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Production Planning in an Operations-Centre Environment

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Abstract

The real-time asset management (RTAM) domain has received a lot of attention over the past several years. A key RTAM component has been the uptake and utilization of operations centers for implementing new work processes. In early stages of this development, the operations centers have been utilized for conducting, e.g., morning meetings and increase the communication between the asset and operational teams (e.g., between onshore and offshore teams). In this paper we will address how existing work processes can be implemented in new ways in such environment, in an attempt to take advantage of the new communication opportunities and data and model availability.

Our focus is on parts of the production optimization work process, namely that connected with production planning. Production optimization requires knowledge of well behaviour and topside processing constraints. The production engineer must consider all wells simultaneously in order to optimize the production from the wells to the processing plant. The objective is to use the equipment effectively to maximize oil and gas production. Finding the operating conditions where this is achieved, requires an integrated production planning - with participation from production engineers, reservoir engineers, offshore operators, and topside processing engineers. A typical challenge related to this is the lack of a common framework for integration of work processes between the disciplines, preventing decisions to be made based on a common view of the status and challenges ahead. This paper outlines how this challenge can be addressed using a real time system approach to production optimization work processes. Features of the real-time system will be described and a new work process for production planning using this system will be outlined.

Introduction

The production planning process is an important task within reservoir and production management, as the overall field economy is heavily influenced by decisions and the consequent actions from this process. The importance of assigning resources into proper production planning is well recognized in the industry. However, to update models for production prediction is time consuming in existing prediction tools. One of the main reasons for this is the need to manual input data to the model and to select the appropriate scenarios and run the predictions. For that reason model parameters may be updated quite infrequently, typically when the model output yields clearly erroneously results (i.e., when the model output and the measured quantities deviates significantly). In addition, most prediction tools do not consider production from several wells when production is balanced in the field towards the topside constraints. These factors may lead to production loss when not employing the total capacity of topside processing facilities. It is important that models applied in the production prediction are as accurate as possible. Secondly must the models be available at an early stage before decisions are made. To achieve this, access to the latest data and fast processing of data to information is a key component.

The final output from the planning process (i.e., the decisions on the actions needed) should be supported by a multi disciplinary team where all field aspects and future effects are considered simultaneously. This objective is a challenge in production planning because it requires the information to be presented in a comprehensible format to all participants. This means that in addition to the data needed for detailed analysis of parts of the problem, one need aggregated data and information so that key points within one discipline is understandable for everyone also outside of that discipline. A key enabler for this is visualizations modules attached to the updated models and a common framework where the information could be inspected.

This paper outlines how a real-time system could be used for production planning. The solution is specified for an operation center environment and how this addresses the support of control and decisions in real time. The paper includes a discussion of how the systems approach of production planning can be utilized in an operation center and addressing some of the challenges associated with production planning in field operations. An exemplified work process of production planning and the associated challenges follows in the next section.

Production planning – Work processes and common challenges

The work processes connected to production planning will eventually result in a production/injection plan (P/I plan). The work process is based on several other work processes as illustrated in **Figure 1**. The supporting work processes (marked yellow) are on-going during the period between two production plans. This paper will only focus on the actual process of generating a production plan for the near future (marked orange in **Figure 1**). This short-time production plan is for many assets revised on a weekly or bi-weekly basis. During the time interval between two successive production plans the production set points are changed from time to time, mainly because of unexpected events within the field itself or in the production system. The framework applied and discussed in this paper could be used in daily production management as well. However, the supporting work processes for generating the production plan (e.g.., well/process maintenance, identify process plant restrictions, other production limitations, production surveillance, and short time/long time production optimizing within the field) is not within scope of this paper.

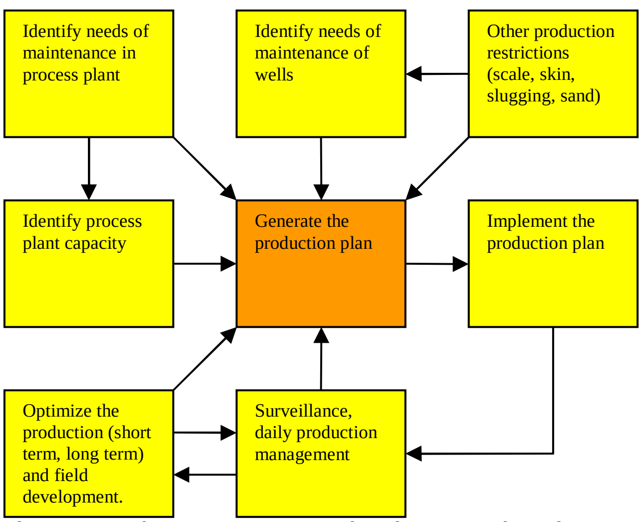

Figure 1: Work processes supporting the generation of a production plan.

