may be termed dynamic proxy models with the inclusion of time to directly estimate NPV and also the EMV at a particular sidetrack time in accounting for uncertainties. The multiple objective function has been appropriately applied by using the split design to solve the issue of non-linearity effect caused by the strong impact of time for some terminal branches of the decision tree model as seen in main effect plots of the ED process.

Though a successful approach was developed, split design into judiciously selected time intervals as considered brings about increasing optimization run time as a result of the handling of the multi-objective function that was created. Accuracy achieved can be extend by increasing the intervals but to the detriment of run time. A compromise can be attained in respect to the fact that proxy models significantly reduces evaluation of uncertainties.

IV. CONCLUSION

When to conducted a sidetrack operation under uncertainty was successfully established, the severity of the non-linear effect due to time, an independent parameter, was reduced by setting-up experimental design over identified time-intervals referred to as split-design. The impact of probability of success (POS) on optimal sidetrack time is far reaching. Shrouded in this term are technical risk and geological uncertainties. As expected, favourable POS means early sidetrack time and unfavourable denotes late consideration for the operation. This, further adds to the credibility of the EMV as a tool apart from the validation step.

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