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Application of Artificial Intelligence for Run-time Well Placement Optimization in Reservoir Simulation

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ABSTRACT

To maximize recovery while minimizing investment costs, performing a sidetrack of existing wells instead of drilling new wells is sometimes necesary. Drilling a sidetrack rather than a new well can significantly reduce drilling costs because the main well has already been drilled. In this study, we discuss the application of artificial intelligence to determine optimum sidetrack locations and directions in numerical simulation and an extension of the methodology for automatic well-placement optimization in simulation run-time.

The artificial intelligence (AI) algorithm considered in this work creates central surveillance vertical wells that penetrate from the top to the bottom of a reservoir model and coincide with the topmost perforation of each simulated historic well. It then creates four cardinal surveillance vertical wells, each at the north, south, east, and west of the central surveillance wells at a distance of ***x***-grid blocks. When the water cut of a historic simulation well reaches a user-defined target, the AI algorithm receives the water saturation (s_w) versus depth log for the historic simulated well and its associated surveillance wells from the simulator. The AI algorithm then uses user-defined parameters to identify reservoir sweet spots defined as porosity*$\log_{10}$(permeability)*thickness*(1-s_w), which is then used to determine the optimal depth and direction of the optimum sidetrack well. The sidetrack well is created automatically in the simulation and replaces the historic well during run-time.

Automating the process of sweet spot identification and creation of perforation resulted in a 95% reduction in engineers' time required to implement optimum sidetrack wells in the numerical simulation. In addition, because the sidetrack or infill wells are targeted at sweet spots, this methodology allows field development that explicitly incorporates water production management objectives. The simulator automatically shuts-in high water producers and replaces them with sidetracks or infill wells intelligently targeted at sweet spots to maintain field production while limiting water production.

It is common practice to use pulsed-neutron logs (PNLs) to detect unswept reservoir zone(s) to be targeted with sidetrack wells. PNLs help to detect the zone, but cannot determine the direction. The present work complements PNL in determining the optimal direction to drill a sidetrack. The AI algorithm also provides an economic evaluation of all the sidetrack wells created in the course of a simulation run to provide information to decide which are the best candidates to maximize return on investment. To the best of our knowledge, this work is the first to consider the application of run-time well placement optimization in numerical reservoir simulation.

EXTENDED ABSTRACT

Introduction

After a history-matching exercise, the resulting model is used for performance forecasting using historic wells (this is termed a *No-Further-Action* forecast scenario) and other scenarios involving infill wells. During forecast runs, an engineer uses a completed simulation run to identify the locations of unswept or bypassed oil. New wells are then included in subsequent simulation runs to target these locations. These new wells can be *infill wells* drilled at new locations or *sidetrack wells* drilled from existing wells.

The usual industry approach used to determine and define a sidetrack well location requires the application of multiple software frameworks and processes. First, a base case prediction simulation is made with e.g., Eclipse. Then, the time step results are loaded into a 3D viewer, such as Floviz or Petrel. A cross-section of the grid was created along the target historic well. Next, a diagnostic map such as net-oil-thickness (HuPhiSo) is created at the date of the intended sidetrack well.

Variants of the diagnostic map are the mobile net-oil-thickness map [HuPhi (s_o-s_{or})] and *sweet_spot* map (HuKPhiSo). The diagnostic map used in the present study shows the sweet spots. Identified sweet spot along a historic well is targeted by a sidetrack well. As illustrated in **Fig. 1**, after some years of production, well P1 was producing with 90% water-cut. The cross section of the calculated sweet_spot at the date when the water-cut reached 90% was made using Petrel (or any other 3D visualization application), and it was observed that the lower section of the well was watered-out and a sidetrack well could be used to target the upper zone. One could argue in this illustration that a water shut-off in the lower zone and reperforation in the upper zone is a possibility. This is correct, but in this case, the well-reservoir contact of the resulting perforation interval could be too short to provide the required productivity. By drilling a horizontal sidetrack, the horizontal well could be drilled such that it would provide the required well-reservoir contact, as shown by well STRK_P1 in Fig. 1(b).

