# SPE 128300

# Real-Time Intelligent Production Monitoring of a North Sea Asset

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## Abstract

The increasing complexity of natural gas extraction because of reducing reserves, complex behavior and more intricate contractual rules (due to liberalization of the West European energy markets) creates a need for more effective production efficiency. In order to deal with these challenges Wintershall is realizing a real-time monitoring system to optimize production for its (Southern) North Sea fields.

As part of this initiative Wintershall and TNO Science and Industry are developing a model-based advisory tool that uses real-time production monitoring data to optimize production. This paper describes deployment of that tool to optimize production from reservoir to export of one of Wintershall's North Sea assets. The tool is being used for early event detection, intelligent condition monitoring and support of operators and engineers to make informed decisions that have direct added value to operations.

The cases in the paper show the system's applicability for early detection of deviation of the measured productivity indices from the mass balance controlled dynamic model predictions and optimizing downtime of wells by mitigating effects of salt precipitation and optimal water washing procedures.

Next to the case data, data preprocessing and validation, two key aspects of the development of the tool will be discussed. Firstly, we will discuss how (dynamic) models are used in model-based monitoring methods that provide the operator with crucial information about production. Secondly, the paper will present a framework that was used to create distinct levels of production monitoring functionality. Next to this, the paper will present application results and validation of the results obtained.

E&P is nowadays getting more familiar with the potential benefits of integrated asset modeling, intelligent monitoring, production optimization and integrated operations – while at the same time it is experiencing many challenges associated with its successful implementation. We feel the work presented in this paper underlines these benefits and offers valuable lessons learned about a successful implementation case.

## Introduction

Wintershall Noordzee B.V. (WINZ) operates a number of gas and oil production facilities on- and offshore in The Netherlands. Wintershall has recently completed the implementation of a Remote Control Operations Project (RCO) to consolidate gas production control functions into a Central Control Room (CCR) located in a new Production Coordination & Control Centre (PCC) in Den Helder (The Netherlands). The objective of the RCO Project is to lower costs associated with operating the offshore platforms and at the same time to improve the effectiveness of the operations, maintenance teams and HS&E aspects. To achieve these improvements Wintershall has made significant organizational, management and technology changes that have included the migration of the individual platform control to the RCO system.

In the North Sea the easy gas for extraction has already been found and is being produced. Recent increase of gas prices has lead to exploration in areas where extraction is more expensive and involves higher operating cost. Extreme deep wells, high pressure – high temperature wells and tight gas require high-technology areas where Wintershall is currently active. In the production operations environment this means that higher complexity is being involved during the gas extraction of such fields. With emphasis of continuity of production and necessity for shorter response times due to more intricate contractual rules, more effective production efficiency is required. Because of that it was recognized that real time production monitoring will enhance production, providing valuable resources for a fast, reliable and operational added value by reducing the back-office complexity to analytical real time solutions.

In order to deal with these challenges Wintershall is realizing an Integrated Production Management System within its RCO way of operating the facilities in the (Southern) North Sea fields. As part of this initiative WINZ and TNO are developing a model-based advisory tool (Condition Based Monitoring) that uses real-time production monitoring data to optimise production from reservoir to export. The tool is being used for early event detection, intelligent condition monitoring and support of operators and engineers to make informed decisions that have direct added value to operations. Currently the tool is deployed for optimization of the F16/E18 asset. This asset consists of 7 wells, a main platform and satellite platform with processing facilities and dry gas export.

Wintershall, like other E&P companies, is investing heavily in acquisition of real time production data from its fields. The quality of this data is not always high enough to be suitable as input into models. Special techniques are required to validate and reconcile these data such that they can be used for input to the models without affecting their stability.
TNO Science and Industry is an independent technology provider which is active in the oil&gas industry and process industry. TNO's experience in industrial applications of real-time data processing, (model-based) monitoring and optimization, and its developed (Matlab® based) monitoring system architecture was combined with Wintershall's asset models and real-time infrastructure to develop a monitoring system, in which real-time data are gathered 24/7 from process equipment in a time stamped database and pre-processed, to be input to models that continuously monitor the main critical components of the asset from source to export (reservoir – well – chokes - separator – flowlines – compressor).
It has been proved that the developed system framework by TNO is a very stable environment for a real time monitoring functionality.

The purpose of this paper is to review the consecutive developments that we have achieved. We will show the coupling and partial integration of the down-hole and surface models, the transgression from static and manual models to automated real-time models, the systematic way of integrating partial models into a complete system and the emphatic move to pro-active flow steering with forecasting models. The main goal is to develop a tool that supports fully an efficient collaboration and integration between production operations and other engineering disciplines such as reservoir engineering, construction and pipeline, as illustrated in Figure 1. Figure 2 shows how the current blocks of data and model interact.

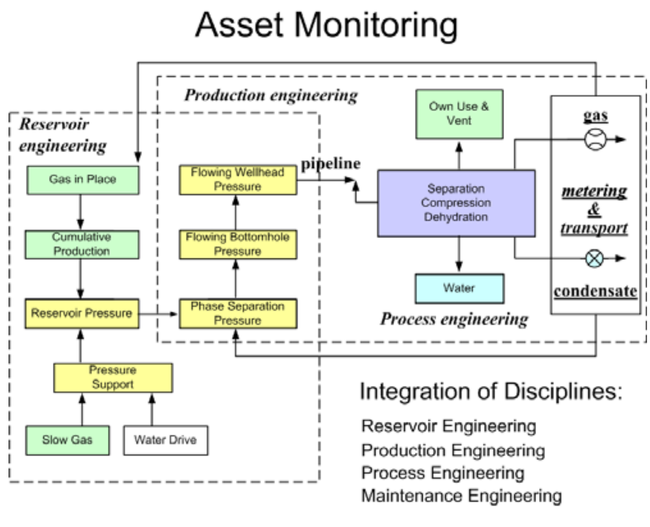


Figure 1. Integration and interaction of disciplines.

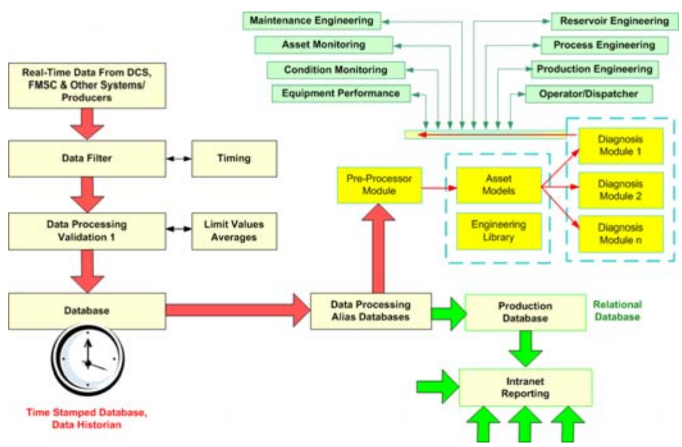


Figure 2. Wintershall architecture

## Real-Time Condition Monitoring

The primary task of real-time condition monitoring is to assist the process operators in making informed decisions on the daily operation of the production process. Prerequisite of condition monitoring is that real-time measurements of key physical variables are available. In the past decade, as a result of computer and communication technology, this has gone through significant development phases. Regrettably, the availability of an abundance of real-time data can easily lead to an overflow of data presented to the operator and not immediately lead to improvement of operation. Real-Time processing of the data, computing Key Performance Indices (KPI's) of the current condition of the process and detecting off-normal events and presenting the operator with less, but more informative data, is the key challenge of Condition Monitoring.

It is convenient to distinguish three levels of monitoring functions:

1. Based on individual variables, exploiting the time sequence of measured variables and the expected dynamical behaviour.
2. Based on multiple measurements of a physical entity, exploiting data redundancy to reduce measurement errors and detect sensor failure.
3. Based on multiple measurements of different, but related, physical entities, exploiting knowledge of the relations between the entities. They will therefore be called model based functions.

In practice the real-time data is not suited for directly feeding it to monitoring functions. Reason is that a measurement value might, for instance, not be available, or have a corrupted value or a high noise level. Using this data right away in monitoring functions would yield erroneous results and lead to a high level of wrong detection of off-normal conditions. A first step is therefore to apply real-time preprocessing of data to, as far as possible, eliminate these conditions from the data. This involves real time methods for detection and repair methods for missing data, spikes, noisy data, data reduction and filtering.

The model based monitoring functions involve physical knowledge (models). This can range from relatively simple models (a mass or energy balance equation) to complete models of well, reservoir or top-side equipment. The model is used to compute key performance indicators and to detect unexpected deviations measured in practice from the expected behavior expected on the basis of the model and the other measured variables. Because real-time data is input to the monitoring functions special care is necessary to deal with its dynamical nature. This results in data processing (time series analysis) to eliminate dynamical effects or, on the other hand, to exploit dynamical models. The use of models adds quanititative "intelligence" to the functions and supplements the operator's insight into the performance of the process.

## Monitoring System Framework

The monitoring system functionality covers the entire asset, from reservoirs, wells, pipe lines to top-side equipment. As a result a large number of monitoring functions for individual units and combinations of these units should be active in parallel and simultaneously. This naturally leads to an object-oriented framework.
Applying monitoring to a large variety of assets and equipment requires a very flexible set up. This has led us to an architecture which allows flexible configuration. Moreover the monitoring application should be able to cope with configuration changes in assets (which may occur frequently in practice).

