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History Matching via Ensemble Kalman Filter of Norne Field

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”History Matching via Ensemble Kalman Filter of Norne Field”

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Chapter 1

Introduction

1.1 Data assimilation

Consider the situation of having a dynamic model describing physical processes in some real system. It can be either an ocean, a weather framework or a reservoir. Apart from the difficulty of creating the numerical model to be a perfect representation of the reality there is very often poor knowledge about initial and boundary conditions. Numerical approximations and omissions of some less significant factors influencing the system are necessary. All this leads to differences between model solution and reality. Of course, our knowledge of the real system is almost always very limited, however, nowadays it is possible to measure some of the properties. The technological advanced tools enable observation and information storage for the future analysis techniques. The measurements as well as the numerical model are not exactly accurate. Associated uncertainty often arises from measure techniques, equipment constraints and computational transformations. Combining a previously created numerical model with the observation data in order to get an accurate estimate of the current state of the system refers to *data assimilation* or *history matching* when it concerns reservoir engineering. Afterwards, the improved numerical model can be used to predict the future performance of the system and benefit from this potentially powerful knowledge.

1.2 Previous work

A number of papers concerning optimization techniques in the reservoir model simulation and history matching has been published in the past two decades. Growing interest of history matching in reservoir engineering induced development of several approaches, direct minimization techniques and gradient based adjoint methods. Evolutionary algorithms as direct search methods have been proposed by Soleng (1999)[1], Romero (2000)[2] and Williams (2004)[3]. Gradient-based techniques were first introduced and further developed by Anterion (1989)[4], Bissell (1994)[5] and Roggero (1998)[6]. Hybrid schemes with different optimization approaches were designed by Gomez (1999)[7], Landa (2003)[8] and Castellini (2006)[9].

Recently, Kalman Filter (KF) techniques have gained popularity in data assimilation. Named after its author Rudolph Kalman, KF method published in 1960 firstly made a major contribution to the stochastic control theory. Later, with a meaningful support of the progress in development of digital computers the method was applied to a wide set of applications. Nowadays, it is used with satisfying results for data assimilation in meteorology, oceanography and reservoir engineering. Ensemble Kalman Filter (EnKF) was first proposed by Evensen, 1994[10] as an improvement of Kalman Filter for large scale systems which solves the problem of high computational cost related to storage and forward integration of the covariance matrix. Application of EnKF in reservoir engineering was first presented by G. Nævdal 2002[11]

1.3 Goals to achieve

Although, EnKF reached significant popularity in the past decade in environmental forecasting, its application to the reservoirs only recently gained more interest. Since it is very important to have good quality observations data and relatively fast simulation it is convenient to use simplified *synthetic models* for tool development. However, the application to real data is a challenge and undoubtedly the future of research on the topic. Hence, the challenge to design a complete history matching workflow has been accepted. Norne Field reservoir is intend to be history matched to the available production data.

A high quality data set for a real reservoir called Norne Field is released by Statoil and partners (ENI and Petoro) through the Norwegian University of Science (NTNU) for research and education purposes. The data for Norne Field consists of the model in ECLIPSE (from Schlumberger) simulator and measurements for the part of the field called E-segment. The EnKF can be applied to history match the available model to existing observations. JOA Jewel Suite is a very user friendly tool for design of the model and interpretation of the simulation results. Therefore, it has been chosen to run EnKF simulation via the EnKF plug-in created and still being developed by Netherlands Organisation for Applied Scientific Research (TNO).

The complete workflow for history matching of a real field brings into interest a number of issues related to treating available data. The history matching of a part of the field called E-segment requires efficient treatment of the boundary conditions. Also, uncertainty of observation data and creation of initial ensemble, characteristic issue for EnKF, need to be assessed.

1.4 Outline of the thesis

Following paper consists of five chapters. Chapter 1 contains general information on the topic and references to previously published papers. This short introduction is followed by Chapter

2 in which statistical background can be acquired or refreshed, if needed, and theory behind history matching, especially the Ensemble Kalman Filter as the method of interest is explained in details. The very brief look into reservoir engineering, with the emphasis on history matching relations, is situated in Chapter 3 together with the presentation of the Norne Field geology. In Chapter 4 one can find the description of Norne Model created in Eclipse software. This Chapter finishes with the results of adapting the ECLIPSE model to Jewel Suite. Finally, Chapter 5 contains the results and conclusions of applying EnKF method to Norne Field. Appendix A is a supplement of Chapter 4 and it covers the principles of working with the chosen software whereas Appendix B collects additional reference figures.

Chapter 2

Techniques, theory and formulas

2.1 Inverse problems

Extensive knowledge of the geology allows engineers to build an accurate model of the reservoir. Subsequently, the model can be created in available software. The simulations via reservoir simulator can be performed in order to observe the behaviour of the reservoir and to predict the production of oil and gas from the wells. Beforehand, the simulator as an input requires field properties, such as porosity and permeability. If these parameters would be known then numerical simulation that solves a system of differential equations can be performed. This is called the *forward problem*. However, usually reservoir is located deep under the surface and measurements are available only at a few wells located hundreds of meters apart. This leads to uncertainty in the description of a field. Fortunately, reservoir parameters can be estimated via a variety of available techniques using wells observations. Such procedures are in the family of *inverse problems*. The relation between the model parameters m and observed data d can be expressed in the term

$$g(m) + \epsilon = d$$

where ϵ represents the errors of the real observations. The goal is to solve this set of equations for model parameters.