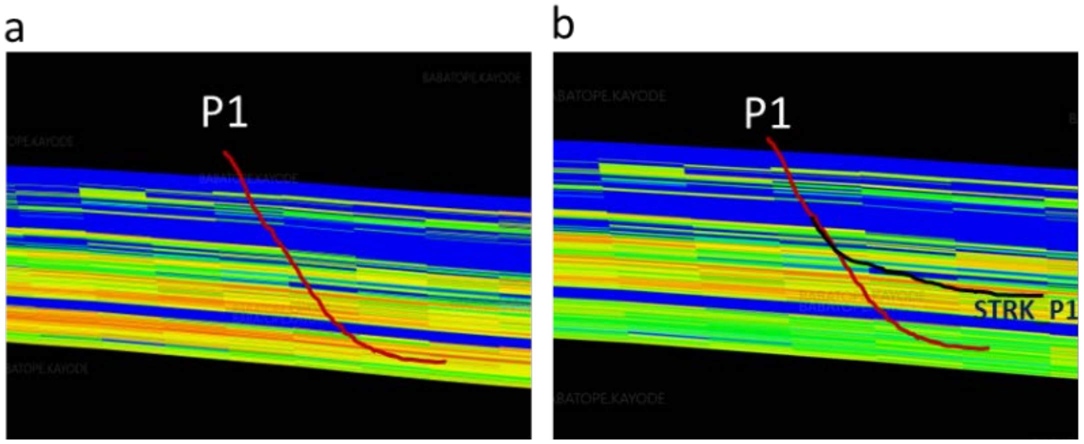

Figure 1: Sweet spot cross-section at a location of Well P1 (a) at the start of the simulation, and (b) at timestep when P1 produced at water-cut of 90%, showing the proposed location of sidetrack well STRK_P1. This cross-section is from a hypothetical model.

Therefore, planning a sidetrack well in a simulation usually requires finding the date at which a historic well reaches the trigger condition (e.g water-cut > 0.9) as well as a post-processor such as Petrel to create a cross-section visualization in various directions. The engineer would then have to make a decision on the zone and direction for a sidetrack well, design the well, export the perforation file for the sidetrack in the simulator's format, and include the exported file as input data for a new simulation run. Next, the well event file must be edited to shut-in the historic well and open its sidetrack at the proper timestep.

In large reservoirs containing several hundreds of wells, the processes described above could take several weeks to complete. In such reservoirs, incorporating all these processes into a numerical simulator is beneficial. Instead of manually designing wells to harness bypassed oil, the numerical simulator performs this by itself during the simulation run.

Autonomously determining the location and direction of a sidetrack with a numerical reservoir simulator involves a few key challenges.

First, the simulator must be able to observe what is happening from the top to the bottom of the reservoir around each historic simulation well. Although historic wells in a reservoir may penetrate from the top to the bottom of the reservoir, such wells may not be perforated across their entire reservoir contact. In reservoir simulations, a well is known only by its well-grid connections. Although numerical simulators calculate the properties for all grids at each time step, well-log plots show only the properties of the well-grid connections. The grid properties at other sections of the well where it has no connection to the grid cannot be monitored by a simulation effectively, and these unmonitored sections could potentially contain the unswept oil being sought.

In **Fig. 2**, the historic well Prod-18 penetrates the top and middle reservoir zones but is only perforated in the middle zone. The inset plot in Fig. 2 (right) shows Prod-18's water-saturation log at different simulation time-steps. It may be observed that the well-log result only covers the middle reservoir zone, where the well has connections to the grid. The well could not monitor the water saturation around itself in the upper and lower reservoir zones. A similar behavior may be observed for the well P1.