The system should furthermore serve two goals:

1. A robust 24 hours per day, 7 days per week real-time monitoring application for operator support.
2. An interactive set of tools to support both reservoir and production engineers in off-line diagnostics, analysis and modelling of production data.

Additional important system requirements were that an extensive set of models, developed by reservoir and production engineers, was already available for use and that model development is generally performed by reservoir and production engineers and not by software engineers. The development and sustainance of monitoring functions should support these user groups, and therefore requires an environment and language that is convenient and suited for this task.

The Matlab® package from The Mathworks is generally considered as a powerful platform for interactive computing and is widely used by engineers in various application areas. Several toolboxes are available from the Mathworks and other parties that contain many useful fully developed functions for statistics, filtering, modelling, and data visualization.
It was therefore decided at an early stage that Matlab extended with an in-house developed toolbox for reservoir, well and equipment modeling would be used to realize the second goal. For the first goal, we decided to look for an approach in which the analysis functions and prototypes of monitoring functions created by/for engineers in Matlab could easily be transferred to the evolving real-time plant monitoring environment at Wintershall based on the OSISOFT PI System.

Several options were available:

1. Use Matlab as a computation engine connected to the real time monitoring environment.
2. Compile Matlab monitoring functions to Windows DLL's or .NET assemblies and embed them into the real-time monitoring environment.

3. Rewrite the Matlab monitoring functions in a language supported by the real-time monitoring environment.
4. Use Matlab itself as the basis of the real-time monitoring application and connect Matlab to the databases of the real-time monitoring environment.

Options 1) and 2) could be accomplished using either the Matlab Engine Library or one of the Matlab Builder products. The advantage is that in principle the Matlab functions can be used "as is" by the real-time environment. The disadvantages are that bugs in the Matlab code could affect the robustness of the real-time environment and that the application becomes a complex mix of Matlab code and code in the real time monitoring environment.

Option 3) involves a larger investment in software development, in which the models and monitoring algorithms developed by the engineers in Matlab must be handed over to and completely understood by the software engineers responsible for the implementation in the real time environment. This is a good solution for a final implementation, but less so when the monitoring functionalities have not yet completely crystalized, and futher development is required/expected. Another significant drawback is that two versions of the same code must now be maintained.

Option 4) looks less attractive at first sight, since Matlab is intended as an interactive enviroment for the end user, not as platform for on-line applications. It lacks some important aspects of such systems like multi-threading and event based computing. However, Matlab is also a complete object oriented programming environment. Experiences in previous projects by TNO have demonstrated Matlab extended with a framework of classes to make it suitable for the event based computing is exactly what is needed for this application.

The advantages of this approach are:

- The complete application is now realized in a single environment (Matlab) and the important parts can be understood, maintained and extended by the engineers responsible for modelling and analysis.
- Decoupling from the PI System environment: if the Matlab application would crash, some calculated results may temporarily not be updated, but the remainder of the PI System would not be affected.
- Rapid development of additional models and updated models
- No vendor lock-in

Even when extended with a special event based framework, Matlab will not be a true real-time operating environment with real concurrency and guaranteed real-time response times, but this would be important only for implementing critical real time computations, such as closed loop control, which is not part of the scope.

The Monitoring System was realized by using Matlab, extended with classes for event-based computing, and classes for external database access, and developing, organizing and configuring an evolving set of re-usable monitoring objects in this framework.

## Monitoring Modules

**Reservoir add-in:**

As a part of the 'F16-A & E18-A' project in 2005 a set of engineering functions has been developed in a Dynamic Link Library (DLL) as a logic continuation of the existing workflow. This reservoir - production engineering toolbox is the result of an in-house development outsourced in C++. It consists of a complete set of modular functions for the full field production modelling and forecasting of a gas field. The DLL add-in can be called from different programming languages and applications, such as Matlab®, Excel®, GAP®, MBAL® or any other software that can have a reference to the library. Reservoir and wellbore models characterized by the engineers in the Microsoft Excel environment can be transferred one to one to the Matlab© real time environment for continuous performance monitoring.

Figure 3 shows a schematic overview of the process and software workflow used by Wintershall Noordzee. This add-in functionality is intended for rapid and simple prototyping and provides nowadays a uniform method for daily performance evaluation and forecasting of the producing natural gas assets of Wintershall in the North Sea.

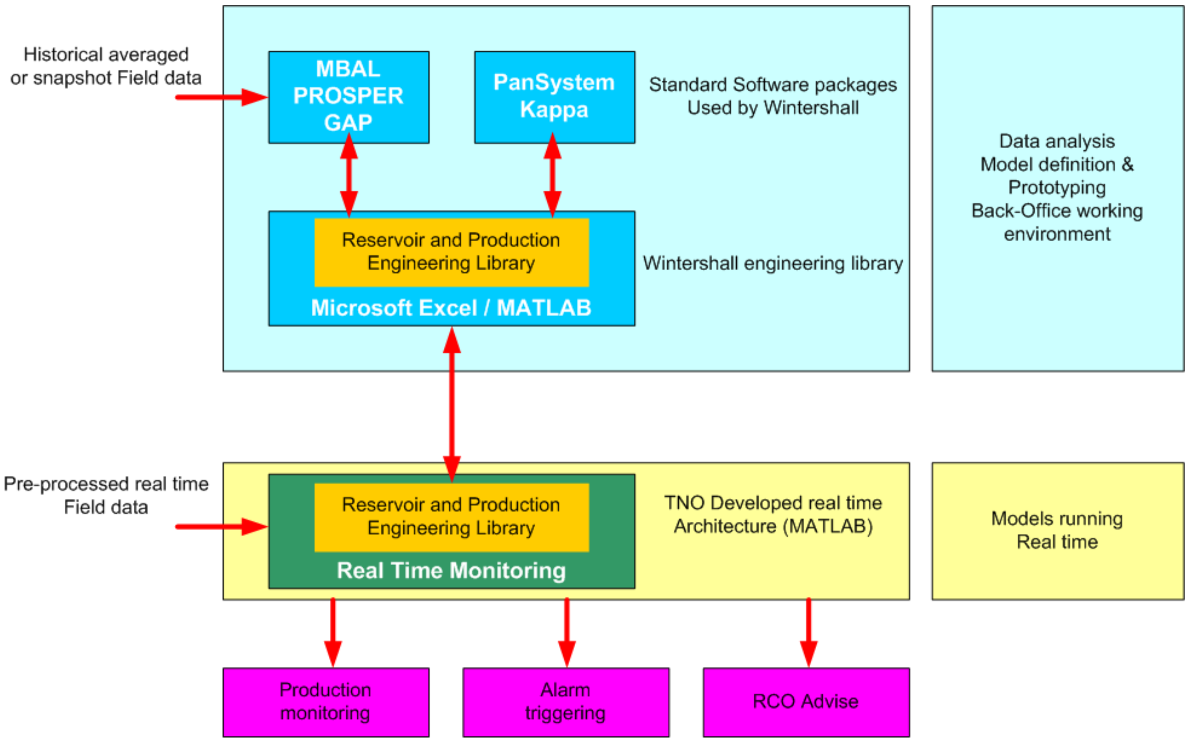


**Figure 3. Schematic overview and iteration of the Wintershall Reservoir and Production Library.**

The theoretical basis for the DLL toolbox functions can be found in the reference textbooks of reservoir and production engineering.

The total well deliverability can be easy determined by a system analysis approach as shown in Figure 4. This illustrates the main points of interest in any gas producing well. At any nodal point the fluid resistance through the systems can to be evaluated as a function of the gas flow rate, pressure and temperature.

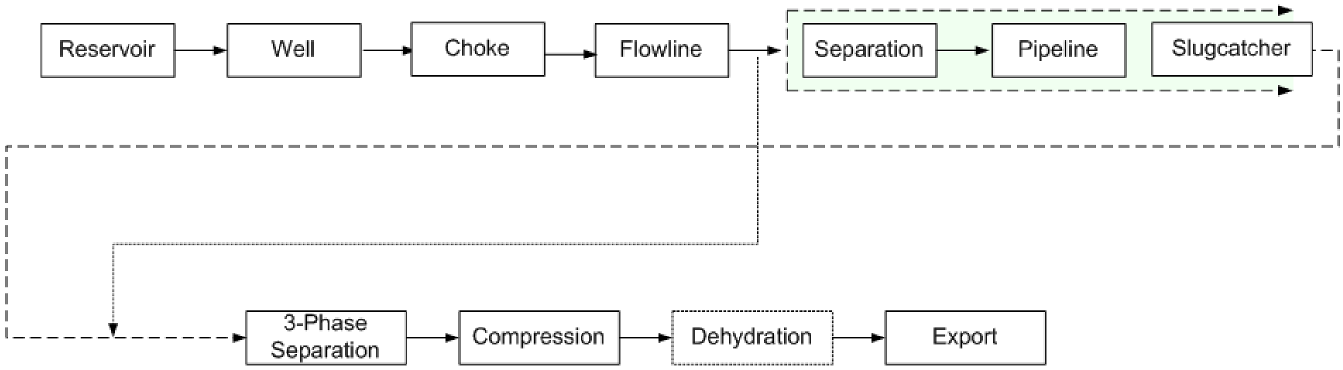


**Figure 4. Main nodal points monitored real time.**

<u>Sub-module PVT – properties:</u>

The core of the DLL is the extensive library of physical and thermodynamic properties for natural gases. The simple real gas equation needs to compute the compressibility term Z (Eq. 1).

$$P \cdot V = n \cdot Z \cdot R \cdot T \tag{1}$$

The Z compressibility term will be used many times such as in the material balance routines, inflow performance relationship and vertical lift performance. Industry standard correlations like Z-Aga8 (ISO-12213), Viscosity (Lee, Gonzales & Eakin) or gas water surface tension computation as described by the Gray[1,2] correlation are used when dealing with PVT properties.

