SNØHVIT LIFECYCLE SIMULATOR FROM WELLHEAD THROUGH PIPELINE AND LNG LIQUEFACTION TO OFFLOADING

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ABSTRACT

The Snøhvit LNG Development Project, operated by Statoil, represents a pioneer project in the history of LNG. It is the first LNG full-scale liquefaction facility ever built in Europe and is located in one of the most fragile marine areas in the world. The 4.3 MTPA LNG plant is constructed by use of novel technologies with strong focus on high energy efficiency and low emissions. It has therefore been essential to develop a lifecycle simulator to be used in design, commissioning and for operation preparations. This paper gives an outline of the benefits of developing a state-of-the-art engineering and operator training simulator. The simulator model is a comprehensive and high fidelity dynamic simulator model that includes subsea facilities (wells, subsea equipment, flowlines and multi-phase pipelines to shore) and all major parts of the onshore LNG liquefaction plant from slug catcher to LNG off-loading.

The system is interfaced with vendor-supplied emulations of the control system and the separate shutdown systems. In plant operation, the online Dynamic Production Model (DPM) of the subsea and inlet facilities will be used by the operators in the control room, to monitor and operate the plant efficiently and safely. It has been recognized that the simulator project has saved considerable time in the commissioning phase of the project. It is also expected that important savings will be done during start-up and in normal operation of the plant.

INTRODUCTION

Adopting new technology has allowed the Norwegian oil company Statoil, to develop the first LNG plant in Europe with subsea installation in the Barents Sea. In order to obtain as high energy efficiencies and low environmental emissions, strong focus has been put on using Best Available Technology (BAT).

The Snøhvit development area was discovered in 1984 and comprises three fields; Snøhvit, Albatross and Askeladd. The gas fields are situated on the Norwegian Continental Shelf at 71° North. The distance to shore is 140-160 kilometres.

The LNG plant has a production capacity of 4.3 MTPA LNG. The overall energy need in the offshore transportation, onshore processing and liquefaction is covered by a fuel consumption of less than 6% of the feed flow.

This paper describes how a dynamic simulator has been used throughout the project to solve the challenges in design, commissioning and operation preparations. Also, plans for how to use the simulator in the operational phase are outlined.

Main data for the Snøhvit LNG Project:

- Recoverable reserves: 193 billion cubic metres natural gas, 113 million barrels of condensate, 5.1 million tonnes of natural gas liquids

- Water depths: 250-345 metres

- Main pipeline: 143 kilometres, 28 inch diameter

- Annual export, 4.3 MTPA LNG, 3.1-5.7 million barrels of condensate, 150-250 000 tonnes of LPG

- Project schedule: Contractual gas deliveries 1 December 2007

- Investment: 58.3 billion NOK (~9.1 billion USD)

- Licensees: Statoil (33.53%), Petero (30%), Total (18.4%), Gaz de France (12%), Hess (3.26%), RWE Dea (2.81%)

- Liquefaction process: MFC (Mixed Fluid Cascade)

- Power consumption: 230 MW

- CO_2 offshore injection: 700 000 tonnes annually

SIMULATOR ARCHITECTURE

The Snøhvit project represents a pioneer project in the history of LNG. Dynamic simulation provides a means of managing the risks involved in several stages in such a project. In order to meet some of the challenges involved, it was decided that a simulator system should be developed. A dynamic model was developed using the D-SPICE dynamic simulator, including the integrated OLGA2000 model, handling the multiphase conditions in the subsea pipeline. This model is connected to a vendor-supplied version of the ABB Industrial IT control system (Melody Connect) as well as the safety system delivered by HIMA (H51q-HRS).