Generally speaking there are three main steps in the process of generating a production plan. The three steps include (1) collection of data, (2) transformation of data to information and (3) decision-making from available information. The work process output will be updated knowledge about the behavior of all wells and production targets taking the process capacities into account. Based on these outputs decisions can be made and implemented. These decisions will have the format of a production plan.

The total production from all wells is constrained by either fluid inflow to well targets and lift capacity in wells, or handling capacity topside. The approach of optimizing production and generating the production plan is different depending on where the bottlenecks are located. Optimizing total production when fluid inflow to well is the restricting factor requires single well improvements, where each well/reservoir area normally is considered independently. The objective is simply to make each of the wells producing at a maximum rate by increasing potential inflow. However, when topside restrictions impair the overall production in field, all wells need to be considered simultaneously. At these conditions a set of optimal production conditions within the boundaries of processing capacity is required. The topside constraint may either be water, gas, oil handling capacity, or in some cases a combination of these. Liquid production supplied to processing plant may also be a constraint. The planned production in each of the wells must be balanced towards these limits, thus some wells may even be choked back in order to increase production from other wells to maximize the overall oil or gas production.

This paper considers this latter case; the field conditions are such that production is constrained by topside restriction. We will utilize a multitude of data sources including single well production tests (multi phase), bottom-hole pressure (BHP), and topside processing capacities. Thus, for this approach to be fully applicable these types of data should be available. In addition, fluid properties are established topside and correlated to reservoir conditions. We assume that the process capacities may vary, but they are constant and known in the time period of production prediction.

Under these conditions, the main objective in the production planning is to determine the set points for the controllable variables in each of the wells so that the topside handling capacity can be utilized as effective as possible. Wells containing down-hole measuring devices, i.e. pressure/temperature gauges, may use the pressure measurement (BHP) as a controllable variable. The choke size/angle may be used for tuning the pressure in combination with the lift supporting equipment (e.g., gas injection rate or pump settings). The specific operation range of BHP and production rate may also be affected by other factors, but these are not considered in this paper. Such factors may include sand production, scale development, skin development, or other aspect related to the reservoir/well/process condition and control (see also **Figure 1**).

Several other issues are of importance for the planning process. At steady-state condition the liquid production could be calculated as a function of BHP, by using inflow performance relationship (IPR). Without a down-hole pressure gauge the topside pressure must be used in conjunction with a flow correlation. Models for water-cut development should be used if this is changing significantly during the planned period. In addition, the water cut models could be used when integrated decisions are made considering the long term versus the short term effects from a producer. At some field conditions the long term production of water may affect the short time production planning. Finally, the reservoir production must be converted to topside conditions by fluid correlations and the production from all wells should be balanced towards the topside constraints. At these specific conditions the details of generating a production plan according to the three steps above can be outlined as follow.

1. <u>Collection of data:</u> This task is limited to gather production data (single well production test) and pressure data (BHP). The assumption is that all these

data are available**.** Output from all supporting work processes must be collected.

2. Transform data to information: The stream of production and pressure data carry information on the specific behavior of each of the wells. To convert the data to information, filtering of transients and outliers is needed to obtain (steady state) pressure versus production behavior (see Olsen and Nordtvedt[1]). A model is selected by physical criteria and mathematical approximation, and the well behavior is captured in the model by regression. By using regression each of the models could be evaluated, thus several different models may be considered. From the production test and pressure data models for inflow performance relationship may be calibrated, and, in addition, water production models may be update for investigating the long term effect of current operation conditions. During a well production test several points on an IPR-curve could be attained, and these data are the main sources of calibration. Historical production data feeds the continuously updated water cut model.
3. Decision making: Based on the new information of well behavior may the estimated future production be determined by tuning operating conditions (controlling BHP during production) towards an optimized pattern within the plant capacity. The final decision on how to produce at the maximal utilization of processing plant should also be governed by long term reservoir strategy and future field operations.