2.2 History matching

The theoretical model is never exact usually due to the taken assumptions. For example, when according to general belief one of the parameters is considered as a constant. However, measured observations follow the same rule generally due to the uncertainties in observation techniques. As already mentioned in Chapter 1 the problem of interest is to combine the numerical model and the observations in order to get the best prediction of the system behaviour. To express the model uncertainty consider a probability density function of the chosen model parameters. If we have in addition observations at different space and time then an evaluation of the model pdf conditioned on measurements stands for data assimilation. The term *history*

matching is used in reservoir engineering instead of data assimilation and it is one of the examples of inverse problems. The model is adjusted until it closely represents the past behaviour of a reservoir. The reservoir parameters are estimated to get a better match of the production history. As a result, the history matched model provides economic benefits since it helps in the prediction of the future production and supports the decisions in the management of the reservoir e.g. decisions concerning placement of the new, expensive wells. The interest is in estimating the rock properties as porosity or permeability using history matching of available production data.

2.3 Bayesian theory

Consider stochastic model parameters and the model described with probability density function. Using Bayesian approach it is possible to compute a *posteriori* estimate of the model. Assuming a Gaussian distribution of the model parameters Bayes theory claims that a posteriori pdf of the model variables is a product of the a priori pdf and the likelihood function. Denoting x containing model parameters, y^o as observations and y representing prior information of the model characteristics (in reservoir engineering: static observations received from log, core and seismic data), Bayes formula is of the form

$$f(x|y, y^o) \propto f(y^o|x) \times f(x|y) \quad (2.1)$$

where \propto denotes proportionality. The term on the left-hand side, $f(x|y, y^o)$ is called posterior density of the model parameters conditioned on the observations whereas prior distribution $f(x|y)$ denotes the same distribution but without contribution of the measurements.

2.4 Ensemble Kalman Filter

Ensemble Kalman Filter belongs to a wide family of *sequential Monte Carlo methods*. These approaches use as a starting point a collection of sample points called *initial ensemble* to capture a prior probability distribution of the *state* - set of information of interest about the model. This distribution is usually assumed to be Gaussian. During the simulation actual probability of the state is approximated by the ensemble of estimates.

The goal is to find estimator that gives an accurate estimate of the true state even though it cannot be directly measured. There are two criteria expected for the estimator to satisfy. Firstly, expected value of the estimate is required to be equal to the expected value of the state. Secondly, it is expected to find estimator with the smallest possible error variance so the state estimate varies from the true state as little as possible. These criteria are satisfied by Kalman Filter method.

Consider the stochastic dynamical system:

$$x_{k+1} = f(x_k) + w_k \quad (2.2)$$

$$y_k = C_k x_k + v_k \quad (2.3)$$

where w_k and v_k are Gaussian white noises with covariance matrices Q_k and R_k , respectively, $w_k \sim N(0, Q_k)$, $v \sim N(0, R_k)$. The y represents measurements and x are simulated values. Gaussian noise is added to the ensemble members as well as to observations at each time step to account for the model and measurements uncertainty. The x is called *state vector*.

In reservoir engineering state vector usually consists of dynamic variables i.e. pressures, saturations and static parameters i.e. porosity, permeability, transmissibility and fluid contacts. Except the data stored for every grid block there are also predicted values for particular wells i.e. gas, oil and water production rates, bottom hole pressure, water cut and gas-oil ratio. Static parameters do not vary during reservoir simulation as opposed to dynamic properties.

Initial Ensemble

The important concept in Ensemble Kalman Filter method is the use of multiply realizations sampled from a prior distributions of a state vector elements at time 0. The structure representing the model uncertainty is called *initial ensemble* and it is denoted as

$$x_0 = [x_0(1), \dots, x_0(n)], \text{ where } x_0(i) \sim N(\bar{x}_0, P_0) \quad (2.4)$$

where \bar{x}_0 is an initial covariance matrix. The aim is to use the available observations y to find the best estimate of the state of the system x .

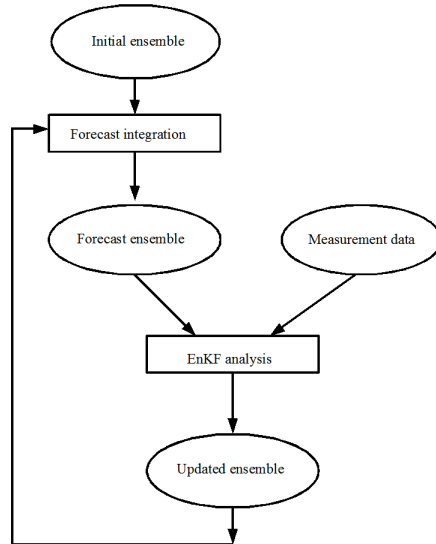


Figure 2.1: Methodology of the Ensemble Kalman Filter

Analysis Scheme

The Ensemble Kalman Filter at each simulation time consists of two steps, i.e. the forecast step (or forward) in which the state vector is simulated in time and the analysis step

(or assimilation step) where it is corrected to honour the observations. Both steps can be done simultaneously. In the analysis procedure the model variables are updated using Kalman equation. Both, static and dynamic variables are adjusted to honour observed data. All the previously simulated estimates are stored in the ensemble.

In the reservoir engineering the forecast step is achieved using a reservoir simulator where the physical system is approximated by a numerical model with discretization of a system of differential equations. It is worth to note that simulation has to be done for every ensemble member separately, however they can be done simultaneously and parallel computing can be applied.