The extent of new technologies and new design concepts implied need for thorough testing and verification. It was crucial that the simulator should meet both the requirement to robustness and high fidelity. The Snøhvit LNG process is highly integrated, and thus very interactive. It was therefore important that the entire plant, from subsea installation and multiphase pipeline throughout the onshore process and LNG loading, should be included in one single model.
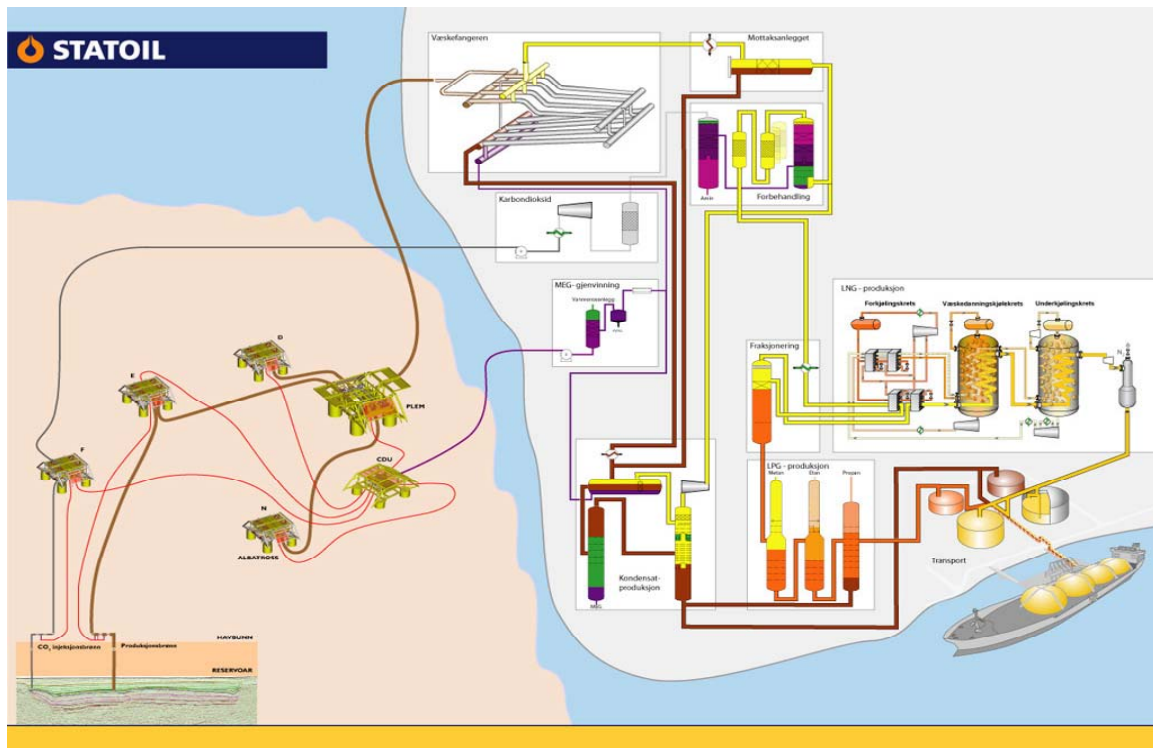