In real life field development the steps listed are not always straight forward and some of the typical challenges associated with the process of production planning are listed below. These challenges are also very analogous to hurdles experienced in other work process, thus any improvement that could be obtained would be advantageous for other work processes as well. The challenges from a perspective of production planning could be summarized as follow.

i. Collection and organization of data may be delayed by security issues and incompatible data formats. Today, these challenges are expected to be relatively straight forward to address in a good way. However, these problems still are obstacles regularly experienced in the industry.
ii. Filtering of outliers and transients is necessary to obtain correct steady state points for the IPR model. The engineers must handle a significant quantity data, which make this task time consuming.
iii. Model updating is erroneous because the filtering routine is not effective. Several data points used for calibration may be outliers or during a transient period.
iv. Consideration of all wells and processing plant simultaneously may be a challenge, as no integrated visualization tools assign to this is available.
v. It is difficult to obtain an integrated decision making process since a common framework to support this is not present.

Figure 2 shows how the supporting work process and the people involved in generating a production plan. The current structure of organization does typically not allow processing engineers and reservoir engineers to integrate their field objectives when different scenarios for a short time production plan are evaluated. Since challenges of production planning bear resembling to challenges experienced in other work process of reservoir engineering, several work process may share the same potential solution. The next section will describe how these hurdles could be addressed by a real-time systems approach and utilization of an operation centre for the production planning process.

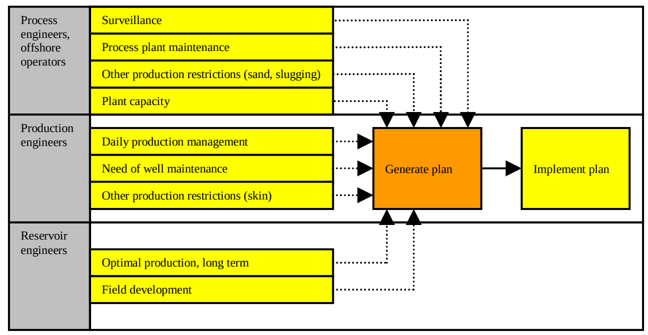

Figure 2: The supporting work processes and people involved in generating a production plan.

New work process of production planning in an operation centre environment

This section will clarify how the challenges of production planning will be attempted addressed within this paper. A brief overview of the real-time system, components and modules applied to address the challenges are presented. The system[2] referred to in this paper uses data sources supplied by a real-time data acquisition system or offline data. The data sources are organized into a hierarchical tree and filtered automatically before feeding them to the chosen module, thus, only data of a selected type and time period may pass to the calculation module. All sources, both raw and processed, may be accessed through a central server and visualized by graphical components. All selected graph components could be displayed in a common interface, and the interface could be used interactively. Several data sources may be utilized simultaneously.

By this functionality the user interface could be constructed to display the result of for any calculation procedure, and to set/change input values for the operation. Several users or computers may share the server network model designed by one user. The design for production planning workspaces may also be flexible between disciplines and the information structure could even be subjective to each user. The system we will use has integrated several engineering modules for analysis. These include IPR analysis, models for water cut development and fluid properties. In addition to analyses the system may be used for surveillance by connecting alarms to a data source or output from a calculating procedure. Thus critical conditions may be identified fast.

The application of this system addresses the challenges of collection and organization of data. The systems filter modules automatically distribute data at a specific criteria, thus the time spend at this task is reduced significantly. The IPR module of the system allows the user to quickly evaluate several updated models and by this functionality the production planning will be based on more accurate models. The visualization modules allow information from several disciplines to be displayed simultaneously. In conjunction with the operation centre, information may be aggregated to a level where a common understanding of the current situation could be reached and decisions made. **Figure 3** shows the new organization structure of the work processes.

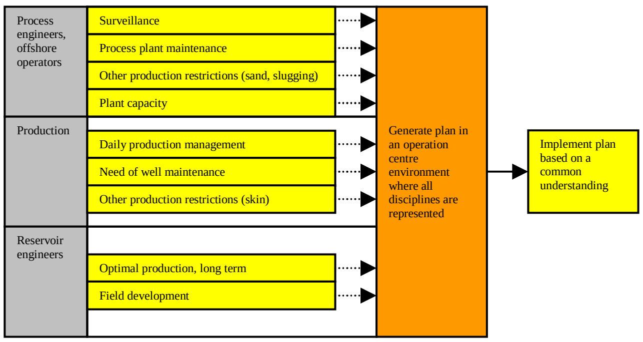

Figure 3: The new work process of production planning involves people from several disciplines.