Density, critical temperature, pressure parameters and gross heating values are under the most widely used functions. Mainly hydrocarbon physical properties used in the DLL proceed mainly from the Gasunie Handbook[3].

Sub-module Material balance:

The current reservoir library contains two material balance equations for reservoir pressure calculation, the linear single tank material balance and the aquifer influx material balance. Over depletion time the reservoir pressure is re-calculated by the classical material balance method, assuming a simple tank model (see Figures 5 and 6).

The reservoir pressure is related to the volume cumulatively produced, the initial volume and the initial pressure. In case of activating the option aquifer pressure support this will create a reservoir pressure more elevated than the expected from normal depletion. The aquifer calculations use the Fetkovitch method, which is based on the amount of water influx, $W_e$. $W_e$ is calculated using the aquifer parameters $W_{ei}$ and $J$. Under this case the calculation of the reservoir pressure is a function of the aquifer support.[1]

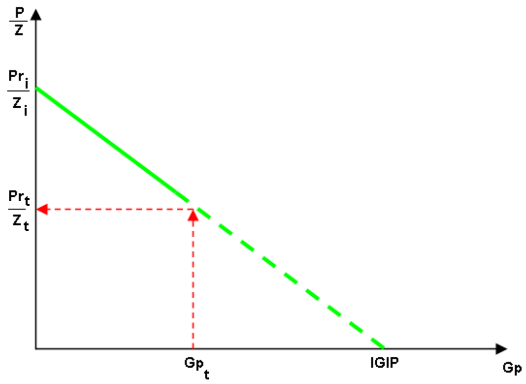


**Figure 5. Material balance and tank model.**

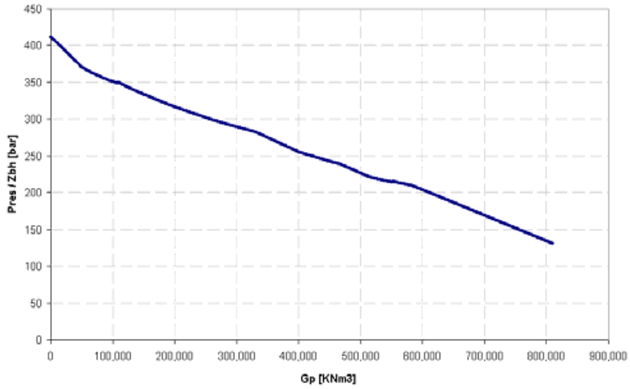


**Figure 6. Material balance in real time.**

Sub-module IPR (Inflow performance relationship):

The current engineering library contains a semi-steady-state inflow performance equation to compute the corresponding pressure from the reservoir to the wellbore. Two options are available in the model to calculate the flowing bottomhole pressure: the Russell and Goodrich approach, also known as the $p^2$ formulation and the Al-Hussainy – Ramey - Crawford solution technique, known as the pseudo pressure technique. The pseudo pressure method incorporates a better technique and is without doubt preferred above the $p^2$-method. Theoretical tests and tests with real time field data have confirmed to give better results over a wider range of pressures. The Forchheimer's equation is used to describe the additional pressure drop due to convective accelerations of fluid particles in passing through the pore spaces (non-Darcy effect)[1,4].

Under this sub-module we take into account all relevant parameters such as reservoir drainage area, reservoir pressure and temperature, reservoir height, permeability, skin, perforated interval, wellbore radius, produced flow rate, etc. Central part of this sub-module is defining the corresponding Inflow performance relationship (IPR).

Sub-module VLP (Vertical lift performance):

The reservoir capability to deliver gas into the well has to be combined with the vertical lift performance. For a known well head flowing pressure (*WHFP*) there is present a related bottom hole flowing pressure (*BHFP*), which is a function of the hydrostatic gas pressure difference and the friction pressure losses. The sub-module VLP includes the Cullender-Smith method to model the pressure drop in the wellbore[5,6]. Currently this is computed based on dry gas assumptions. The vertical dynamic and static parameters, lift parameters $B_{lift}$ and $C_{lift}$, can be calculated with real time data and/or establish from a three rate test. The gas production rates and their corresponding measured *WHFP* and calculated BHFP are illustrated in Figure 7.

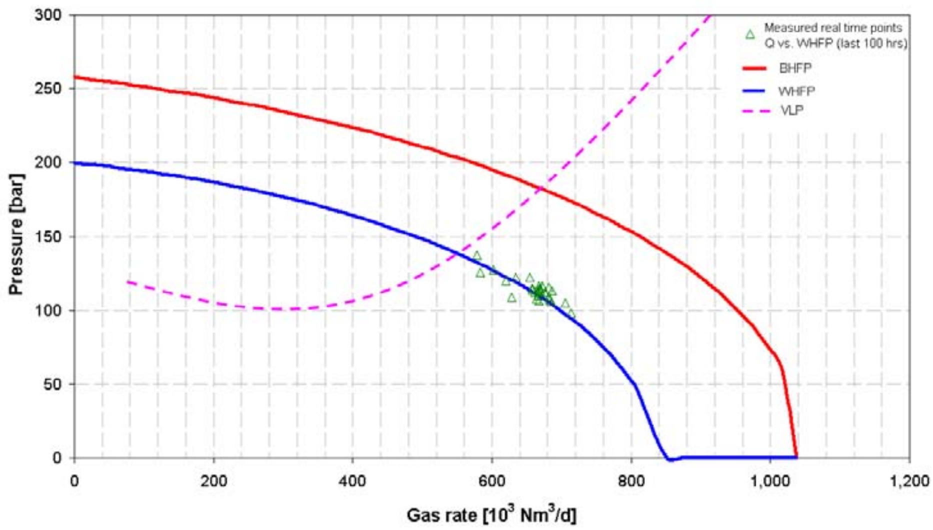


**Figure 7. Material balance and tank model.**

Sub-module choke:

Under current development there is a model to predict the pressure drop over a choke. This will give valuable information for the subsurface modelling which will allow to calculate the pressure drop over the manifold comparing it with real performance and identify if the choke is a bottleneck in the system, wear of a choke, hydrates formation near it (by monitoring the related temperature before and after the restriction), plugging by salt accumulation or excessive water formation being produced in a well. This submodel can be applied at many nodal points of the system.

Sub-module separator:

The essence of this model is to keep a track on the mass balance for the gas, water and condensate amounts. This model calculates the associated water production rates per day. Associated water is water condensing from the gas due to the difference of reservoir conditions to separator pressure and temperate conditions. This module makes use of the water-vapour curves[7]. It has already proved to be a useful tool to detect water mass imbalance, allocate water production per well and advice on flow meter calibrations. Currently more research and testing is required to be full functional in the real time environment.

Overall interaction and results:

The reservoir function library offers a transparent set of engineering functions that are used by the Wintershall engineers as a basis for performance evaluation and production forecasting. From the source (reservoir) to the sales points the most important and critical components can be modelled and checked with real time data coming out from the offshore platform. Figure 8 shows the reservoir-well GUI (graphical user interface) running real time under the Matlab® environment. This illustrates for a specific selected well: flow rates, measured well head flowing pressure, the corresponding calculated *WHFP* and underneath the residue on measured and calculated surface production data ($WHFP_{measured} - WHFP_{calcuated}$). In addition, the overboard density is continuously monitored and an important parameter is always kept in eye to be alerted in case of formation water production. A residue of zero in the *WHFP* will verify that the reservoir-well model is tuned to measure field data and confirm performance matching. Observing trends on the residue is an immediate action point for the reservoir and/or production engineers to start finding the source for the alteration, model different scenarios and make if it is necessary forecast predictions with numerical simulators to avoid imminent production losses.

Extending the functionality to the real time environment was a straightforward step as the DLL has permitted its easy integration. Standardizing the unit system and extending the library with additional functionality will assist each component of the upstream and downstream process to be checked in real time on performance, deterioration and maintaining fine-tuned models of the entire processes. This will improve the control of the processes enabling a better, more reliable and faster decision-making.