Figure 1. Illustration of the Snøhvit LNG process

For such a comprehensive process it was necessary to find a way to run large models faster than real time. The solution was to divide the total model in smaller sections and distribute them on multiple computers. However, even though the model and graphics are distributed, the user should only have to operate one model, i.e. run/freeze and save/load operations should only have to be done once. The complete model was split into 10 sub-models, as shown in figure 2, organized and synchronized by the master model. The master model coordinates all data transfer between the sub-models based on TCP/IP communication. The 50 graphic drawings of the whole process are based on PFD layout and are accessible from the master model. Even though the graphics are based on PFD's, the model detail is on P&ID level.
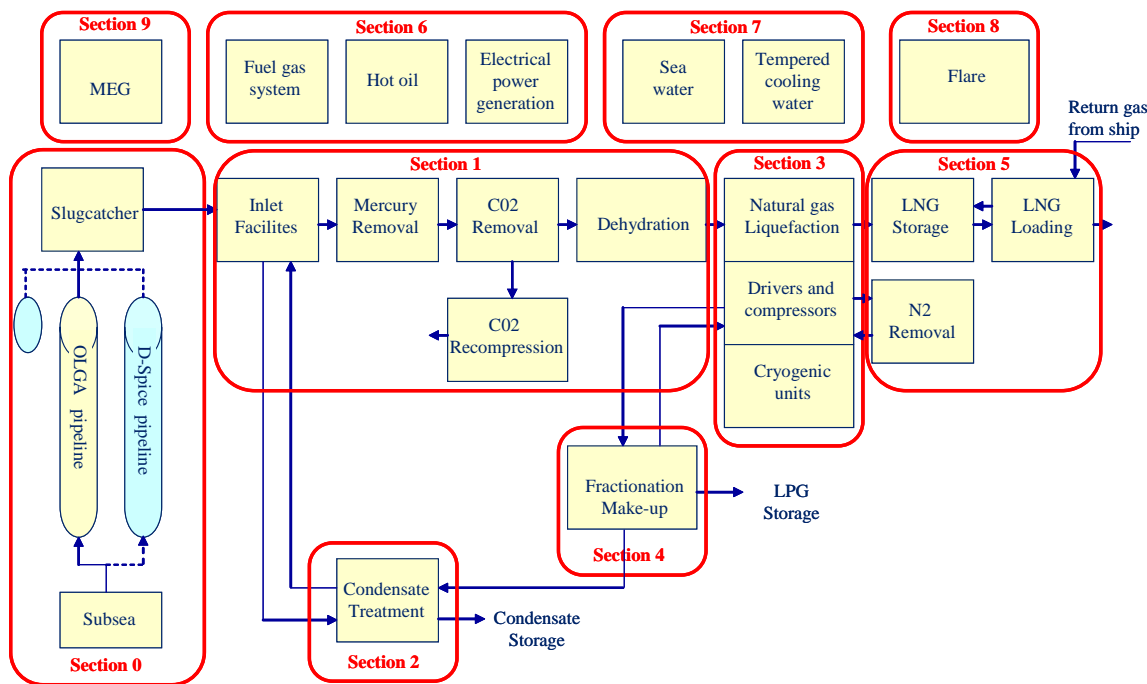
Figure 2. Overview of total model, divided in sub-models

A stimulated simulator comprising connection to third party systems adds complexity to the overall simulator package. More than 30 000 signals are transferred to and from the process model every 500 milliseconds. The signal transfer to the ABB control system emulator and the HIMA safety system emulator is performed by OPC with the process model acting as the OPC client.
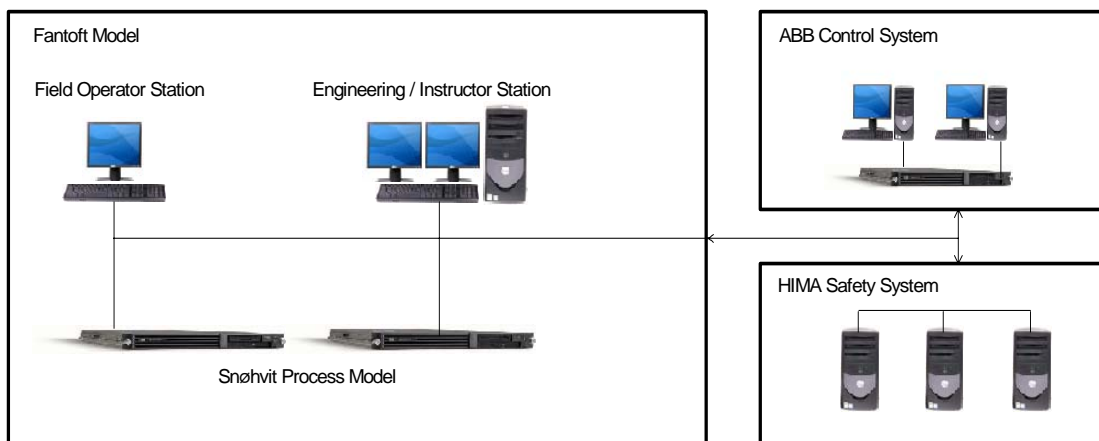
Figure 3. Architecture of the Operator Training Simulator

In order to connect the proper signals, an application was developed that could create field I/O lists based on I/O lists from both ABB and HIMA. Based on these lists a single I/O cross-reference list for the complete model is created with all the signals available in the model directly connected to both ABB and HIMA. Signals to or from equipment that are not included in the simulator model are connected to a response-emulator, within D-SPICE, where a dynamic response or static values for these signals can be set. In addition to provide process values to both HIMA and ABB, the D-SPICE model has to

act as the field bus. Communication directly between HIMA and ABB in the real plant is not supported in the software emulation of these systems, hence all signals transferred between ABB and HIMA using field bus in the real plant are emulated in the D-SPICE model. This resulted in an even more complex integration where detailed knowledge of these systems and how their signals are transferred and interpreted was required.