Denoting k as a current time step, the equation of the forward step takes the form of

$$x_k^f = f(x_{k-1}^a) + w_k \quad (2.5)$$

Function f represents here the work done by the reservoir simulator. Defining now the mean of the forecast ensemble as

$$Ex_k^f = \frac{1}{n} \sum_{i=1}^n x_k^f(i) \quad (2.6)$$

and the matrix of differences

$$L_k^f = [x_k^f(1) - Ex_k^f, \dots, x_k^f(n) - Ex_k^f] \quad (2.7)$$

ensemble covariance matrix can be expressed in terms of

$$P_k^f = \frac{1}{n-1} L_k^f L_k^{fT} \quad (2.8)$$

The ensemble mean defined in equation (2.6) is interpreted as the best estimate of the state and the spread of the ensemble reflects the associated uncertainty.

the second step is called analysis step as the forecast is conditioned on observations

$$x_k^a = x_k^f + K(y_k + v_k - C_k x_k^f) \quad (2.9)$$

From the last equation we can observe that the modification of the state vector depends on the disagreement between simulated values and observations. The larger the difference, the larger the adjustment is performed. Note that observations y_k were perturbed as mentioned before by the Gaussian white noise v_k . The errors of measurements are assumed to be independent and thus the covariance matrix is diagonal. The matrix denoted as K in equation (2.9) is so called *kalman gain matrix* defined by

$$K_k = P_k^f C_k^T (C_k P_k^f C_k^T + R_k)^{-1} \quad (2.10)$$

where the term R_k stands for the measurement error covariance matrix defined as

$$R_k = \frac{1}{N-1} H_k H_k^T \quad (2.11)$$

with H_k storing perturbations of measurements. The ensemble covariance matrix takes the form of

$$P_k^a = (I - K_k C_k) P_k^f \quad (2.12)$$

Simple Kalman Filter example

To illustrate that the Kalman gain matrix plays here simply a role of assigning a weight to the model and observations, consider scalar time invariant model (one dimensional)

$$x_{k+1} = x_k + w_k \quad (2.13)$$

$$y_k = x_k + v_k \quad (2.14)$$

and Q , R as variances of noise processes w and v , respectively. For sufficiently large k the kalman gain matrix becomes constant

$$K_\infty = \frac{1 + \sqrt{1 + 4\frac{R}{Q}}}{1 + 2\frac{R}{Q} + \sqrt{1 + 4\frac{R}{Q}}} \quad (2.15)$$

The mean is then updated as follows

$$\begin{aligned} x_k^a &= x_{k-1}^a + K_\infty (y_k - x_{k-1}^a) \\ &= (1 - K_\infty) x_{k-1}^a + K_\infty y_k \end{aligned} \quad (2.16)$$

It can be noticed in the equation (2.17) the linear combination between the simulated values in the previous time step and measurements at the current time k . If the observations noise R is very large relatively to the model noise Q then K_∞ is closed to zero and new measurements have little impact on the state. The other way around, K is near 1 thus observations get the higher weight.

2.5 Sensitivity analysis and Sequential Gaussian Simulation

Before the EnKF method is applied, there is a need to choose parameters to update in the procedure. From a number of parameters it is important to select the properties of the reservoir (usually porosity and permeability) that have the greater impact on the flow simulation results. It can be done by slightly perturbing each parameter, then running a simulation and obtaining reservoir response. Each parameter change requires separate flow simulation thus the process can be time consuming.

When the parameters specified to create initial ensemble has been chosen the ensemble can be created. Very popular method to simulate multivariate Gaussian field is *sequential Gaussian simulation* (SeGS). The values are simulated sequentially and they are conditioned on the

original data and previously simulated values in the neighbourhood of considered point. SeGS consists of the following steps:

- (1) Transform the data to standard normal distribution if needed
- (2) Compute and model the variogram
- (3) Specify the path of visiting points z_i on the grid
- (4) Apply at every point the procedure:
 - (4.1) Obtain the mean and the variance of the property at the point z_i via kriging with the variogram
 - (4.2) Draw the value from normal distribution with the input from kriging and add the value to the dataset
 - (4.3) Go to the (4.1) and repeat for the next point z_{i+1} until all the points are finished
- (5) Transform back from the normal distribution if there is a need to.

Kriging provides the best unbiased estimator of the unknown parameter at the considered point. Such estimator is a linear combination of the values within the specified neighbourhood of the kriging point. The degree of relationship between the points is described by semi-variogram. More detailed theory on kriging is presented by Brown and Falade[2003] [12].

2.6 Localization and inflation

Spurious Correlations

The EnKF method requires sufficient size of an ensemble to capture the statistics. Nowadays, it is common to use about 100 members however it can be still computationally demanding in several applications. Hence, the focus is on developing techniques which allow to reduce the number of ensemble members. The limit of the size of an ensemble leads to sampling errors represented by *spurious correlations*. It can happen either when variables are far away or they are supposed to be uncorrelated. As a result the error covariance matrix is underestimated [13].

Localization

Evensen [13] describes the *localization* method to reduce impact of spurious correlations. Considering the model grid it can be assumed that the observations only in neighbourhood have impact on analysis of considered grid point thus only them can be involve in computation. Moreover, the advantage of this method is the reduction of the simulation time in case when the measurement data is large comparing to the ensemble size.