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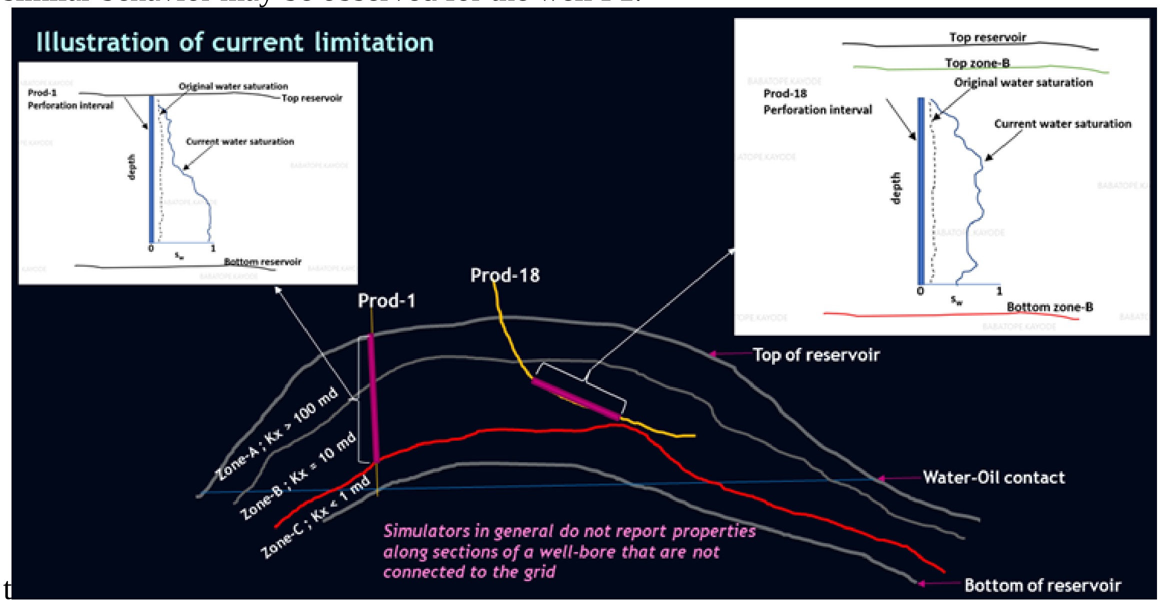

Figure 2: Illustration of a challenge with commercial simulators regarding monitoring grid properties in the vicinity of the simulation wells.

Second, the simulator must be able to determine the direction in which sidetrack well performance would be optimal. Identifying un-swept oil in the vicinity of historic simulation wells with the simulator does not suffice; it is also important to know if this un-swept oil seen at the historic well is laterally continuous. The lateral continuity of the sweet spot forms the basis for selecting the optimal sidetrack well direction.

Third, some wells may have sidetrack opportunities in multiple zones, and the simulator must be able to screen and determine the optimum zone to locate the sidetrack well.

Traditional simulator technology allows for the replacement of watered-out wells with new wells, but these new wells must be pre-defined in the simulation run and are simply activated when needed. An example is the use of the Eclipse QDRILL keyword to activate the well(s) from a prior queue of wells defined in the simulation. The limitation of this approach is that one cannot always know in advance where the unswept oil would be, and thus the locations of the predefined wells may not be the optimum at the time of activation.

It is also noted that commercial simulators (e.g., Eclipse) permit the management of water production through workover options, such as CON (shut-in worst-offending connection) and CON+ (shut-in worst-offending connection and all connections below it). This simulated water management approach provides numerically reasonable results, but the processes clearly cannot be implemented in field operations.

In this study, we consider a hypothetical model to describe the proposed methodology. First, the application of the methodology for sidetrack well placement is discussed. Owing to space limitations, the extension of the methodology for automatic placement of infill wells in a green or brown field is not discussed in this extended abstract. The author can be reached at babkay2000@yahoo.co.uk for the full manuscript.

Methodology

The user inputs a keyword into the simulator that triggers the performance of the automatic sidetrack action. The user also specifies the well performance criteria at which sidetracking should be triggered, for example, a well water cut greater than 90%.

Once a simulation run is launched and the simulator encounters the sidetrack trigger keyword, for every historic simulation well, five observation wells are automatically created at the run initialization stage. The locations of the observation wells associated with each historic well are stored by the simulator, which would be then used to monitor the reservoir properties in the vicinity of each historic simulation well. The configuration and characteristics of these observational wells are briefly discussed below.