The total dynamic simulator model for Snøhvit runs on two servers each having two AMD Dual-Core Opteron 280 / 2.4 GHz processor. These servers run both the process model as well as handle all communication between the model, HIMA and ABB. A workstation with dual screen setup is used to run the instructor and engineering stations interface, and a field operator station is provided to simulate field operated actions.

LIFECYCLE MODEL STRATEGY

Utilizing lifecycle concept principles, it has been possible to use the same dynamic model throughout the different project phases. The coupling of the engineering model to the control system means that only one process model has to be held up to date. Constant development of the concept, based on experience gained from earlier complex project, has resulted in a lifecycle concept that prevails as state-of-the-art.

The following sections describe how the lifecycle concept has been applied in the Snøhvit LNG project. The lifecycle concept is illustrated in Figure 4 below.
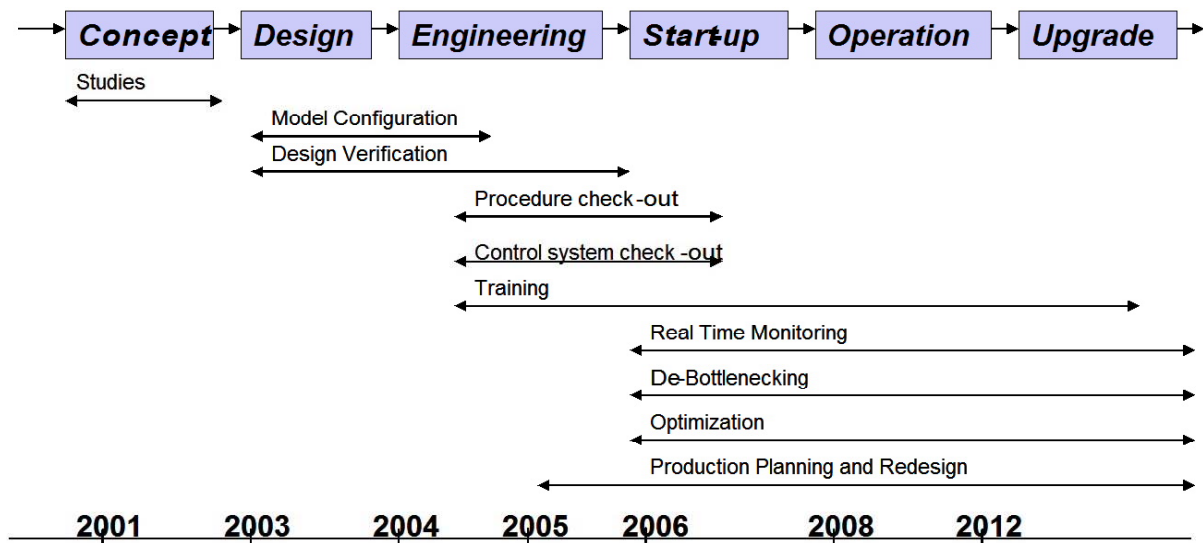
Figure 4. The Lifecycle Concept Applied in the Snøhvit LNG Project

The Simulator As An Engineering Tool. From the earliest stage the lifecycle concept was to be exploited to it's fullest. Fantoft Process Technologies (now a part of Kongsberg Maritime) was chosen to perform analysis and verification of slug catcher capacity and control philosophy at an early design stage. Having built a model for the slug catcher system, the D-SPICE model was then extended to incorporate all the primary process equipment plus major utility systems.

Process And Control Design Verification. Typical issues discovered and revised during verification of process and control design included:

- Valves sizing and stroke times

- Vessel capacity

- Compressor performance and surge protection

- Analysis of liquid entrainment in the compressor suction drums

- Pump performance

- Control structure performance. In the fractionation train, for example, the control strategy has been revised to improve the operational stability of the columns.