From the analysis equation (2.9) in EnKF, denote so called *innovation* as

$$d_k = y_k - v_k - C_k x_k^f. \quad (2.17)$$

Using (2.8) and (2.11) we can write (2.9) in the form of

$$x_k^a = x_k^f + L_k L_k^T C_k (C_k L_k L_k^T C_k^T + H_k H_k^T)^{-1} d_k \quad (2.18)$$

Introducing

$$s_k = C_k L_k^T \quad \text{and} \quad z_k = s_k s_k^T + (N - 1) R_k. \quad (2.19)$$

it is possible to rewrite the analysis scheme (2.9) as

$$x_k^a = x_k^f + L_k (I + s_k^T z_k^{-1} d_k). \quad (2.20)$$

Denoting the expression between brackets as U_k , the EnKF analysis simplifies to

$$x_k^a = x_k^f U_k. \quad (2.21)$$

The calculations above, presented with more details in Evensen [13], show that the analysis step equation in EnKF is a combination of the forecast ensemble members i.e. spanned by the ensemble members.

Denoting visited gridpoint as j and considering U_k introduced before the local analysis scheme for j th grid block goes as follows

$$x_{k,j}^a = x_{k,j}^f U_{k,j} \quad (2.22)$$

$$= x_{k,j}^f U_k + x_{k,j}^f (U_{k,j} - U_k) \quad (2.23)$$

The U_k is a global analysis term whereas in $U_{k,j}$ only observations within specified distance from j th grid point are used and thus it refers to local analysis solution.

Inflation

There is another method described in Evensen [13] to deal with the spurious correlations, namely, covariance inflation method. Underestimation of the covariance matrix can be improved by modifying each ensemble forecast accordingly to the formula

$$x_k^f(i) = c(x_k^f(i) - E x_k^f) + E x_k^f \quad (2.24)$$

where the index i represents the ensemble of interest and c is a constant greater than 1. It was shown that setting c too large causes overweighting the measurements [14]. Hence, there is several approaches to optimize the *inflation factor* [15] [16] [17].

Chapter 3

Reservoir engineering basics and Norne Field

3.1 Reservoir Engineering

Reservoir structure can in many cases consist of sand and shale layers. Each layer has specified parameters like porosity and permeability. The porosity of the reservoir sands is about 10–30 %. Typical permeabilities are in the range 0.1 – 10 D. Reservoir must be bounded by caprocks or impermeable faults which enclose oil and gas inside the reservoir. Usually there are three main phases in a reservoir i.e. water, oil and gas. Additionally, sometimes there are two more phases included. The gas which becomes fluid at a surface called vapour fluid and fluid that becomes gas i.e. dissolved gas. Differences between their physical properties, i.e. in density, determines their vertical location in the reservoir. According to this gas-oil (GOC) and oil-water (WOC) contacts can be observed. The state of oil, gas and water is described in a reservoir simulation model by pressure and saturations. Some basic nomenclature associated with reservoir engineering is explained in this section with the emphasis on terms used further in this paper.

Porosity and permeability are two factors that influence fluid movement and storage in rocks. Porosity measures how much void space is in the rock. It is a fraction of the volume of void space to the total volume. Thus it is a number between 0 and 1 or a percentage. Mathematically speaking

$$\Phi = \frac{V_p}{V_b} \quad (3.1)$$

where Φ is the porosity, V_p is the pore volume and V_b is the bulk volume. Another important reservoir property related to pore volume is phase saturation. It is a ratio of the volume of the phase to the volume of the rock. Since three phases are considered in the reservoir it can be

expressed for each of them

$$S_{\text{phase}} = \frac{V_{\text{phase}}}{V_p} \quad (3.2)$$

where S_{fluid} is fluid saturation (of oil S_o , water S_w or gas S_g) and V_p is the pore volume. It is natural that $S_o + S_w + S_g = 1$ and $V_o + V_w + V_g = V_p$. Permeability is a measure of the ease with which fluids will flow through a porous material. Widely use in reservoir engineering Darcy law is of the form

$$u = \frac{q}{A_c} = -\frac{k}{\mu} \frac{d(p + \rho gh)}{dl} \quad (3.3)$$

where u is fluid velocity [$\frac{cm}{s}$], A_c is cross sectional area of the rock [cm^2], q is the flow rate [$\frac{cm^3}{s}$], k is notation of permeability [D](Darcy), μ is viscosity of the fluid [cP](centipoises), $\frac{dp}{dl}$ is pressure gradient in the direction of flow [$\frac{atm}{cm}$], ρ is fluid density, g gravitational constant and h is vertical depth. Since most of the reservoirs have permeability smaller than 1 [D], the more convenient unit is milidarcy [mD]. Permeability in the equation (3.3) is called absolute permeability (the rock is saturated with only one fluid). In the case of multiple number of fluids in the rock we consider effective permeabilities of oil k_o , water k_w and gas k_g . The ratio of effective permeability to the absolute is called relative permeability

$$k_o^r = \frac{k_o}{k}, \quad k_w^r = \frac{k_w}{k}, \quad k_g^r = \frac{k_g}{k}. \quad (3.4)$$

In Darcy equation not yet explained term viscosity appears. It is defined as a measure of resistance of fluid which is being deformed by a stress. Its unit is called poise and it is $\frac{kg}{m \cdot s}$ in SI system.