One *central observation well* is defined as a vertical well perforated from the top to the bottom of the reservoir and intersecting the top perforation of the historic simulation well as shown in **Fig. 3** for the slanted well Prod-18.

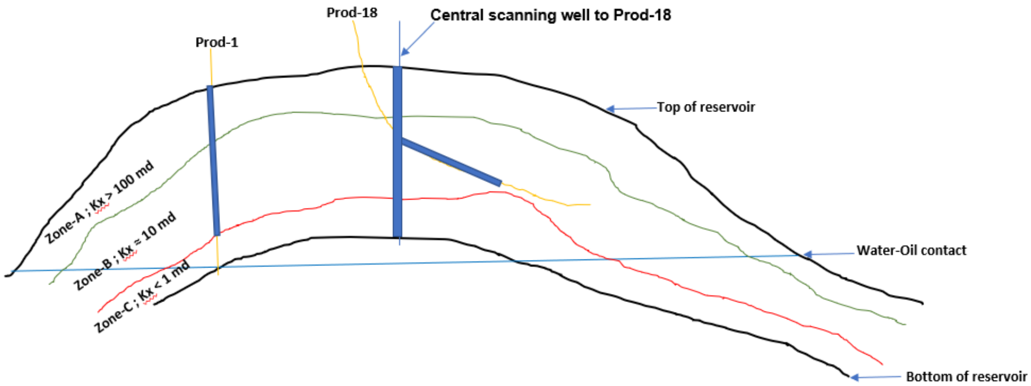

Figure 3: Illustration of the definition of central observation (scanning) well of historic simulation well Prod-18

Four *cardinal observation wells* are defined as vertical wells located in the four cardinal directions north, south, east and west of the *central observation well*, at a distance **x**, defined as the number of grid blocks equivalent to the expected length of a horizontal sidetrack well and input by the user. For example, if horizontal sidetrack wells are expected to be 500m long, the simulation grid block sizes is 100m*100m. Then, each cardinal observation well would be located at a distance of five grid blocks away from the central observation well, as shown in **Fig. 4.**

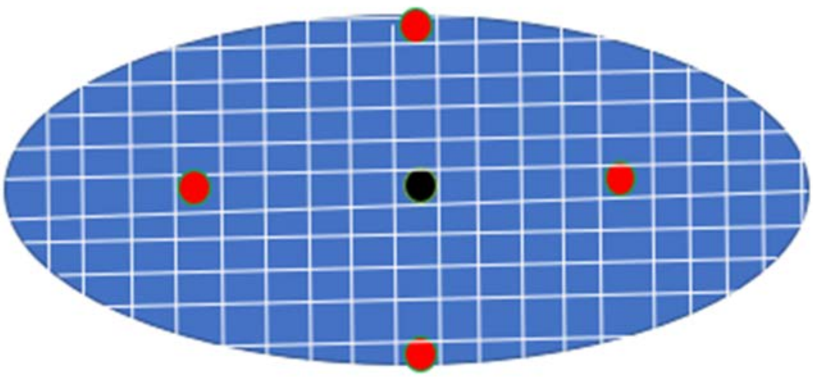

Figure 4: Top view illustration of the central and cardinal observation wells whose locations are created in memory for each historic simulation well

A total of *5n* vertical observation well locations are stored in memory at initialization, where n is the number of historic simulation wells. In the current discussion, the term historic simulation wells refers to all the producing simulation wells.

At each simulation timestep, the simulator checks for any historic simulation well that meets the sidetrack trigger criteria (in this case, well water cut > 0.9). For any well that meets the sidetrack criteria at a given timestep, the simulator extracts the water saturation logs of the historic well and its five associated observation wells, as illustrated in **Fig. 5a**. Figure 5a is a plot of water saturation versus the k-index of the simulation model for the five observation wells associated with a historic simulation well at the time-step its water-cut reaches 90%. The water saturation log along the well-grid connections of the historic well is shown as black dots. The saturations of the central (c) and cardinal directions (north, south, east, west) are shown as line plots. In addition, the permeability and porosity logs of the five observation wells were extracted as shown in Fig.5b and 5c, respectively.