- Sequence logic improvement

Modification of the process design was carried out in several steps with each step implemented in the model to reflect the improvements. In this way the new design was verified and validated through simulation. The simulation package includes standard control modules so that control strategies can be implemented directly from the process drawings. This functionality also allows for the prototyping of new or alternate control strategies in the model before implemented in the control system. More than 500 items were identified during this activity resulting in the resolution of several major problems and the overall improvement in the design.

Control System Checkout. As a result of using the simulator for Process Control and Data Acquisition (PCDA) checkout, several control system and process design issues were discovered and resolved before the final design of these systems was completed. Checkout of the control system has been carried out over an extended period that will have payback during the commissioning period. Issues sorted out in the control system checkout are typically reversed logic, inconsistent logic, missing signals and signal mismatch.

The simulator has during the checkout period been used to test a number of design philosophies for the Human Machine Interface (HMI) on PCDA. This testing includes redesign and new design of operator graphics and alarm management system. In order to have a stable and realistic model for training, tuning of controller parameters in PCDA has been done during checkout of the simulator. These parameters will serve as a starting point for tuning parameters in the real PCDA prior to start-up.

Procedure Checkout. The Snøhvit LNG plant is first of its kind. It is therefore, even more than in other plants, important to have well tested procedures before start-up. The engineering company and the various equipment vendors provided procedures. Even though the engineering company recommends and develops procedures for different scenarios, it is challenging to predict the plant behaviour, especially in upset situations. In close cooperation with the plant designers, the simulator has allowed the procedures to be tested, evaluated and revised. Procedures for both initial start-up and normal operation have all been undertaken on the simulator. Based on these different tests, new and fit-for-purpose procedures have been developed and tested, and operational issues are passed back to the engineering team for revision.

Since the real control system has been used and the dynamic simulator provides representative dynamics similar to the real plant, the procedures are expected to function on the complete and commissioned facility.

Training. Training of process operators has been executed more than two years in advance of the plant start-up. A total of 80 operators along with several engineers have been trained in topics such as process control, plant dynamics and operational procedures. The operational staff are now highly qualified for the demanding task of operating this complex process efficiently and safely.

The operators use the simulator to learn and rehearse a number of operational situations. Typical elements included in the simulator courses are:

- Familiarization of control and logic
- Process understanding
- Normal operation of the LNG facility
- Process start-up and shut-down
- Handling of process upsets and unplanned situations
- Emergency training
- Alarm management

Use of the simulator for operator training will continue also after plant start-up. When the plant is in stable operation, operator refreshment courses will be necessary to maintain skills as handling upsets and emergency situations. In addition, the system will be used to train new operators.

Real Time Monitoring. Remote operation of offshore fields and pipelines over a distance of 143 kilometres calls for careful monitoring. The pipeline can be blocked by the formation of hydrates, ice or scale. In addition liquid may accumulate in the pipeline. The pipeline must then be operated so that the liquid emerging from the pipeline does not exceed the capacity of the receiving and processing plant.

The Dynamic Production Model (DPM) for Snøhvit was developed in order to assist the operators in handling the pipeline in a safe and efficient way. The DPM will, as indicated in Figure 4, first come into operation when the plant is ready for start-up. However, the model was finalised more then two years before plant start-up. This has made the operators able to train on the DPM more then 18 months prior to start-up. A more detailed description of the DPM will follow in a later section of this paper.

Optimization. The simulator will continue to be used for engineering after initial start-up for plant optimization. By updating the simulator with real steady state values the operating conditions can be optimized through de-bottlenecking and connection via OPC to optimizer tools such as SEPTIC (Statoil Estimation and Prediction Tool for Identification and Control). SEPTIC is Statoil's in-house software for model predictive control (MPC) and real time optimization (RTO). At Snøhvit, MPC controllers are intended to be used on the fractionation columns and on the control and optimization of the refrigerant composition in the three refrigerant loops.

MAIN DETAILS IN SIMULATOR DEVELOPMENT

The D-SPICE simulator development tool uses a drag-an-drop online graphical HMI for model configuration that includes a standard module library. The D-SPICE environment is open, flexible and makes extension of new functionality straightforward. This section will describe some of the main details of the simulator developed.