Another meaningful reservoir property is compressibility which measures how the pore volume changes due to the changes in pressure while the temperature is constant. It is given by the equation

$$c = -\frac{1}{v} \frac{dv}{dp} \quad (3.5)$$

where c states for compressibility, v is the volume and p is the pressure.

Capillary pressure is the difference between two immiscible fluids across the interface. It is generally defined as

$$p_c = p_{nw} - p_w \quad (3.6)$$

where p_{nw} is called non-wetting phase and p_w wetting phase. In oil-water systems, water is usually the wetting phase, whereas in gas-oil systems it is oil.

Another important reservoir property that influences oil reserves is net-to-gross (N/G) ratio. Reservoir usually consist of sand and shale while shale reserves should not be included in final reserve calculation. N/G discounts proportion of shale to the total volume. Thus it is a number between 0 and 1.

3.2 Reservoir data

The oil, gas and water are acquiring in the reservoir from the *wells* called producers. One of the possibilities to force fluid to travel to particular producer is water or gas injection into an injection wells. This technique requires at the beginning to study the reservoir in order to make a plan of setting up a network of drilled wells. After the well is drilled it can be completed. Completion is the process of preparing well to be enable to produce or inject. During the production after reaching an economic limit, which means that expenses of the production from the particular well bore are higher then the cost of produced oil, the well is usually abandoned and buried. Wells are also employed to collect the observations used further in a reservoir and research study e.g the history matching process. The data obtained from the well bore is called either the *log data* or the *core data* depending on whether it is received by a sensor located in the well or read out at a surface laboratory from a sample core removed from the reservoir. Usually the production data, the injection data and the bottom hole pressure are measured or calculated. The rates data may consist of oil, gas and water rates observed at the well locations in the reservoir for the defined periods of time for instance days. The bottom hole pressure (BHP) is the pressure at the bottom of the well bore. It can be either measured using special equipment or estimated using available techniques, e.g.

$$BHP = \rho gh + THP \quad (3.7)$$

where ρ is fluid density [kg/m^3], g is gravitational constant [m/s^2], h stands for the vertical depth of the well [m] and THP (tubing-head pressure) is the pressure measured near the surface in the well [18]. The bottom hole pressure is an important tool to maintenance the reservoir. If its value is less than formation pressure (pressure of fluid within the pores) than the fluid can flow into the wellbore. There are costs related with the placement of each well thus there is a constraint on number of wells in a reservoir. For the engineers it results in working with locally available data and thus the uncertainty of the rock properties in the reservoir rises with the distance from the well.

Another type of the data possible to obtain is *seismic data*. The signal from a source mounted at a surface of the reservoir is partially reflecting from the layer surface and recorded again at the top of the reservoir by receivers. Thus the method is very helpful in describing the layers lithology and regional properties of the reservoir. In 3D seismic a large number of 2D parallel lines of signals are shoot into reservoir and after repeating this experiment, called survey, the 4D seismic are acquired as the fourth dimension is time. Comparing it to the log data which

can be collected very often in time (even every few seconds) the surveys are usually done in a distance of a years.

3.3 Norne Reservoir

Norne Field is located 200 km from Norwegian coast line in the geological blocks 6608/10 and 6508/1 in the Norwegian Sea. Structure size is approximately 3x9 km and sea depth in the area is 380 m whereas reservoir depth is 2500 - 2700 m. It was discovered in December 1991. The production of oil and gas started November 1997 and 2001 respectively. Reservoir is operated by Statoil Hydro Petroleum AS (63.95%) and partners: Petoro (24.55%) and Eni Norge AS (11.5%). Data is provided through Integrated Operations in the Petroleum Industry (IO). The field parameters have quite good quality. Porosity is in the range of 25-30%, net-to-gross ratio 0.7 - 1 and permeability varies from 20 to 25000 mD. Reservoir thickness changes from 120 m to 260 m from south to north.



Figure 3.1: Location of Norne Field, Statoil(2001)

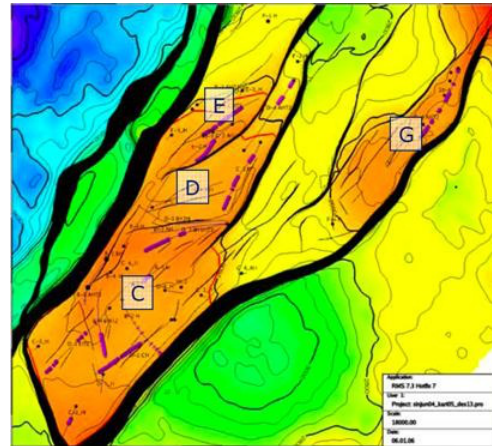


Figure 3.2: Structure of Norne, Statoil(2006)

The Norne Field consists of Main Structure (segments C, D and E) and G segment. About 98% of oil is located in Main Structure. Particular segments can be seen in the Figure 3.2. Since reservoir consist of horizontal, geological formations, in the Figure 3.3 one can find zonation table. Two the most important formations are Ile and Tofte where is 36% and 44% of reservoir oil, respectively. Gas is accumulated in the Garn formation at the top of the reservoir. Neighbouring picture demonstrates cross section through the reservoir and major faults. Since gas is more lighter then oil and water, in the hydrostatic equilibrium one can find gas above oil and oil above water. This induces placement of gas-oil and oil-water contact.