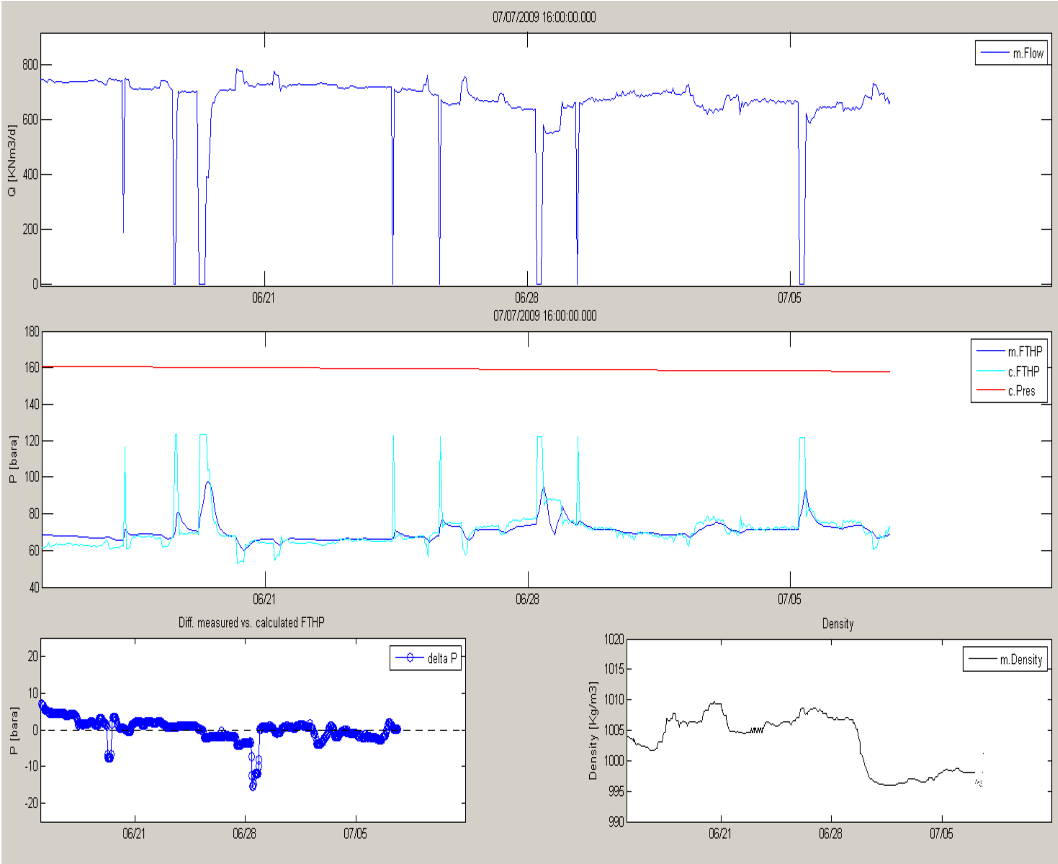


Figure 8. Reservoir-well GUI.

## Salt precipitation module:

The F16-A and E18-A reservoirs show a strong tendency for salt precipitation in the (near) wellbore region. As the recovery progresses it was noticed that halite crystallisation decreases significantly the production rate and in the worst case, if the well is not treated it might complete block the flow path leading to a production stop. The effect of the accumulation of salt in the matrix and wellbore can be appreciated in Figure 9, with the characteristic of a rapid decline in flow rates and a divergence in the model response. For the specific well F16-A6 a stable production rate can not be maintained for more than 4 days without a water-wash.

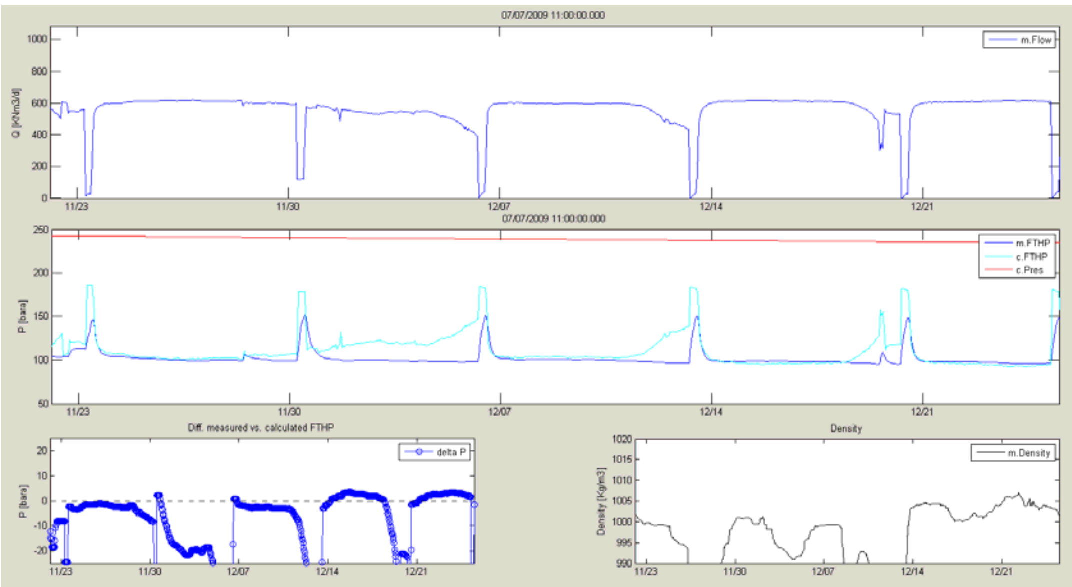


Figure 9. Reservoir well GUI for a well with extreme salt plugging effect (well F16-A6).

Current practice in F16-A is to wash the wells with a fixed amount of sweet water in order to restore fully production. The examination of productivity index decline reveals that halite precipitation is due to connate water evaporation as a function of the pressure drop in the vicinity of the wellbore and around the perforated zone. Salt accumulations have been confirmed by mechanical wireline and video camera surveys (Figures 10 and 11).[8,9]


**Figure 10. NaCl scale in the perforated zone (well F16-A1).**


**Figure 11. Perforated zone of Fig 7 after a water-wash (well F16-A1).**

In addition to the salt precipitation studies performed by Winterhall, it was necessary to have a tool to evaluate changes in productivity index real time and react more rapidly in a consistent and reliable way to this type of NaCl scaling. As part of the extension of unit modules and for further production optimization of the F16-A and E18-A asset, two functional modules have been developed to mitigate this type of problems. Figure 12 shows the structure and the interaction of the models considered in the build application.

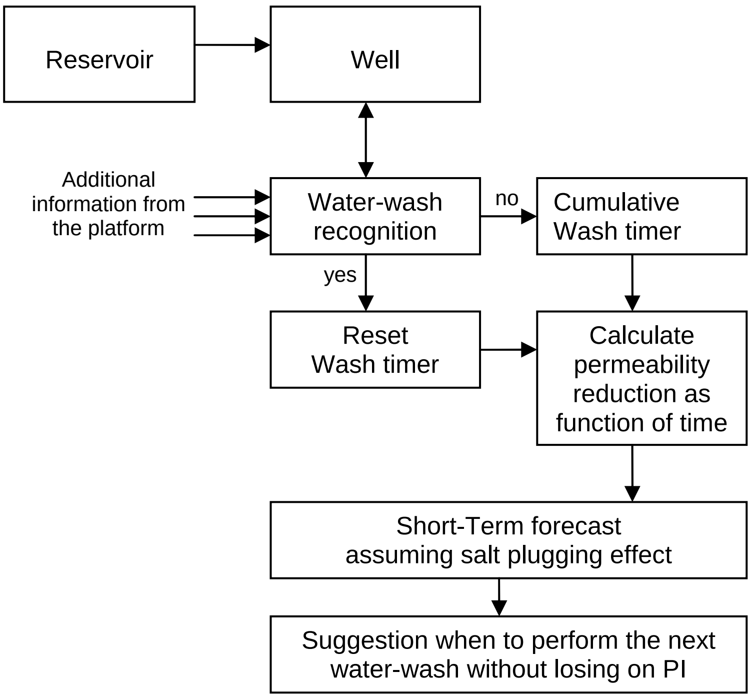


**Figure 12. Structural flow diagram for estimating salt precipitation.**

## Water-wash module:

The water-wash module has the functionality to detect when a water wash is performed in any well of the platform. It is necessary to have a virtual time counter in each well and reset it in case of a water-wash treatment. It consists primarily of five independent events:

1. Detection of a well-shut in.
2. Water pumping units are switched on.
3. Detection of start of production of same well in 1) (at least after 2 hrs).
4. Typical recognition of the overboard density peak after wash (salt is being removed).
5. Confirmation of the restored productivity of the well i) in between 12 hours of production.

## Salt precipitation module:

The salt precipitation behaviour in the near wellbore reservoir was physical described and simulated with Matlab© using a standard IMPES simulation method and taking into account: [8,9]

- The evaporation and salt precipitation kinetics.
- The loss of part of the porosity and permeability distributions due to NaCl precipitation.

Choosing this approach the salt prediction models contain sufficient complexity to describe salt scaling around the well, while at the same time the model is kept as simple as possible. Each well prediction and the analysis of deterioration in PI have shown that each treatment restores fully the original productivity and a similar decline is imposed every time to the production as can be seen in Figure 13.