Model Decomposition. In order to distribute models on several CPUs, a system was developed that could handle the flow of material between two sub-models. This can be solved either explicitly or implicitly. The explicit solution is to copy the pressure from the upstream sub-model, into the down-stream sub-model. For this to work, it is necessary to make the break between sub-models in a vessel width large enough capacity to damp numerical instabilities. To overcome this limitation an implicit solution was developed. In this approach each boundary in a sub-model communicates flow, pressure and derivatives of flow width respect to pressure to the master model. The master model contain an equation solver that co-ordinates the solution for all sub-model boundaries.

To make the user able to operate one large main model, a sub-model handler was developed. This module represents a complete D-SPICE sub-model within the main model comprising several sub-models. The module encapsulates the model structure within the structure of the main model. Commands, such as load, save, run or freeze given to the main model will be forwarded to the sub-model through functions implemented in the handler. This insure that each separate sub-model within a main model can be handled in synchronism

Module Library Update. The Mixed Fluid Cascade (MFC) process developed in the Statoil/Linde alliance is in principle a cascade process, with the important difference that pure refrigerant cycles are replaced with mixed refrigerant cycles, and thereby improving efficiency and operational flexibility. The process is new, and without any industrial references. Therefore, developing high fidelity modules that could be used in the model was of great importance to test the design. The concept consists of well-known elements, where the liquefaction process utilizes Plate-Fin Heat Exchanger (PFHE) for pre-cooling and separate Spiral-Wound Heat Exchangers (SWHE) for liquefaction and sub-cooling.

A new highly configurable module was developed in order to model both the PFHE and SWHE. This module simulates the behaviour of a process stream inside a heat exchanger. Two or more instances of this module can be used to configure ordinary two-stream heat exchangers as well as multi-stream heat exchangers. The module has two main parts: the fluid and the wall surrounding it. The fluid exchanges heat with the surrounding wall. In addition, it is possible to connect external surfaces (walls) that exchange heat with the fluid. Furthermore, it is possible to configure direct heat transfer between the local wall and external walls. The new module can be used for many different process design configurations. Besides the PFHE and SWHE this module can be used to simulate process stream coils in a vessel. For instance, the module is used in the fractionation columns to simulate the condenser (heat exchanger) that is integrated in the top of the column.

Thermodynamics Update. In the Snøhvit simulator model, Fantoft Process Technologies (now a part of Kongsberg Maritime) applies first principle thermodynamics using Multiflash (from InfoChem), which provides accurate and robust calculation of the

conditions and fluid properties using Equation of State thermodynamics. Through the Snøhvit simulator project the thermodynamic package has been verified to handle the conditions relevant for the LNG process. The network solver and several modules were updated in order to ensure stability and robustness of the model.

DYNAMIC PRODUCTION MODEL – AN ONLINE SIMULATOR

The Dynamic Production Model (DPM) is used as a "window-into-the-pipeline" and is a dynamic simulation model of the pipeline conditions. Each pipeline segment (branch) in the DPM is represented either by the D-SPICE's dynamic single-phase pipeline model D-PIPE or OLGA2000 multi-phase pipeline simulator. There are no measurements in the pipeline, the boundary conditions for the model is therefore based on the inlet and outlet conditions. An illustration of a typical DPM setup in D-SPICE is shown in figure 5.
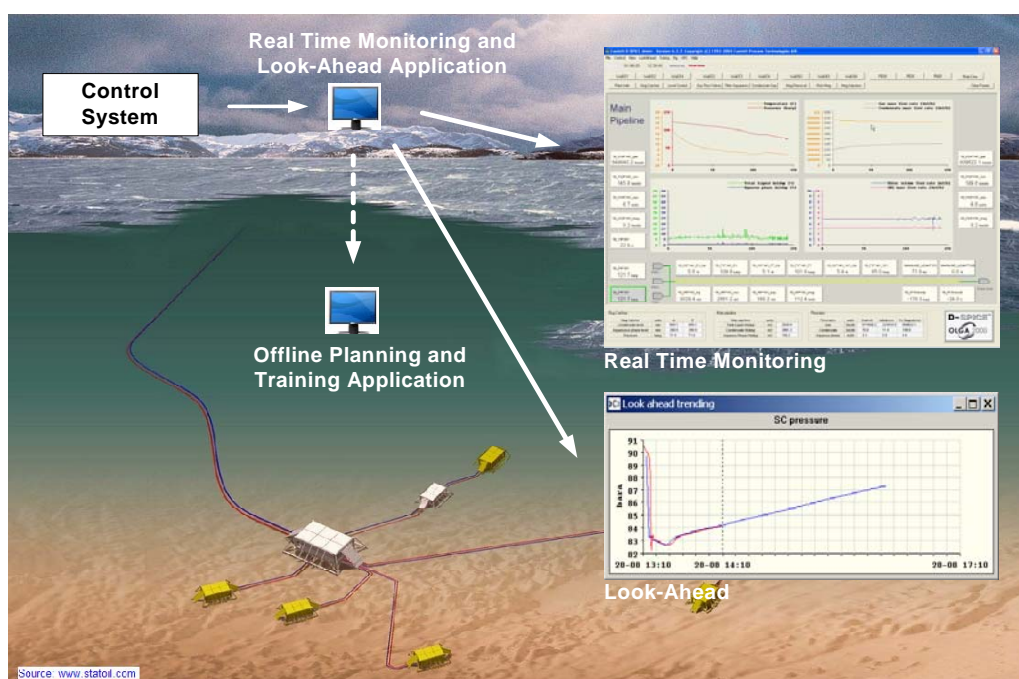
Figure 5. Illustration of the online Dynamic Production Model