As observed in Fig.5a,b, and c, the well-grid connections of the historic simulation well traverse only the model k_index 15 – 39; hence, the associated observation wells could allow an assessment of the properties of the model above and below the perforation interval of the historic well.

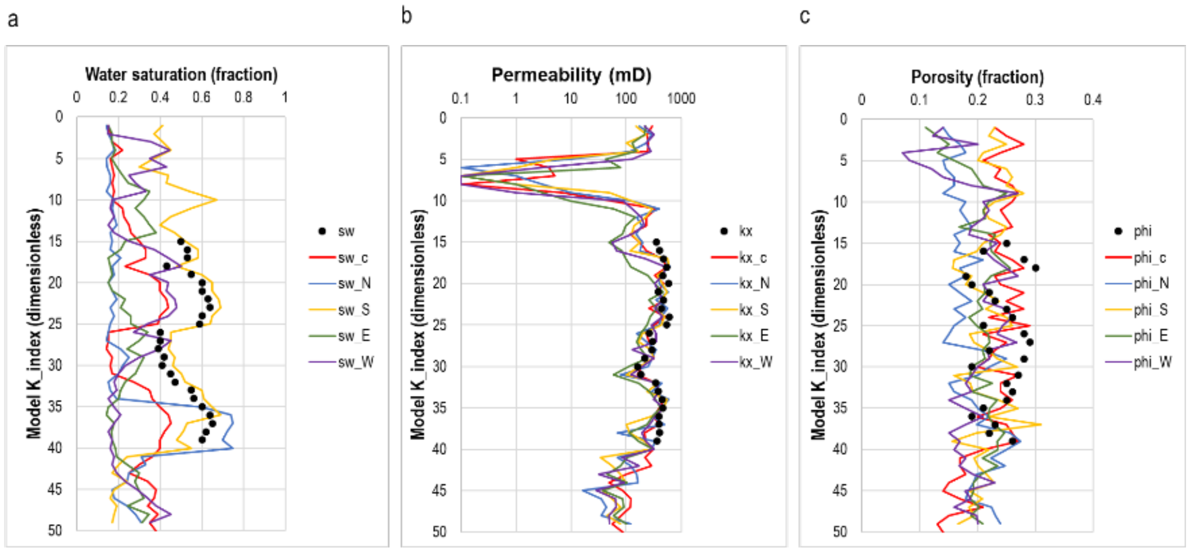

Figure 5: (a) Water saturation, (b) permeability, (c) porosity of historic simulation well and its associated observation wells, extracted at simulation run time for calculation of sweet_spot to be used for placement of sidetrack well

The simulator calculates the sweet_spot log given by Eq. 1 for the five scanning wells

$$sweet_{spot} = dz * \phi * log_{10}(k) * (1 - s_w). \quad Eq.1$$

The full complement of the required user input information is described in Table. 1

Kx_cutoff	Minimum permeability of target interval
Sw_cutoff	Maximum water saturation of target interval
Min_Perf_thickness	Minimum thickness of target interval
zone_merge_threshold	Minimum thickness between adjacent target intervals
Scanning wells spacing	Number of cells between central and cardinal observation wells
Water_cut_trigger	Value of water-cut at which sidetrack workflow should be activated
kmax	Number of k-layers in the model

Table 1: User input parameters for AI driven sidetrack well placement and their description

The value of sweet_spot is set to zero at any grid block where water saturation is greater than input *sw_cutoff* or less than input *kx_cutoff*, resulting in zones of sweet_spot having different thicknesses separated by zones of zero values of sweet_spot. **Fig.6a** shows the sweet_spot log of the central observation well for sw_cutoff = 0.25 and kx_cutoff = 1md, showing six zones separated by zero values.

If the zone thickness is less than the user input *Min_Perf_thickness*, the sweet_spot zone is discarded. If the number of k_ indices between two successive sweet_spot zones is less than the user input *zone_merge_threshold*, these two zones are merged into a single zone. Fig. 6b shows the result of fine-tuning Fig. 6a using *zone_merge_threshhold* = 3 and

Min_Perf_thickness = 5. The six sweet_spot zones identified in Fig. 6a are merged into two sweet_spot zones in Fig. 6b.