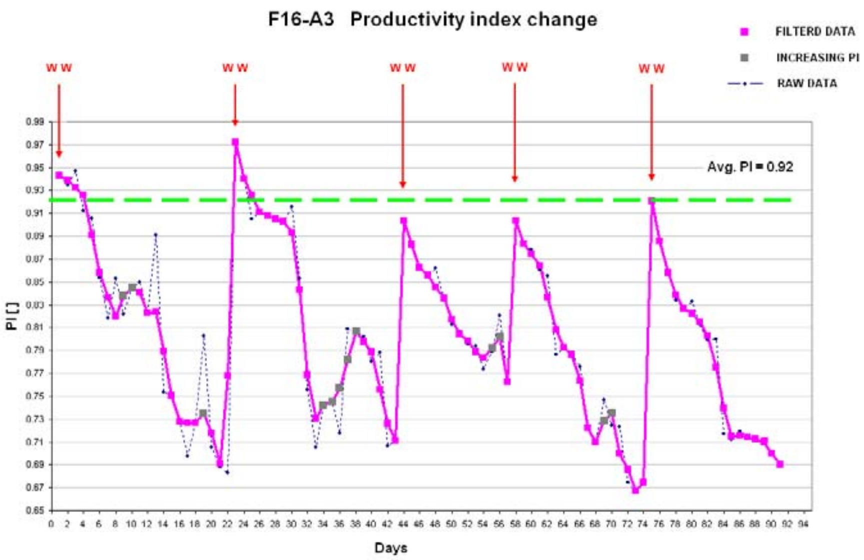


**Figure 13. Evaluation of the productivity index over time after each water-wash.**

The analysis in each individual well has shown that the degradation of PI behaves exponentially over time and can be fitted to the Eq. 2:

$$PI_{change\ over\ time} = A \cdot \left[ 1 - e^{\frac{t}{tau}} \right] + B \qquad (2)$$

Evaluated real time data with Eq. 2 was translated back to a deterioration of the matrix permeability to allow a prediction forecast as a function of time. Figure 14 shows as raw data the necessary permeability to have a 0 (zero) *WHFP* residue over a history of ½ a year and the best fit through the data (using the same formula as Eq. 2).

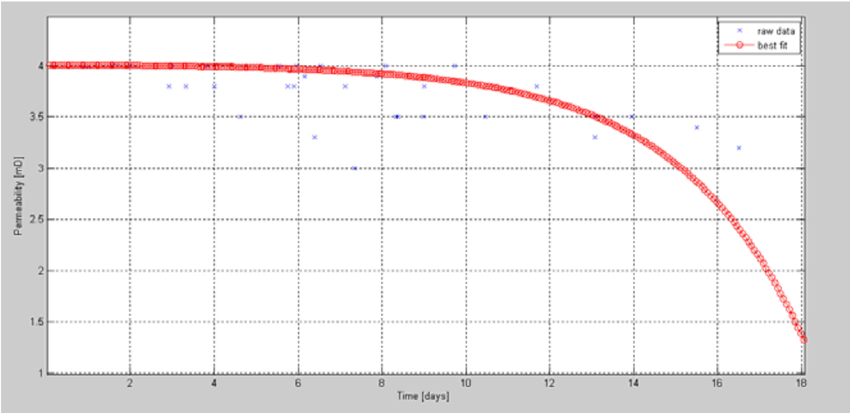


**Figure 14. Permeability reduction as a function of time.**

Using this approach an effective, reliable and accurate method based on the coarse regulator (change of permeability over time) was found to be used in a real time environment. Figure 15 shows the graphical interface presenting the most important data for the engineers and operators:

- On the top chart the current flow rates of the well selected.
- On the second chart the model *WHFP* vs. measured *WHFP,* and expected WHFP over the next 150 hours.
- On the bottom chart the predicted left time for production without a wash.

This figure shows that 90 hours are left for a stable production. Over previous intervals can be seen when the water-washes courter was reset to zero.

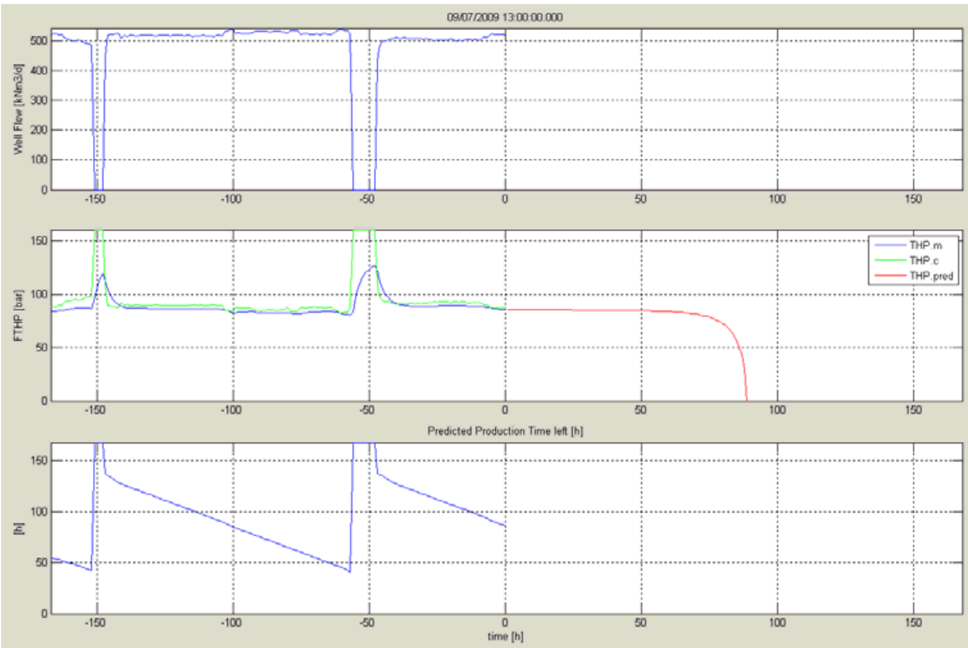


**Figure 15. Salt precipitation GUI.**

## Compressor module:

This model has identified a key area for improvement that could be used based on real time monitoring of a compressor and gas turbine unit, increasing the reliability of the short,- medium and long term forecasting. Once a gas field has reached the stage where it can not flow freely with fully opened chokes, a gas compression unit is required to maintain production. The actual maximum volume of gas delivered becomes dependent upon the performance of the gas compressor and the gas turbine. These compressor units determine operating conditions that may affect the reservoir, wells, gathering system and process equipment.[15] In order to determine actual and future operating points of the compressors and keep a track real time on the performance, a "3D compressor" module was developed at the first stage under visual basic code for Excel environment.[10] This code was migrated partially in 2009 to Matlab© environment and has allowed a faster and more sophisticated analysis as it will be briefly discussed in this section.

The most important parameters related to the aerodynamic and thermodynamic theory in centrifugal compressors have been taken into account and described as functions that can be found at many specialized publications and books of gas compressors.[11-14] It is relative simple and straight forward to monitor the efficiency and performance of a compressor using Equations 3 to 8.

$$Isen\_head = \frac{287{,}04 \cdot T_1 \cdot Z_{av}}{\left(\frac{k-1}{k}\right) \cdot SG}\left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right] \tag{3}$$

$$k \cong 1{,}3 - (0{,}31) \cdot (SG - 0{,}55) \tag{4}$$

$$P_2 = \left[\frac{P_1^{\frac{\kappa-1}{k}} \cdot \left(\Delta h_{isen} + \frac{T_1 \cdot z_a \cdot R}{\left(\frac{\kappa-1}{k}\right) \cdot SG}\right)}{\frac{T_1 \cdot z_a \cdot R}{\left(\frac{k-1}{k}\right) \cdot SG}}\right]^{\frac{\kappa}{\kappa-1}} \tag{5}$$

$$\Delta T = 100 \frac{T_1}{\eta_{isentropic}}\left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right] \tag{6}$$

$$T_2 = \Delta T + T_1 \tag{7}$$

$$PKW = \frac{14{,}961 \cdot (H_{isen}) \cdot Q_{std}}{\eta_{total}} \tag{8}$$

As shown in Figure 15, the performance of centrifugal gas compressors is best displayed in a map showing isentropic efficiency and isentropic head as a function of the actual inlet flow with the compressor speed as a parameter. Compressor performance curves show, on coordinated of isentropic head and actual volumetric flow rates, lines of constant speed and lines of constant isentropic efficiency.

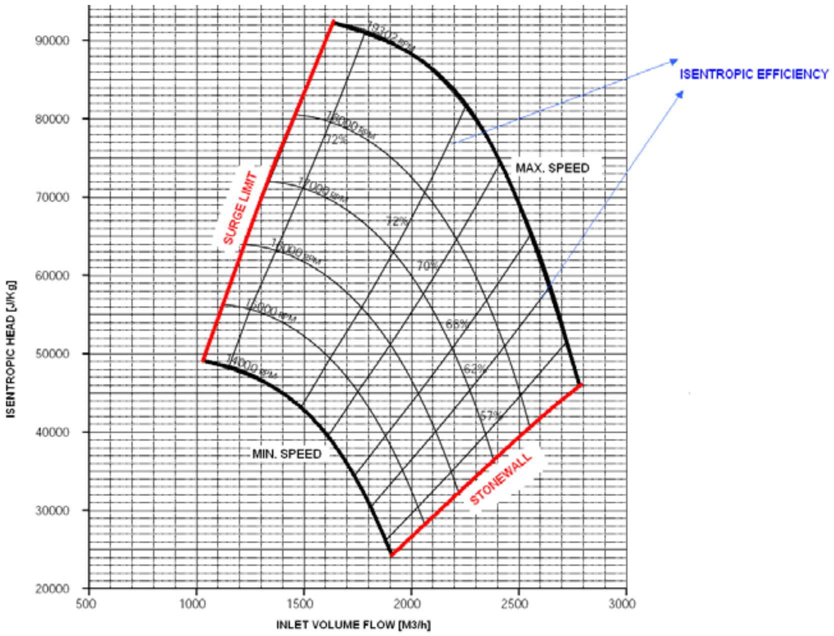


**Figure 16. Typical performance curve for a centrifugal compressor.**

The developed 3D compressor module uses the performance curves as provided by the manufacture. Making use of all the equations stated before it is possible to evaluate the expected values with the one measured real time on the field (rotational speed, suction temperature / pressure and discharge temperature / pressure).