A full DPM concept uses three models of the pipeline system:

- A real-time model
- A look-ahead model
- An operation-support and training model

These exchange data with each other and the PCDA system in order to provide the full range of functions available.

Real-time Model. The real-time model serves as a copy of the plant process. As it simulates alongside the plant, it provides a wide range of information that cannot be measured, such as the pressure and flow profiles inside a pipe. The real-time model also supplies the look-ahead and simulator models with a snap shot of current process conditions, which they use as their initial conditions. It is also the basic tool for the detection of leaks and the formation of hydrates. The real-time model receives data from

the PCDA system through an online connection. Measurements from the PCDA system are used to continuously update the model's boundary conditions and state variables. Other measurements are used, over a longer time-scale, to tune the models for the pipelines and the other process equipment. This tuning is essential to keep the model tracking the real plant. Changes in for example ambient conditions, fluid properties or plant operations will cause the model to diverge slowly over time.

Look-ahead Model. The Look-ahead model predicts the future behaviour of the process. This prediction is based on the current process state, supplied by the real-time model. The look-ahead model checks for a situation that cause alarms and notify the user if such events are found. The model can be configured to automatically calculate a prediction over a specified time horizon at a specified interval. The results from the look-ahead model are made available to the user as extensions to the trend-curves in the HMI for the real-time model as shown in Figure 6.
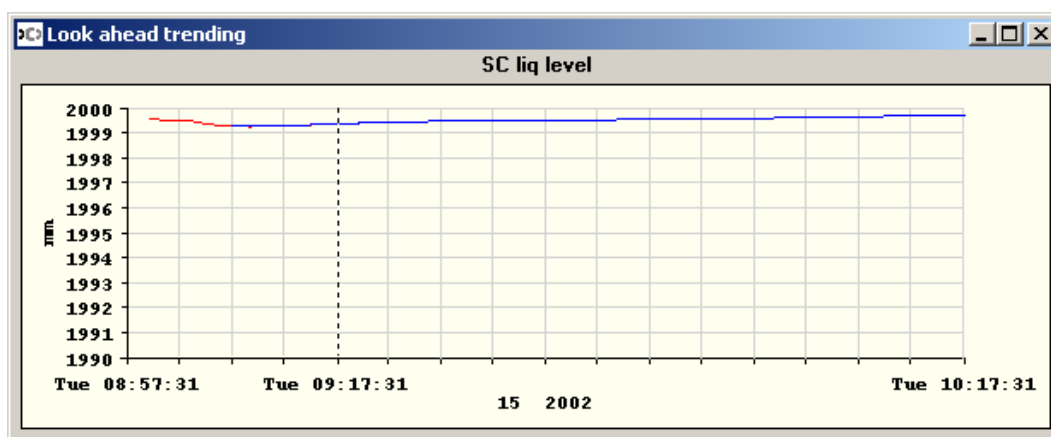
Figure 6. Look-ahead trend

Operation-Support and Training Model. The Operations-Support Simulator (OSS) is a stand-alone offline model that is used by production planners to test and verify alternative production strategies and study the effect of various operational actions. There is no online connection to the PCDA system, but the current conditions in the real-time model (or any earlier stored snapshot) can be loaded into the simulator model as a starting point for calculations. This simulator model has been configured as a training simulator. The model then communicates with the soft emulated version of PCDA.