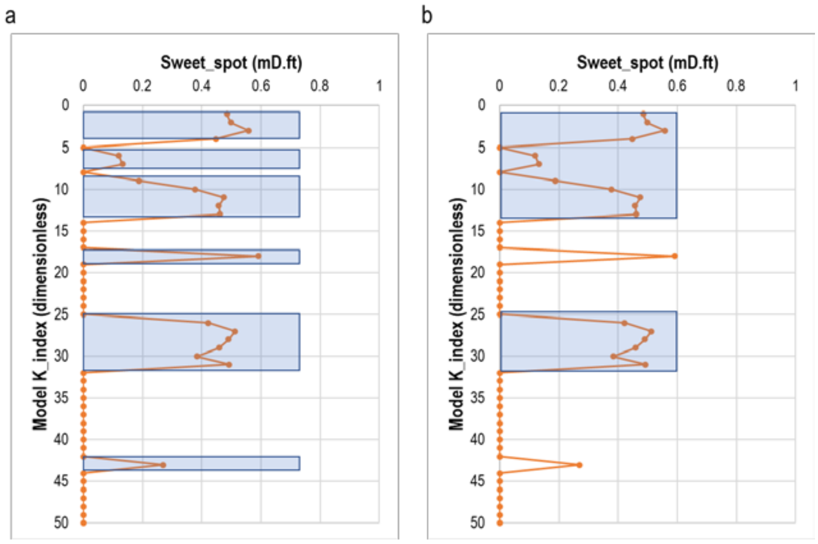

Figure 6: Shaded rectangles representing (a) All the identified sweet_spot zones based on input sw_cutoff and kx_cutoff, (b) Refined sweet_spot zones using input zone_merge_threshhold and Min_Perf_thickness.

The sweet_spot zone of the *central observation well* with the largest sweet_spot coefficient is selected for locating the sidetrack well. The sweet_spot coefficient is defined as the area under the sweet_spot log, measured in md.ft.

In the illustration shown in Fig. 6b, the upper sweet_spot zone has a coefficient of 4.2 md.ft while the lower zone has 2.8 md.ft. The sidetrack is placed in the upper zone.

The *central observation well* is closer to the historic simulation well than the *cardinal observation wells*, and it is used to observe the immediate vicinity of the historic well, which has no well-grid connection. Therefore, the use of the *central observation well* to determine the sidetrack target allows the simulator's decision to be checked against a time-lapse PNL prior to the actual drilling of the proposed sidetrack.

Using the same interval as the largest sweet_spot coefficient on the central observation well, the sweet_spot coefficient on each of the *cardinal observation wells* are calculated, and the direction that gives the largest value is selected as the direction of the sidetrack well. We assumed here that the reservoir is continuous between the central and cardinal observation wells; therefore, the larger the magnitude of the sweetspot coefficient at a *cardinal observation well*, the larger the total reservoir capacity (kh) between that direction and the *central observation well* would be. It is also assumed that the larger the kh within which a sidetrack well is located, the better its instantaneous and long-term production performance would be.

Fig. 7 shows the sweet spot zones along the *cardinal observation wells*. The zone of interest is the k_index interval from 1 to 13 because it is the interval chosen from the central observation well. In the illustration, the largest cumulative sweet_spot coefficient occurs along the south observation well (3.9 md.ft). Hence, the sidetrack well is oriented towards the south.