There are several benefits of using an operation centre for this decision process. The main rewards are enabling capitalization on integrated reservoir management, better decisions, and establish a common understanding of future challenges. Integration of the production planning and analysis process with surveillance of well status and reservoir condition may increase the decision understanding during surveillance as well. Measurement of effects by the implemented decisions will be done faster and better. Decisions are also visualized in the open which make understanding effects of new implementations easier across disciplines. In addition, a number of people may work within the process as decisions are made. Thus, the physical environment and equipment gives a common platform of integrated field and production management.

Figure 4: The operation centre design.

Using the system effectively requires knowledge of the flexibility of the system and the implemented modules. Details of the modules and variety of models implementation in the system are therefore presented in the next section and appendix A.

Well models and system implementation

This section provides an overview the basic models implemented in the system. A detailed presentation of these models is given in **Appendix A**. Inflow performance relationship models are commonly used for production prediction and allocation. The IPR models are basically a relationship between normalized bottom-hole pressures (BHP) and normalized production. Several models of IPR-curves have been developed the past 40 years and implemented into off-line software[3]. The fluid phases present in the reservoir are a governing factor of model approach. Some examples of models under different reservoir conditions implemented in the system are discussed in this paper along with some details of the implementation.

Normally at short-time production planning the constant water-cut approximation is reasonable and is not significant with respect to the model residual. However, if the water-cut is changing significantly during the prediction period a model for water-cut development should be used. This will decrease the error in phase fraction input, but the prediction error of liquid IPR is still unaffected. When the system is used for forecasting longer time periods of production, the system may apply a model for water cut development. Water cut models also serve as a tool for long term evaluations of the current operation settings. Change of fluid distribution is one of the main sources of diverging IPR, thus the water cut development may also be an indicator for when the current IPR model need updating. Several extrapolated models of water-cut behavior have been suggested in engineering literature, and two of them are implemented in this system. All models or model types implemented in this system are based on other authors' publications and this paper does not evaluate the actual approaches or results. However, the implemented models generally do have some recognition by industrial application and implementations in modern commercial software applied in the industry.

System filter module

The system uses a chosen wavelet filter for detecting data of outliers and starts of transients. In addition the well test module will detect start of steady state and semi steady state period. In combination the outliers and transients periods will be detected. These data points are removed before model regression. The data source may also contain periodic fluctuation around the measured signal. The wavelet filter may reduce these fluctuations by transform data towards the signal. Several types of wavelet filters may be used in the system. However, details concerning algorithm of wavelet filtering are not considered in this text (see Olsen and Nordtvedt[1]).

Designing a framework for production planning

Application of the system is dependent on the specific field condition and designing an optimal framework for production planning. Examples of utilizing the system for integrated decision support will be presented in this section. It is important to recognize that the solution presented here is not representing an absolute design, and could be adjusted rapidly if reservoir or topside condition is change during the lifetime of field development. The solution specified here utilizes three connected information templates (also referred to as *work spaces*) throughout the work process. In addition this solution the system filter module settings specified for the work process.

Before using the production planner or any other analysis tool in the system, all relevant data must be connected to the systems' server. This is a one time operation and all future application of the system for analysis or surveillance could use these data links and data sources. The data links must then be filtered to obtain steady state measurement separated from transient data. In addition, all outliers are removed from the signals. If the measured signal contains noise significant to alter the model updating the wavelet filter could reduce these fluctuations. In the filter module specific periods of time may be selected. This can reduce the number of data points and speed up the regression calculation. Only data from the latest production test is wanted for the model regression of IPR, thus this period could then be singled out. **Figure 5** displays the filter configuration work space.

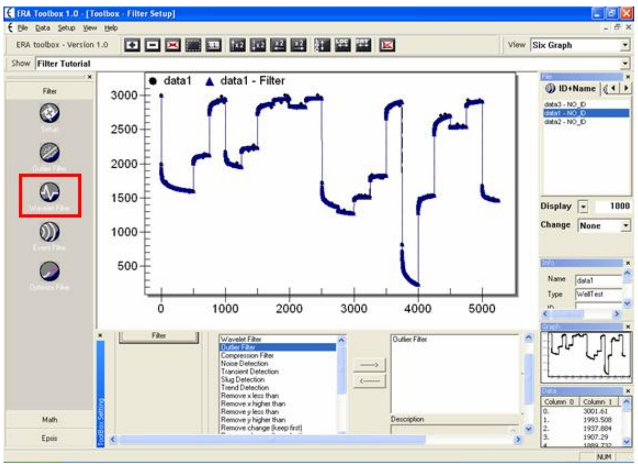

Figure 5: The systems filter configuration work space.