Figure 16 shows where all operating points should be theoretically located (assuming one to one the operating envelop as delivered by the manufacturer). A filled 2-D contour plot of Figure 17 is shown in Figure 18. This confirms a smooth increase in isentropic head when increasing the rotational speed of the compressor.

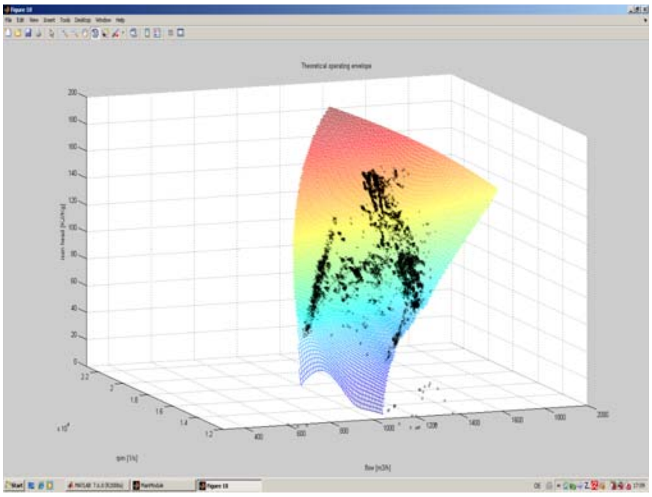

**Figure 17. Theoretical 3D Performance of the compressor (Isentropic head).**

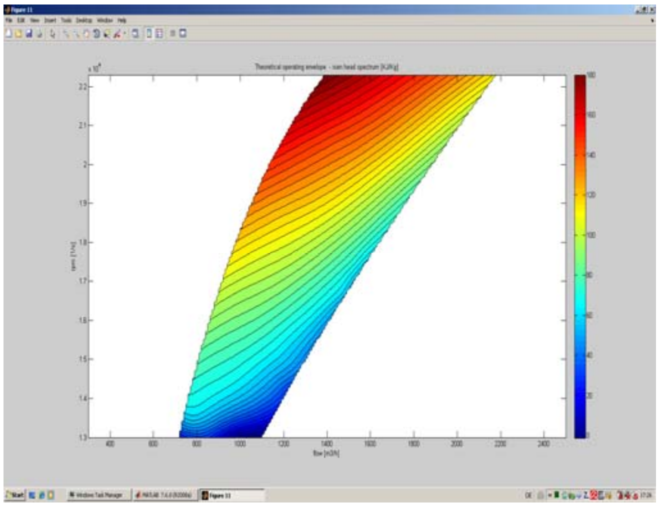

**Figure 18. Theoretical 2-D contour plot performance of the compressor (Isentropic head).**

Looking now at a compressor that was running for over 12.000 running hours, the reality is complete different. Figure 15 shows the real measured operating points over a period of 3 months. Solving the equations for the isentropic efficiency it is possible to evaluate how the isentropic efficiency behaves over the operating points. Figures 19 and 20 illustrate the actual real available isentropic head and isentropic efficiency that the compressor is having on the offshore platform F16-A. The analysed 2D contour plots show a significant reduction in isentropic head and efficiency at a flow of 1400 m3/h.

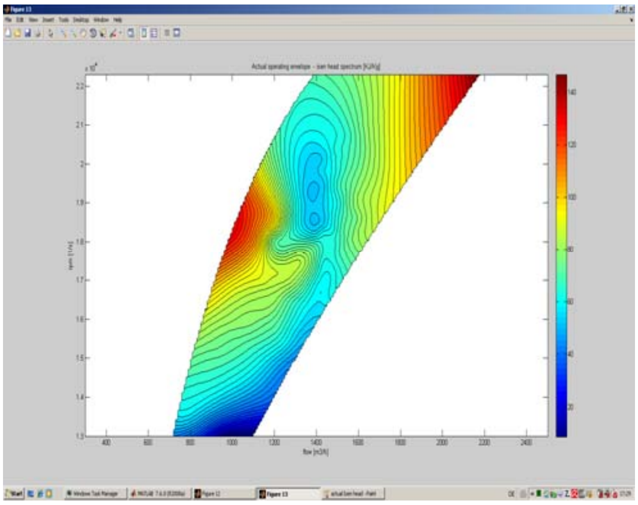

**Figure 19. Real time measured 2-D contour plot performance of the compressor (Isentropic head).**

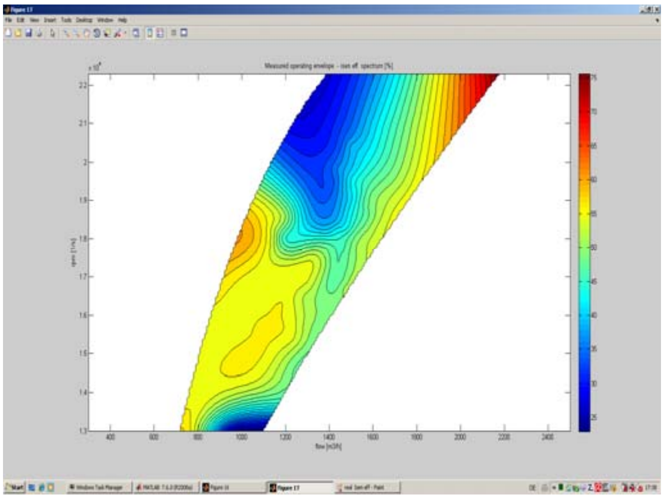

**Figure 20. Real time measured 2-D contour plot performance of the compressor (Isentropic efficiency).**

The original running conditions of a centrifugal compressor may be altered over time by different conditions like:

- Contamination by impurities.
- Erosion.
- High vibration.
- Unusual recirculation losses.

These detrimental factors can change significantly the original operating performance curves. In the analyzed compressor of F16-A we expect the aerodynamic properties to be altered. Figure 21 gives an idea what might be ongoing in the interior of the centrifugal compressor. It shows a picture of the condition of the impeller of the offshore platform L8-P4 after disassembly (this unit was still running up with ca. 18.000 running hours. At that time a decrease of -13 % in isentropic head and -15 % in isentropic efficiency was noticed).

**Figure 21. Corrosion and pitting noted at the impeller.**

The performance curves delivered by the manufacturer are always for new compressors as measured on aerodynamic performance tests. Since the performance of the compressor can change significantly over time it is essential to keep a track of the real potential that certain units can deliver. This is necessary to assure current production rates and evaluate which effects might be on the future production.

Figure 22 shows the expected operating envelope vs. the tuned real time for a discharge pressure of 107 bar. As can be appreciated at high flow rates and low pressures a considerable part of the operating envelope is currently limited. For a flow rate of 2200 KNm3/d the current minimum suction pressure is 55.0 bar instead of 46.0 bar. This 9.0 bar that are missing are currently being under investigation. The shown pink envelope is the overall and line of maximum performance that the entire units gas compressor – gas turbine can deliver.

The current develop compressor module has proved to assist us with:

- Coupling well productivity indices to the operating envelope of the compressor.
- Guarantee nominal daily contracted quantities (DCQ).
- Guarantee maximum daily quantities (MCQ).
- Assist to make a much reliable short and medium term forecast.
- Find immediately if we have potential to produce more if required.
- Assist with future scheduling for restaging, cleaning and maintenance.