Oil is enclosed in the reservoir thanks to faults and the cap rock (Melke Formation) which seals the reservoir. Not Formation prevents communication between Garn and Ile formation thus the decision has been made of switching the gas injection at the top of the field to the

NORNE 2002		NORNE 2006		
Lower Melke		Not 3	Upper Not Shale	
Garn 3		Not 2	Not 2.3	Not Sst
Garn 2			Not 2.2	
Garn 1			Not 2.1	
Not		Not 1	Lower Not Shale	
Ile 2	Ile 2.2	Ile 2	Ile 2.2	Ile 2.2.2
	Ile 2.1		Ile 2.1	Ile 2.2.1
Ile 1	Ile 1.3	Ile 1	Ile 1.3	
	Ile 1.2		Ile 1.2	
	Ile 1.1		Ile 1.1	
Tofte 2	Tofte 2.2	Tofte 2	Tofte 2.2	
	Tofte 2.1		Tofte 2.1	
Tofte 1	Tofte 1.2	Tofte 1	Tofte 1.2	
	Tofte 1.1		Tofte 1.1	

Figure 3.3: Zonation of Norne Field, Fawke(2008)

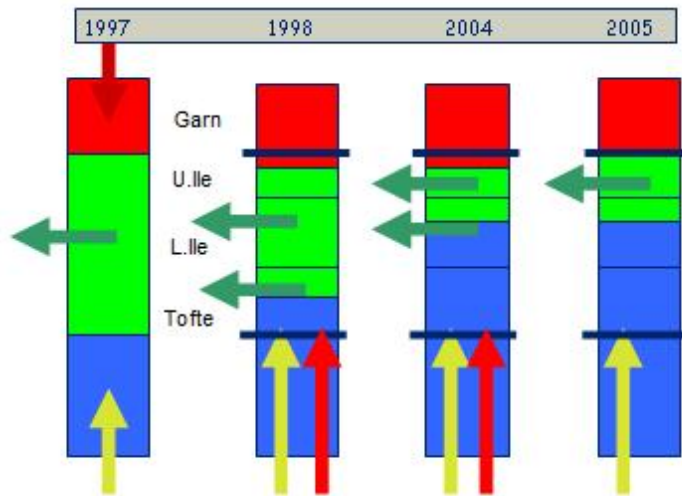


Figure 3.4: Development technique for Norne, Statoil(2004)

water injection at the bottom of the reservoir, see Figure 3.4. According to the Norwegian Petroleum Directorate (2010) recoverable reserves in Norne Field are: 94.90 mill Sm^3 of oil and 11.00 bill Sm^3 of gas. There is still 14.00 mill Sm^3 of oil and 5.20 bill Sm^3 of gas as a remaining reserves. The details can be found in Statoil PL128-Norne Reservoir Management Plan [2001]. [19] [20] [21]. There are two types of barriers that can prevent flow going through the reservoir. Faults discovered mainly by studying seismic data can either facilitate or block

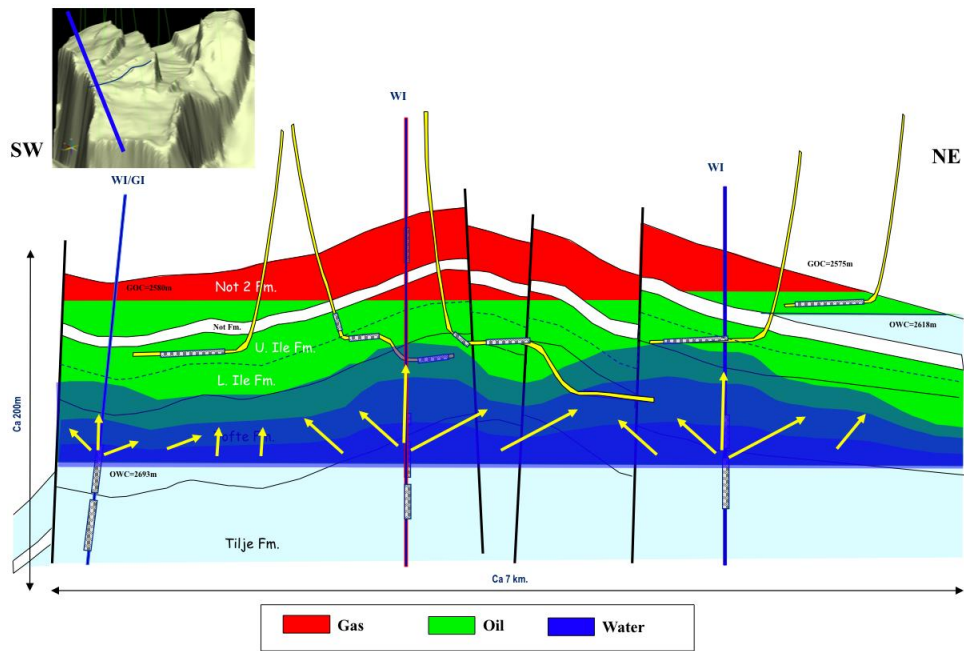


Figure 3.5: Cross section through Norne, Statoil(2006)

the flow of fluid in a reservoir. Except faults there are horizontal Stratigraphic Barriers in Norne mainly at a contact places between neighbouring formations: Garn3/Garn2, Not Formation, Ile3/Ile2, Ile2/Ile1, Ile1/Tofte4, Tofte2/Tofte1 and Tilje3/Tilje2.

Chapter 4

ECLIPSE model import into Jewel Suite

4.1 Norne Model in ECLIPSE

ECLIPSE from Schlumberger is one of the leading reservoir simulators in oil industry. It is a batch program. As an input user creates text file with a set of keywords that must be located in particular section. Such data file gives complete description of a reservoir. The following section describes shortly the model built in ECLIPSE simulator. Detailed description of the deck and the particular keywords can be found in Appendix A.