By the filter setup several types of filter configurations could be generated and the corresponding data set may be transferred to any calculation module in the system. The data set could be isolated as a tag in the system or saved as a file. When the filtered dataset is establish as a tag, new data may be collected here every time the data source is filtered through the same procedure. The data in this tag could be edited and older measurement could be deleted when obsolete for model updating. A tag containing fluid data for each well could also be entered in prior to using correlations specified in the system. The tag of fluid data could be edited in the same manner.

As described in the previous section several models may be chosen for inflow performance relationship. The first of the three connected information templates allows the user to evaluate several models simultaneously and compare the model performance in respect of measured data. Each of the IPR-curves is plotted with the graph component and measured point scattered around the curve. In addition is model performance parameters as average relative error, RMS of relative error and relative model shift plotted for each of the models. The parameter definitions are included in **Appendix B**. The user of the system may inspect the performance from each of the models and chose the correlation of most consistent. When a model is selected it remains active until a new update is done and a possible new model is chosen. **Figure 6** shows the information template for model selection.

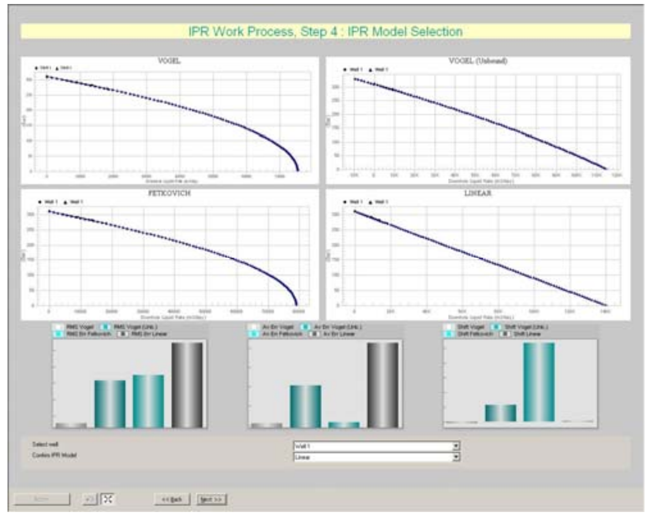

Figure 6: The model selection work space.

The second information template in this specific solution shows the historical trend of production and pressure. These trends were selected primary for controlling the pressure and rate behavior are consistent with the calculations done in this framework. As explained in the system details any data sources can be visualized in the graph component and for instance a field constrained by water handling capacity may consider plotting the future water cut behavior. The current used IPR model is also shown in this window and the model could be updated by adding new data and make a new regression through the model selection template.

The bottom right in **Figure 7** shows the calculating function in this solution. By inserting a pressure in the pressure box the corresponding rate topside and at reservoir condition is calculated for all phases. The calculator could be used in the reverse order, thus inserting a rate will provide the pressure required. The rate obtained or used in calculation will be added to tag which sums up all the planned production from each phase. The total planned production from all phases in all wells is updated in the template and compared with a fixed value, representing the constraint in the handling capacity. This functionality allows the user to evaluate the effect of increase or decrease the production of a well in respect of the overall constraints. The operating pressure required to obtain this production is calculated simultaneously.

Figure 7 show the single well production planner. All production wells attached to the defined limits of processing plant have an information template with the calculating function and are connected through the overall estimated production tag.

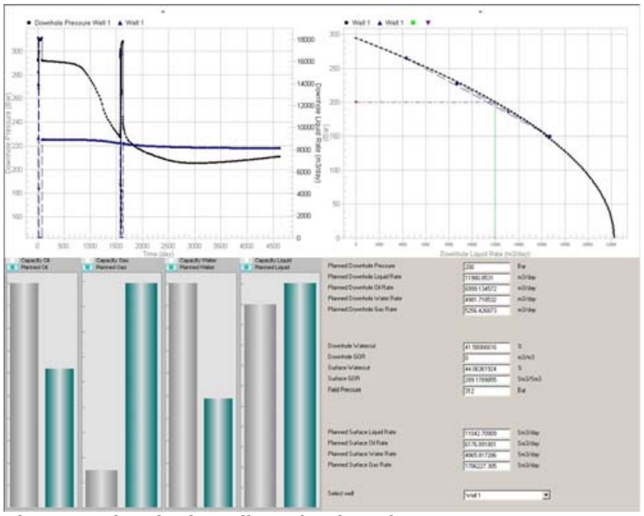

Figure 7: The single well production planner.