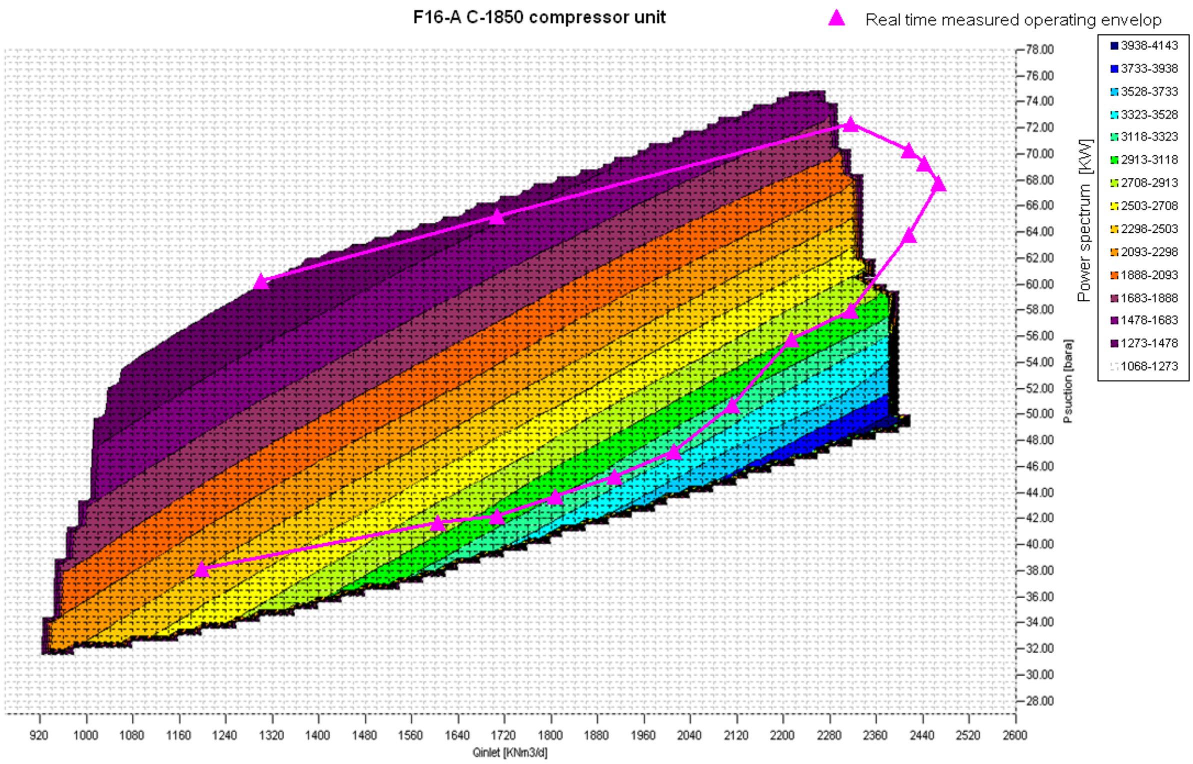


**Figure 22. Original operating envelop spectrum vs. real time calibrated.**

## Overall Dry Gas Mass Balance Monitoring

The overall mass imbalance e(t) is a function of time and is calculated as:

$$e(t) = \left[ Q_{export}(t) + Q_{vent}(t) + Q_{own\_use}(t) - \sum_i C_i(t) Q_{well\_i}(t) \right]$$

where $Q_{export}$ is the dry export flow, $Q_{vent}$ the vent flow, $Q_{own\_use}$ the gas flow used by the platform, $Q_{well\_i}$ the wet gas flows from individual wells and $C_i$ the dry/wet gas correction factors.

The mass imbalance is real-time monitored. The mass balance monitoring module also computes the limits between which the mass imbalance is in its normal range. Exceding the limits is detected as an off-normal condition (event). Figure 23 shows the computed mass imbalance and its computed normal range limits.

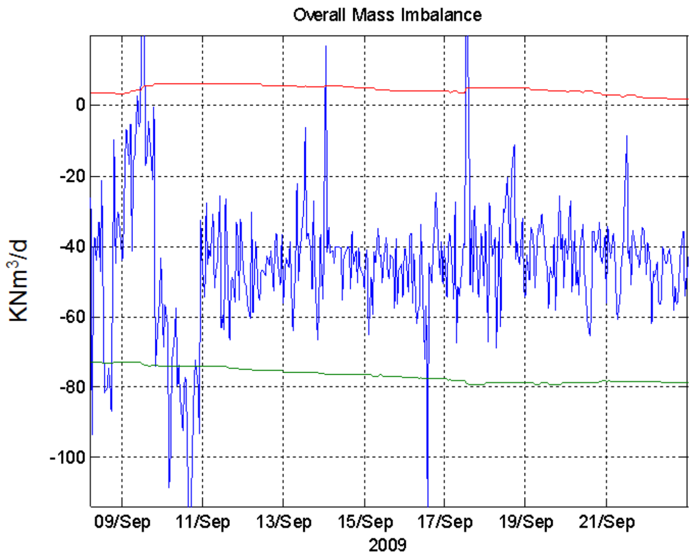


**Figure 23. Overall mass imbalance monitoring function.**

### Wet gas Well Flow Correction Monitoring

The precise allocation of gas flow to a well is an important issue. Each well is metered, but flow measurement is based on the wet gas flow and is therefore influenced by a changing water content of the flow. The normal procedure is to calibrate measurements in a scheduled way several times a year. Real-Time monitoring provides a way to improve on this. The measurements of the wet flows, the dry flows and the overall mass balance (model) make it possible to monitor the dry gas flow contribution of each well to the total flow, check the well flow measurement and estimate the water content of each flow. Furthermore the water content is an important reservoir monitoring aspect.

The well flow monitoring module uses the overall mass balance as the model and the measurements of the wet gas well flows and the accurate measurement of the dry gas export flow, vented gas and gas used for own use by the platform as the inputs. The correction factors $C_i$ of the well flows are the parameters to be estimated. In steady state operation it is not possible to estimate the correction factors, because there is no unique way to distribute the overall mass imbalance to the wells. However, we exploit the dynamical nature of normal operation (dynamic changes in well flow setpoints and well shut-ins) to discriminate between wells and to estimate correction factors for each well. We do this by taking the mass-balance model and the flow measurement data as inputs to an optimizer that estimates the water content dependent correction factors for the measured wet gas flows. The result is used as an indicator for water content (calibration), back allocation and flow measurement failure. As an example Figure 24 shows the result for one of the wells. The correction factor for the measured well flow is shown together with its 95% confidence region.

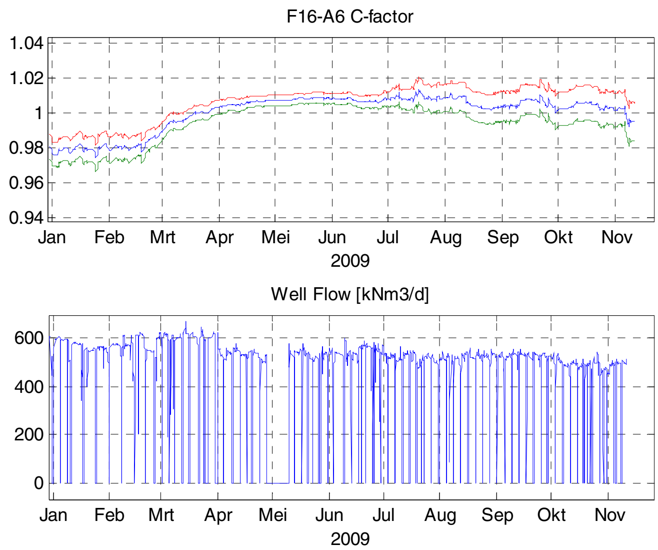


**Figure 24. Monitoring of the wet/dry gas well correction factors.**

## Results and Discussion

The process of coupling dynamic models with real time data at different nodal points from the source to the export point has shown practical and important benefits achieved so far. The data acquisition part, the validation, reconciliation and the implementation of a number of models are functioning in real time. The prototyping and engineering phase is progressing. The system is full functional, exclusive the functionality for data display and intelligent advice for the central control room. Extension of the models, the step to bring the system to the operational environment needs a careful implementation path which is currently under evaluation. Nevertheless, we have brought the already available static models in the dynamic Matlab® based framework. Petroleum engineers are able to develop and test their own models and implement them in a simple way to the existing framework.

The salt precipitation part is an example with direct production optimization improvements. Working with real time reservoir management has already generated in half a year measurable improvements in the total production of F16-A and E18-A. The nomination of sales amounts to buyers is slightly above its targets and the well performance is considerable better. The current developed application is assisting reservoir and production engineers to have early event detection of the salt plugging effect and give insight into the characteristic well performance deterioration.

The overall platform production for the year 2009 has increased to +3.2 % for F16-A (Figure 29) and +7.0 % for E18-A (last data available 1/12/2009, Figure 30). For E18-A it was possible a considerable increase in production in the last half of the 4$^{th}$ quarter 2009 due to recognition of a slow reservoir response, a dampened matrix response and a severe salt accumulation in the near wellbore area by the time the first forecast was presented. In the last years, as can be appreciated in Figure 25, important under deliveries were caused by the rapid salt plugging effect. Figure 26 shows the cumulative effect during the 1$^{st}$ quarter 2009. Comparing it with the 3$^{rd}$ quarter 2009 during the full implementation of the real time monitoring application a considerable better well response was maintained over time.