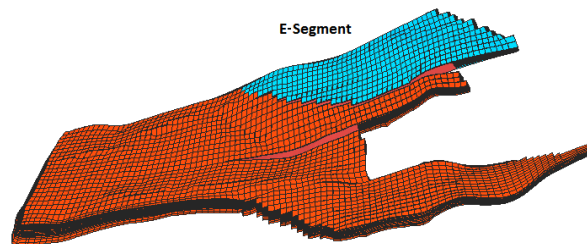


Figure 4.1: Norne model grid and E-segment

The Norne Field model starts at 06 November 1997. The dimensions are $46 \times 112 \times 22$, the unit system is metric and five phases gas, oil, water, dissolved oil and vapour gas are activated in the simulation. The grid consists of 113344 cells, where 44927 are active cells and the grid units are meters. Reservoir properties are assigned to every cell then they are modified according to specific segments, wells and layers. Net-to-gross, porosity and permeability appears to have a layer-dependent structure. The defined permeability in X direction is copied to Y direction and Z direction. However, permeability Z is reduced using multipliers according to particular layer. This means that permeability in X and Y direction are the same while permeability Z differs. Specified transmissibilities are modified further in the edit section to honour the changes in a reservoir structure made by drilling through the faults and the layers. Areas near the wells have set increased transmissibility multipliers. For Norne the values varies from 0.00075 to 20. Transmissibility multipliers only for two faults are bigger than 1 what means that appearing of this faults increased easy with which flow goes through that fault.

The reservoir can be subdivided into regions if there is a need to set different local properties for the field. There are 4 flux regions for each geological layer: Garn, Ile, Tofte, Tilje-top and Tilje-bottom. Thus there is 20 regions in total in Norne Field. There are transmissibility multipliers specified between each pair of neighbouring regions. Since the interest is in

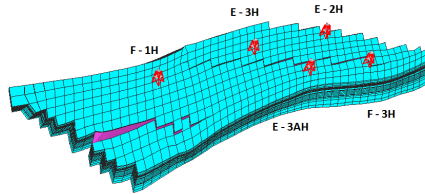


Figure 4.2: Localization of wells in E-segment

E-segment, only the wells located in considered area are typed. There is five wells in the E segment, two injectors and three producers. Wells localization can be seen in the Figure 4.2.

If there is a need to separate a part of the model, i.e. when only a sector of the field is history matched, the time required for the simulation can be reduced by use of *flux* or *coarse* option. In the first case the full grid model is simulated and the flow rates between specified

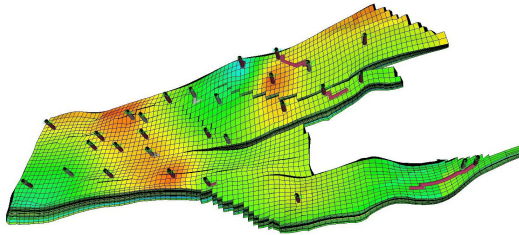


Figure 4.3: Norne Field original grid model

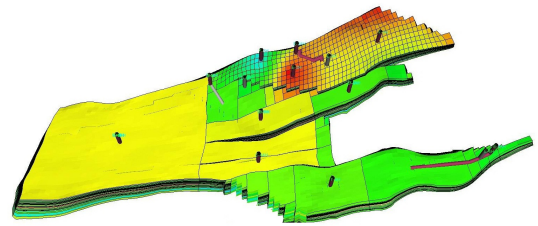


Figure 4.4: Norne Field coarsened grid model

region and the rest of the field are saved to the flux file. Then it is possible to perform reduced run when only the region of interest is active and the boundary flow rates are read from the previously created file. As an alternative, the coarse option allows to merge a number of cells in a specified box which is treated further by a simulator as a cell. The properties previously assigned to the cells in the box are up scaled. Original and a coarsened grid for Norne Field is presented in the Figure 4.3 and Figure 4.4, respectively.

More informations on Norne can be found in *Norne Comparative Case Study*, SPE127538 [22] and also on the Norne website[23] where the dataset and publications on the topic are available.

4.2 Norne Model transfer from ECLIPSE to Jewel Suite

JOA Oil & Gas Jewel Suite is a full workflow-integration framework which allows to build and design from the seismic interpretation, the grid representation to static and dynamic

programming and the wells structure. It has a user friendly interface guiding step by step through preparation of the model and its workflow. Reservoir simulators such SENSOR, ECLIPSE and IMEX can be plugged in and the results of the simulation can be imported and viewed or prepared for another simulation.