The last information template (**Figure 8**) shows a summary of all production wells and the capacity limits. The constraints may be changed in this window and the estimated production could be edited here as well. When using the field overview template directly, all other information templates will be updated to the entered value. This information template serves as the output for decisions and future implementation.

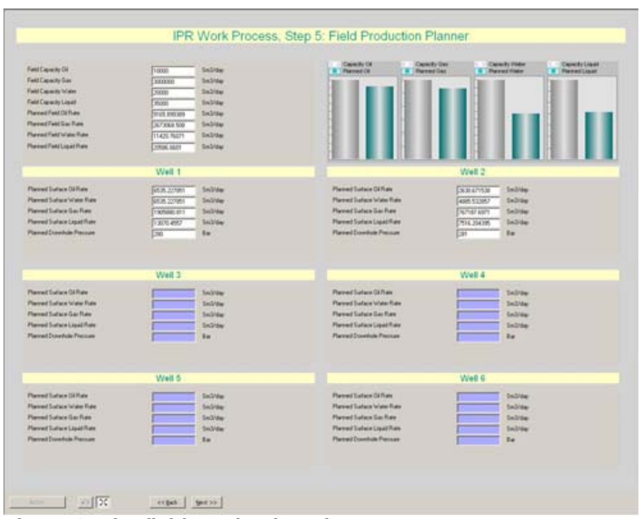

Figure 8: The field production planner.

Utilization of the system – example of real-time analysis and production planning in an operation center environment

This section will demonstrate the use of production planning and model analysis in a real-time system. The constructed information templates discussed in this text were attached to the tag of production data and pressure data. The data streams were supplied from a server to the system and the system setup was done in an operation centre.

Example: Application of the system

The test of the system was made by use of simulator generated data. The generated data were stored at the system server and fixed values for processing constraint and fluid data were created. The data stream was then made accessible from the server to the workspaces. Even if the data streams are feed from a server the example will demonstrate application of the system, analogous to using the system with live industrial data link. The main objective for this test was using the system under controlled circumstances and accomplishes the new work process by using the system. To challenge the functionality within use of the system were three independent work groups were assign to the same task of production planning, using the suggested workspaces in this paper.

Case specification

The case were made as elementary as possible to highlight the application of the system, thus only two production wells with rate and production history were made available from the server. All fluid data were given and topside constraints in processing equipment. No further restrictions were given for either down-hole pressure or fluid production. The following task made for three different work groups in this case:

- Create an updated IPR model for the two production wells by using the system. The basis for model updating is a recent separator test.
- Evaluate the best well models by using the model performance parameters.
- Use the selected model to obtain optimal condition for short time future production within the given topside constraints.

The production/pressure data were generated from reservoir simulator[4]. The fluid properties, topside constraints, and well conditions are listed in **Appendix C**.

Discussion of results

All three work groups selected the same type of models from the model selection work space. The IPR model selected is the bounded-parameter Vogel[5] type approach. The model updating procedure was experienced as very swift with the systems organization of data. The time spent was considerably higher in the model selection workspace and production planner workspace, then the model updating. This is an important objective in using the system approach, transfer time applied on data processing to information evaluation and decision making. When applying the model in the production planning workspace each of group could iteratively work toward an approximated optimal production set point for both the wells. This trial and error procedure explains the small divergence in planned production from the three groups. The highly comparable output is a good indicator for repeatable functionality of the system. **Appendix C**, table 1-3 lists the production suggestion obtained from all groups.

Conclusions

This paper documents how a real time systems approach could be applied in an operation centre for production planning and analysis. Challenges including data availability, organization, filtration and model updating are addressed by the use of the system.

An operation centre provides the physical environment and tools for integrated decision making and understanding. Work spaces have been created for production prediction and model analysis for decision support in a real time system.

The main benefits of using a real-time system are the transform of focus in the work processes from data processing to information evaluation. By applying the system in an operation centre is new work process of production planning demonstrated.

The potential capitalization of increased oil production by producing at the limits of process constraints is highlighted in this work space. Several initiatives are taken within the industry towards real time analysis and surveillance. The operation centre approach provides an excellent frame work for using a real time system and frontiers in the industry are already using this approach.

This paper documents how traditional work process could be transform into this approach and the benefits are discussed.

Acknowledgement

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Nomenclature

q = production rate
p = pressure
Q = cumulative production
f = fractional production rate
B = formation volume factors
R_s *= Solution gas-oil ratio.*

Subscript:
L = Liquid
o = oil
w = water
g = gas
w = well
r = reservoir
max = theoretical maximum

Appendix A – Well models and system details

This appendix presents the IPR models and water-cut models implemented in the system used in this paper.