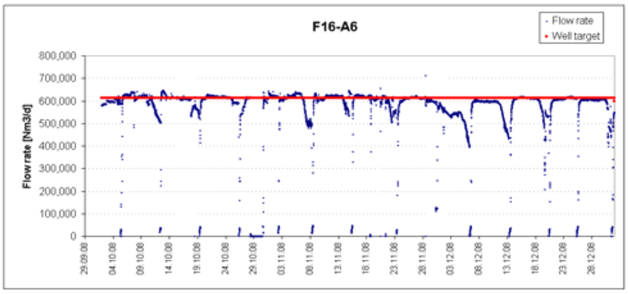


**Figure 25. Flow rate for F16-A6 during 1$^{st}$ quarter 2009.**

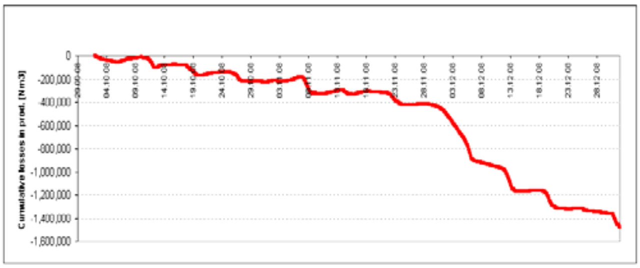


**Figure 26. Under deliveries due to salt plugging for F16-A6 during 1$^{st}$ quarter 2009.**

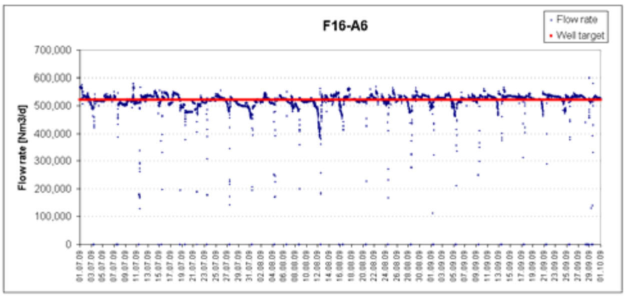


**Figure 27. Flow rate for F16-A6 during 3$^{rd}$ quarter 2009.**

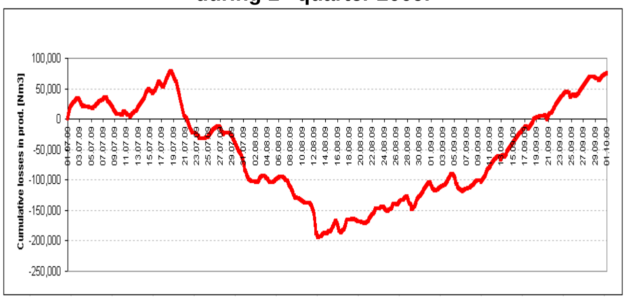


**Figure 28. Under deliveries due to salt plugging for F16-A6 during 3$^{rd}$ quarter 2009.**

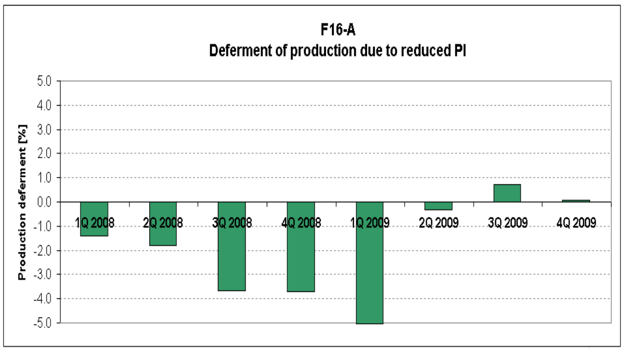


**Figure 29. Deferment of production for F16-A caused by rapid well deterioration.**

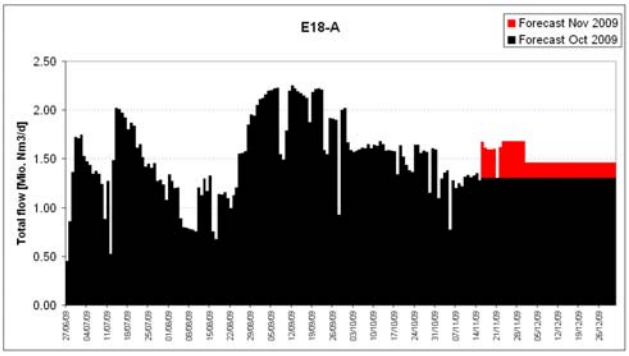


**Figure 30. Realisation of E18-A production and comparison with forecasted production from November 2009 onwards.**

## Conclusion

In an advanced production and reservoir management level, computational power helps us nowadays not only in the solution of severe production problems and the early event detection, but also in the optimization of production and the support to operators and engineers in their daily work. Subsurface and surface capacity is correctly aligned. The amount of underdeliveries is reduced. Well performance is presented at high resolution, which enables us to interpret the reservoir, matrix and well response individually. Discussions between production engineers and reservoir engineers have taken place on a higher level. They look at the same pre-processed and validated data which allow aligned communication between the different disciplines.

Resulting significant improvements are:

a) To identify and determine the nature of pressure maintenance effects in the reservoir.
b) The capability to identify salt plugging and remove salt accumulation in the matrix before this leads to a reduced well capacity.
c) Debottlenecking of production at the centrifugal compressor, by having update operating performance curves and identify possible production reduction before this results in reduce capacity.

Calculating and visualising equipment performance allows a fast response to anomalies such as mass balance inconsistencies, identification of out of calibration instrumentation and or instrumentation errors which results in an improved work efficiency. Equipment monitoring allows production efficiency improvements and brings maintenance engineering on a higher level.

The project has been executed in close cooperation with TNO as step by step independent partial project blocks. Each block was engineered separately and generated the next block's specifications from the pilot onwards. It resulted in fast development of models, easy exchange of models and short development cycles without vendor lock-in.
The current monitoring system is already running 24/7 for several months, running about 40 monitoring functions in parallel, and proves to be very robust. The system proved to be easily extendible with new modules and deals flexibly with platform configuration changes.

## Acknowledgments

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## References

[1] Van Soest, C.: "Reservoir Add-In Function Description", Wintershall Noordzee BV internal report – Reservoir Engineering Department, 2006.
[2] Gray correlation, American Petroleum Institute, 1978
[3] Physical properties of natural gases, Nederlandse Gasunie, 1980.
[4] Fundamentals of Reservoir Engineering, L.P. Dake, ISBN 0-444-41830-X

[5] Cullender-Smith method: "Practical solution of gas flow equations for wells and pipelines", Trans AIME 207, p.281-287 / PETROLEUM PRODUCTION HANDBOOK, VOLUME 2, T.C. Frick and R.W. Taylor, SPE of AIME, 1962, p. 31-18
[6] Cullender, M.H. and Smith. R.V.: “Practical Solution of Gas-Flow Equations for Wells and Pipelines with Large Temperature Gradients.” ***J. Per. Tech.*** (Dec. 1956) 281-87: 7”ww. AIME. 207.
[7] Fundamentals of gas reservoir engineering”, (§3.2, p. 28-30), Jacques Hagoort, Elsevier 1988, ISBN 0-444-42991-3
[8] Salt Precipitation in Gas Reservoirs, SPE 122140-MS, Q. T. van Dorp, Delft University of Technology, M. Slijkhuis, Wintershall and P.L.J. Zitha, Delft University of Technology.
[9] SPEAD project report Bryan Hall Thompson, internal Wintershall Noorzee report, 2009.
[10] SPEAD project report Esteban Muñoz, internal Wintershall Noorzee report, 2006.
[11] Sapiro, L.: “Centrifugal compressor”, Aero-Thermodynamic concepts for selection and performance evaluation Solar Turbines, 1995
[12] Kurz, R. and Ohanian, S.: “Modeling turbomachinery in pipeline simulations”, Pipeline simulation Interest Group PSIG 03A1, 2003.
[13] Campbell, J. M.: “Gas conditioning and processing”, Vol. 2, 2000.
[14] Dr. Bohnenstingl and Bräuer, L.: “Natural Gas Technology”, Institute of petroleum engineering - University of Leoben Autria, 2002.
[15] Dr. Akhtar, M.S.; MSE Consultants Ltd. and Balls, N.: “The challenge of design and optimization of centrifugal compressors for the UK’s largest production offshore gas field”, Hydrocarbon resources Ltd, 2001.

## Symbols and abbreviations

| | |
|---|---|
| $Q_{export}$ | Dry export flow [Nm$^3$/d] |
| $Q_{vent}$ | Vent flow [Nm$^3$/d] |
| $Q_{own\_use}$ | Own used gas in the platform [Nm$^3$/d] |
| $Q_{well\_i}$ | Wet gas flow at each individual well [Nm$^3$/d] |
| $C_i$ | Dry/wet correction factors [Nm$^3$/d] |
| *BHFP* | Bottom hole flowing pressure [bar] |
| $B_{lift}$ | Static vertical lift parameter for Cullender-Smith correlation [] |
| $C_{lift}$ | Dynamic vertical lift parameter for Cullender-Smith correlation [Pa$^2$·s$^2$/Sm$^6$] |
| $G_p$ | Cumulative produced gas [Nm$^3$] |
| *IGIP* | Initial gas in place [MMm$^3$] |
| *IPR* | Inflow performance relationship [] |
| *J* | Aquifer productivity index [] |
| *n* | Chemical amount of gas [moles] |
| *P* | Pressure [bar] |
| *R* | Gas constant [8.314 J·K$^{-1}$mol$^{-1}$ ] |
| *t* | Time [s] |
| *T* | Temperature [K] |
| *V* | Volume [m$^3$] |
| *VLP* | Vertical lift performance [] |
| $W_{ei}$ | Initial amount of encroachable water in the aquifer [m$^3$] |
| *WHFP* | Well head flowing pressure [bar] |
| $WHFP_{calcuated}$ | Calculated well head flowing pressure [bar] |
| $WHFP_{measured}$ | Measured well head flowing pressure [bar] |
| *WW* | Water wash [] |
| *Z* | Compressibility factor [] |

Subscripts:

| | |
|---|---|
| *i* | Initial condition |
| *t* | At certain time step |