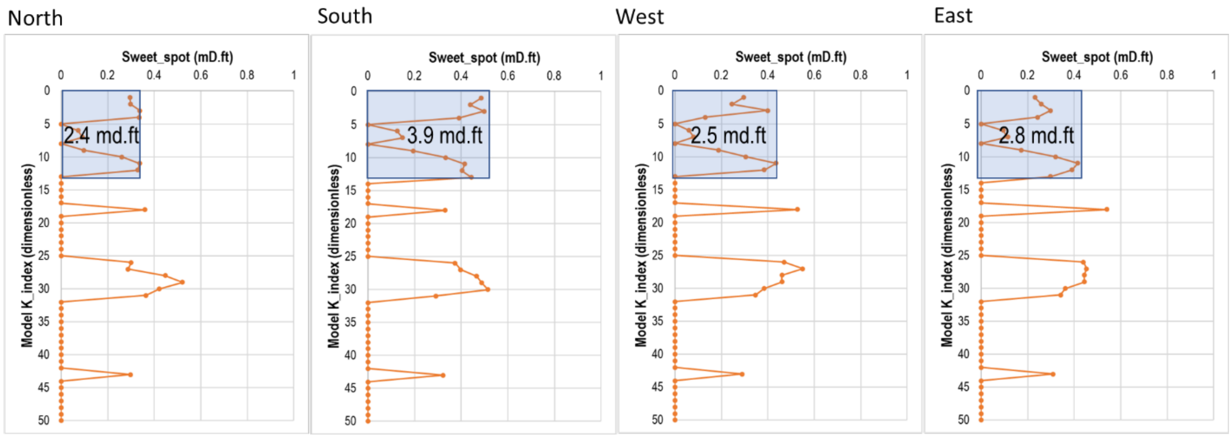

Figure 7: Sweet_spot zones identified along the cardinal observation wells, showing the cumulative sweet_spot coefficient of the zone of interest

Using the *i,j* coordinates of the *central observation well*, and having determined the top *k_index*, bottom k_index, and the orientation (I or J) of the sidetrack well, a well-grid connection can be defined for the sidetrack well. In an example application, the sidetrack is defined as a horizontal well parallel to the structure, that is, passing through a fixed value of *k_index*. To maximize the reservoir's sweep efficiency, especially in the case of aquifer influx or water injection, a horizontal lateral could be placed at the upper section of the identified sweet_spot zone.

In the current illustration, let the *i,j* location of central observation well be (60,35), top *k_index* = 1, bottom k_index = 13, well orientation = South (J-), and the horizontal lateral be placed two cells below the top of the sweet_spot zone. Then, for an example commercial simulator, the well-grid connection (i,j,k) is automatically defined as

Wellname = STRK_P1
60 35 3 /
60 34 3 /
60 33 3 /
60 32 3 /
60 31 3 /

Note that because the horizontal sidetrack is oriented south, the *J_index* decreases along the well path.

A full-field simulation run with an automatic sidetrack enabled could be used as a reservoir management tool for planning the acquisition of time-lapse PNL to validate the zone and orientation of simulator-derived unswept zones. Such a full-field run could also provide insight into the sidetrack wells having the most incremental benefits, thereby ensuring that investments are targeted at the sidetracks with the highest potential.

Discussion of results

Conventionally, numerical simulators perform calculations related to the physics of fluid flow within a reservoir. However, they could be coupled with VLP tables to enable the calculation of wellhead pressures. In the same way, the present work couples artificial intelligence to the numerical simulator to help automate the placement of simulation wells.

To optimize field development costs, operators aim not only to maximize oil production, but also to minimize water production. This is because produced water needs to be treated before disposal, and the treatment criteria are becoming more stringent with the development of green economies and reduced tolerance for environmental pollution. We expect this new functionality to significantly help to approach the objective of oil production with minimum associated water production.

Nomenclature

Hu:	Net cell thickness (ft)
Phi:	Porosity (fraction)
K:	Permeability (mD)
So:	Oil saturation (fraction)
Sor:	Residual oil saturation (fraction)

References

Magizov, Bulat , Topalova, Tatyana , Loznyuk, Oleg , Simon, Evgeniy , Orlov, Alexandr , Krupeev, Vsevolod , and Dmitry Shakhov. "Automated Identification of the Optimal Sidetrack Location by Multivariant Analysis and Numerical Modeling. A Real Case Study on a Gas Field." Paper presented at the SPE Russian Petroleum Technology Conference, Moscow, Russia, October 2019. doi: https://doi.org/10.2118/196922-MS

NB: space limitations imposed by AAPG extended abstract did not permit the inclusion of the extension of this methodology for infill well placement in green and brown fields. The author can be reached on babkay2000@yahoo.co.uk for the full manuscript.