IPR in two phase area

The Vogel[5] relationship has been widely used in the two phase area. The Vogel relationship relates the production and pressure as follow.

$$\frac{q_o}{q_{o,\max}} = 1 - 0.2 \cdot \frac{p_w}{p_r} - 0.8 \cdot \left[\frac{p_w}{p_r}\right]^2 , \qquad (1)$$

where q_o and $q_{o,max}$ are production and maximal production respectively, and p_w/p_r is the ratio of BHP and reservoir pressure. Similar relationships have been developed by linear regression of the model form

$$y = b_0 + b_1 \cdot x + b_2 \cdot x^2 \quad , \qquad (2)$$

where y and x is the normalized production and normalized pressure, respectively. These models have the main application in the two phase. In order to obtain exact convergences at the limiting pressure values, the regression parameters are commonly bounded by (Wiggins et al[6])

$b_1 + b_2 = 1$,

and

$b_0 = 1$.

However, in a specific working range models without these parameters boundaries may be selected when favorable. This should be governed by the models range of utilization (that is when extrapolation towards the limiting pressure values is not needed).

Fetcovich[7] suggested a different approach, more similar to gas-models. Based on experimental data the oil production could be fitted to the model form of

$$q_o = b_0 \cdot \left[1 - \left(\frac{p_w}{p_r}\right)^2\right]^n \quad . \qquad (3)$$

There are no documentation suggesting one approach over the other, but the Vogel-type models have the best theoretical fundament. The best procedure is evaluating both approaches before using them. In the system a Vogel type relationship is implemented and the user may specify if the regression parameters are bounded or uncorrelated. The user of the system may compare both these approaches by evaluating the average model error and RMS from the selected data for updating. The Fetcovich model is implemented in the system as well, and both models could be compared by the statistical parameters.

IPR of single phase gas

The Fetcovich approach for two-phase reservoir could be used at single gas phase. However, the exponential parameter *n* is commonly set to unity if all fluid movement is in the gaseous state in the reservoir, thus reducing equation 3 to the familiar form of

$$q_g = b_0 \cdot \left[1 - \left(\frac{p_w}{p_r}\right)^2\right] \quad . \tag{4}$$

Due to non-darcy effects the *n* is normally lower than 1 in gas wells, thus is it recommended to include *n* as a regression parameter. The exponent *n* is suggested to be in the range between 0.5 and 1 for all types of flow, and closer to 0.5 when liquid phase increase (see Brill and Mukherjee[8]). Free gas production at two-phase reservoir flow could be determined by the Fetcovich approach as well. Pressure depletion will influence the volumetric phase distribution in the reservoir thus a model should be always be updated if the average reservoir pressure is changed significantly.

Single phase oil/water

At pressure above the bobble-point all fluid transport is restricted to liquid flow, and Darcy's law yield a straight line relationship between production rate and pressure drop in the reservoir. The slope of this straight line is the production index, and this is assumed to be constant for liquid flow. Thus

$$q_o = J \cdot \left(p_r - p_w\right), \tag{5}$$

where J is the production index. Modeling water production has been approached with inflow performance curves similar to single phase oil models. Thus,

$$q_W = J_W \cdot \left(p_r - p_w\right), \tag{6}$$

where q_w is the water production and J_w is the water production index. This approach should be used at a constant water-cut, because the water production index is influenced by the water-cut. This model obviously should be used with great care, and only for short-time production prediction. The prediction time period of model use is depending on how fast the water cut is changing, and some analysis in this respect could be done. The constant PI relationship may be chosen in the system.

Liquid IPR

An equivalent method is to sum the mathematical solutions from both liquid phases. This yield a liquid IPR where rates from each of the phases could be obtained by multiplying the liquid rate with the respective phase fractions. Thus by the Vogel-type model approach this yields

$$\frac{q_L}{q_{L,\max}} = b_0 - b_1 \cdot \frac{p_w}{p_r} - b_2 \cdot \left[\frac{p_w}{p_r}\right]^2 \quad , \tag{7}$$

and by multiplying the liquid rate by the volumetric fraction of oil and water, f_o and f_w respectively

$$q_o = f_o \cdot q_L \, , \tag{8}$$

and

$$q_W = f_W \cdot q_L \, . \tag{9}$$

The default setting in the system is liquid IPR model.