EXAMPLES

Some practical examples where the simulator has increased the process understanding and helped in developing operational strategies are outlined in this section.

The 143 km long pipeline from the subsea installations to the slug-catcher has long time constants. It can take days to reach equilibrium conditions between the water/MEG, condensate and gas phase in the pipeline. The slug-catcher pressure floats on the pipeline pressure, while the inlet pressure to the LNG process plant needs to be kept constant to avoid process disturbances. At varying loads of the LNG process, the subsea operator needs to adjust the opening of the choke valves, to maintain sufficient, but not too high, slug-catcher pressure. Also, to avoid too large liquid slugs arriving at the slug catcher, limitations are set on how rapid changes can be done on the pipeline flow rates. The

simulator has been extensively used to develop operational procedures, such that upset conditions, due to varying loads on the subsea system, develop. Also, the online DPM model will be of invaluable help to the operators in such situations.

From the slug-catcher, the condensate phase is routed to the condensate system, where the liquid condensate phase is stabilised before sent to the storage tank. At varying load on the subsea pipeline, the condensate feed to the slug-catcher can vary greatly. Thus, also the condensate system can loose feed from the slug catcher. By sending the stabilised condensate in return to the inlet of the condensate system, via the flare knock-out drum, the system can be kept warm, at low load, and ready for operation as soon as liquid arrives from the subsea pipeline again. By use of the dynamic simulator, operator guidelines for how to react in different pipeline scenarios have been developed.

The heat demand of the process plant is covered by use of a closed hot oil circuit. Heat is extracted in five waste heat recovery units on the LM6000 gas turbines. At varying plant loads, e.g. start-up and shut-down, the heat demand can change quite rapidly. This puts strong demands on the regulation of the hot-oil system with phasing in and out waste heat recovery units. The dynamic simulator has been used to optimize the control system of the hot oil circuits, such that varying heat demands can be handled without too large disturbances in hot oil temperatures and flow rates.

Packaged equipment, such as anti-surge and performance controls, is emulated as a part of the D-SPICE control system. This has enabled Statoil to run detailed compressor operation simulations. The as-tested performance curves of the refrigerant compressors were used to verify that the compressors, together with other equipment, would meet the requirements for the LNG production.

The design of the blow-down system has been verified on the dynamic simulator. The plant is divided in eleven ESD groups that can be blocked in and depressurised independently. The process equipment in critical areas of the plant shall be depressurised to 4 barg within 30 minutes. Due to the load limitations on the flare and blowdown system, the depressurisation of the ESD groups cannot be done simultaneously, but are restricted by sequences. Due to the detailed modelling of the flare and blowdown system, the simulator could be used to verify the blow-down times as well as checking that the capacity of the flare system was not overloaded during different blowdown scenarios. These scenarios has also been used in the operator training, where also the operators can rehearse on restarting after blowdown, while taking into account for example low temperature restrictions in equipment and high liquid filling in columns.

CHALLENGES AND FUTURE DEVELOPMENTS

The development of the dynamic plant simulator has proven to be highly valuable in engineering, commissioning and operation preparation of the Snøhvit LNG plant. It is also foreseen that the model will be an important tool in plant operation, e.g. for debottlenecking studies, process optimisation and for evaluation of alternative operational strategies.

One of the major challenges, often faced when using dynamic simulators, is the evaluation of how accurate the model reflects the real plant behaviour, both steady state and in dynamic situations. A development project is ongoing, where the aim is to couple

the full-scale plant simulator to live data from the plant. Methods developed in the more limited DPM will be exploited, such that the model can be validated against real plant data and objective values can be given for the accuracy of the model. Parameters in the model can also be tuned online to improve the accuracy. A further development, using the concepts of "real time monitoring" and "look-ahead model" is also believed to have large operational potential and will be explored when the plant is in stable operation.