Water cut models

The Ershagi[9] water cut model is based on the concepts of fractional flow and the Buckley-Leverett recovery formula. The model utilize a straight line relationship between total oil production (or recovery) and a function of water cut $X(f_w)$. Thus

$$Q_o = a \cdot X(f_w) + b \, , \tag{10}$$

where *a* is the slope of the straight line and *b* the constant. The function of water cut is given by

$$X(f_w) = \ln\left(\frac{1}{f_w} - 1\right) - \frac{1}{f_w} \, , \tag{11}$$

where f_w is the fractional water flow. The model requires unchanged operation condition. In the model of Torabi[10], a straight line behavior between the square rot of cumulative water production and square root of cumulative liquid production is suggested. The model is obviously only valid after water breakthrough in the well.

$$\sqrt{Q_w} = a \cdot \sqrt{Q_L} - b \, , \tag{12}$$

where Q_w and Q_L are cumulative water and liquid production respectively. The instant water fraction of production rate may be calculated by differencing the cumulative water production in respect of total liquid production. By equation 12 this yield

$$f_w = a^2 - \frac{a \cdot b}{Q_L} \, . \tag{13}$$

Normally data points at early time after water breakthrough do not fit well into the overall trend. These points may preferably be excluded from the dataset when regression parameters *a* and *b* are determined. This problem is experienced both models.

Appendix B – Model performance parameters

This appendix gives a detailed description of the three parameters used for evaluation of the models performances. The parameters are evaluated in terms of relative error. The relative percent deviation for a single model point is defined as

$$S_i = \frac{X_{pi} - X_{mi}}{X_{mi}} \cdot 100,$$

where X_{pi} and X_{mi} are model predicted and actual measured value, respectively. The sum of single point deviation divided by numbers of measured points gives the average shift of data points. A perfect model yields zero for the shift parameter. If N is number of measured point, the shift parameter is defined as

$$shift = \frac{\sum_{i=1}^{N} S_i}{N}.$$

The second parameter is the rot mean square (RMS). This parameter increases when the model deviation is distributed at a fixed average. The RMS parameter is defined as

$$RMS = \sqrt{\frac{\sum_{i=1}^{N} S_i^2}{N}}.$$

The third parameter used in model evaluation is the average absolute value of deviation. Thus

$$\overline{|S|} = \frac{\sum_{i=1}^{N} |S_i|}{N}.$$

Appendix C – Input and results from the case study

This appendix list the detailed input and results/suggestions for the production planner used in the case study.

Input values for production planner used in the case study

Topside restrictions:
Water handling capacity = 4000 bbl/d
Gas processing capacity = 29.2 MM scf/d

Fluid formation volume factors:
$B_o = 1.13$
$B_g = 0.003$
$B_w = 1.02$
$R_s = 290$

Producing Well 1:
GOR = 512 (2.87 M scf/STB)
Water cut = 0.2

Producing Well 2:
GOR = 321 (1.8 M scf/STB)
Water cut = 0.4

Actual reservoir pressure:
p_r = 317 bar

Case results

The following models were obtained and chosen from the separator test. Well 1 were best represented by

$$\frac{q_L}{q_{L,\max}} = 1 - 0.24 \cdot \frac{p_w}{p_r} - 0.76 \cdot \left[\frac{p_w}{p_r}\right]^2 \qquad (14)$$

with maximum rate and reservoir pressure at 23,500 STB/d and 299.6 bar, respectively. The corresponding model obtained for well 2 were

$$\frac{q_L}{q_{L,\max}} = 1 - 0.35 \cdot \frac{p_w}{p_r} - 0.65 \cdot \left[\frac{p_w}{p_r}\right]^2, \qquad (15)$$

with maximum rate and reservoir pressure at 19,800 STB/d and 303 bar, respectively.

Work Group 1-3 production suggestions:

Table C-1 Production suggestions of group 1

	Oil (STB/d)	Water (bbl/d)	Gas (MM scf/d)	BHP (bar)
Well 1	8364	2091	24.0	201.4
Well 2	2865	1910	5.2	251.6
Total	11229	4001	29.2	

Table C-2 Production suggestion of group 2

	Oil (STB/d)	Water (bbl/d)	Gas (MM scf/d)	BHP (bar)
Well 1	8093	2023	23.2	204.3
Well 2	2908	1938	5.2	249.2
Total	11001	3961	28.4	

Table C-3 Production suggestions of group 3

	Oil (STB/d)	Water (bbl/d)	Gas (MM scf/d)	BHP (bar)
Well 1	8811	2442	25.3	193
Well 2	2115	1563	3.8	265
Total	10926	4005	29.1	