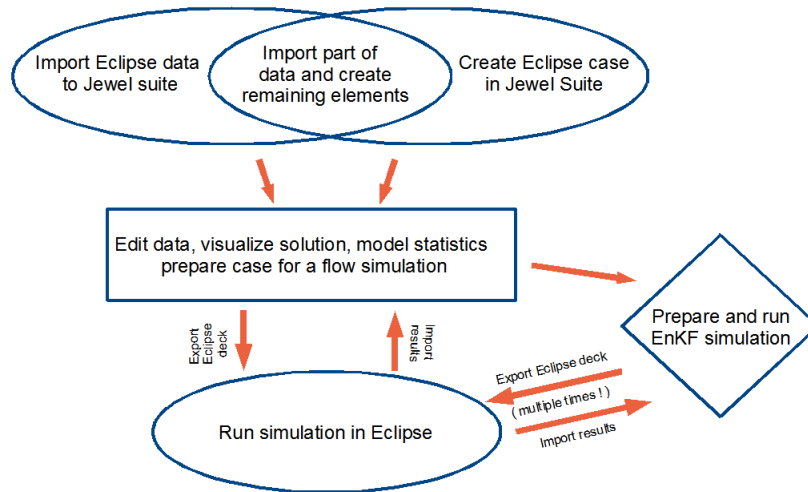


Figure 4.5: Cooperation between ECLIPSE and Jewelsuite

It can be seen in Figure 4.5 that integration of Jewel Suite with ECLIPSE requires as a first step import of the ECLIPSE deck to Jewel Suite. Unfortunately not all of the keywords used in Norne Field model were supported in Jewel Suite 2009. To avoid errors appearance in Jewel Suite and to import data correctly these keywords were commented out in the deck. Fortunately, in Jewel Suite there is an editor of the deck pushed out further to run by ECLIPSE. Thus allows user to make so called journal edits to deck before it is going to be run in ECLIPSE. Some of the commands were added again as journal edits but some of them were skipped due to the reimplementation issues. The list of trouble keywords and their meaning is presented in Table 4.1.

Keywords ZIPPY2 and PIMULTAB were added to the output deck in Jewel Suite thus they are include in the simulation. ZIPPY2 controls time step length to prevent convergence errors and PIMULTAB sets productivity index scaling factor for the well for particular maximum water cut value. There is a few more keywords in the SCHEDULE section that were omitted and they can be seen in the Table 4.2. Generally they control behaviour of the well network i.e. pressure and field economic data. Some of them appears more than once for multiply number of time steps i.e. GECON.

keyword	section	purpose
TRACERS	RUNSPEC	specifies dimensions for tracers required to allocate memory
TRACER	PROPS	used to define tracers and their properties
WTRACER	SCHEDULE	defines value of concentration in the related phase for an injector
DRSDT	SCHEDULE	with this keyword user sets maximum rate of gas-oil ratio increase, if it is set to zero then free gas does not dissolve in undersaturated oil, however this keyword has no effect in models with vaporized oil and dissolved gas(VAPOIL and DISGAS in RUNSPEC section) which is a case for Norne Field, here DRSDT is automatically reset to a large number.
VAPPARS	SCHEDULE	used in the systems with VAPOIL and DISGAS instead of DRSDT. User enters two arguments: first represents ability of oil to vaporize and the second tendency to get heavier.

Table 4.1: Keywords omitted in Norne Deck

keyword	section	purpose
WPAVE	SCHEDULE	controls computation of average pressure in the grid cells containing well, alternatively it can be done for particular well block using WWPAVE
GRUPNET	SCHEDULE	defines well production network structure required when using Network Option
NETBALAN	SCHEDULE	tunes on Network Option - balancing flow rates and pressure losses to calculate THP limits for a group of wells
GECON	SCHEDULE	allows specification of economic limit data (gas (oil) minimum production rate limits, maximum gas-oil ratio)

Tab 4.2: Keywords from SCHEDULE section omitted in Jewel Suite

4.3 EnKF plug-in to Jewel Suite

For the purpose of history matching there is available Ensemble Kalman Filter plug-in in Jewel Suite created and currently being developed by TNO. There is four subpanels in the main *TNO EnKF History Matching* panel. In the *Generate ensemble* panel it is possible to create initial ensemble first choosing previously specified realizations of the reservoir properties and the size of an ensemble with the *truth case* included if needed. Continue to the next window *Setup EnKF Case* several options for the EnKF can be chosen and finally the *Control panel* allows to validate the correctness of the ensemble and observations table and to start the simulation.

In the *Setup panel* user can create or choose an existing EnKF case and link it to the ensemble of interest. Thereafter the parameters to update are chosen from available list. After the measurement table view is opened the assimilation and observation values for particular wells can be filled or alternatively a complete table can be simple copied from popular formats as Excel files. In *Edit general settings* an important aspects of the simulation can be controlled. After specification of the choice of the reservoir simulator it need to be declared if *the truth is synthetic* and if the reservoir simulation need to be restarted from the beginning after every time step. Note that it can improve EnKF accuracy however it forbids updating of dynamic reservoir parameters. Before declaration of the number of ensemble members and simulation time is specified, in addition, EnKF option need to be selected.

There are four options to choose in the EnKF option field: *none, standard, localization or inflation*. The difference between one and standard option is that when the first *none* is active it means there is no updates of reservoir parameters in the simulation. This option can be used to investigate performance of the initial ensemble members without analysis scheme. The option *standard* turns on the updates and the theory behind the two remaining choices, localization and inflation as a methods of reducing spurious correlations was described in Chapter 2.

4.4 Discrepancies between coarsened and flux based model

Since the observations are available only for E-segment and the size of the grid is an issue it is convenient to history match only E-segment. Two methods for reducing the simulation grid, namely coarsening and flux boundary option, were presented previously in this paragraph. Applying any of these methods brings the question how the performance of the model changes. This was investigated for Norne Field and the results are presented in the Picture 4.6.

It is shown in the Figure 4.6 how the oil production over the whole field behaves when the coarse (red line) and the flux (blue dashed line) option is used. The second choice appears to have the advantage over the coarsened grid since the field production stays closer to the

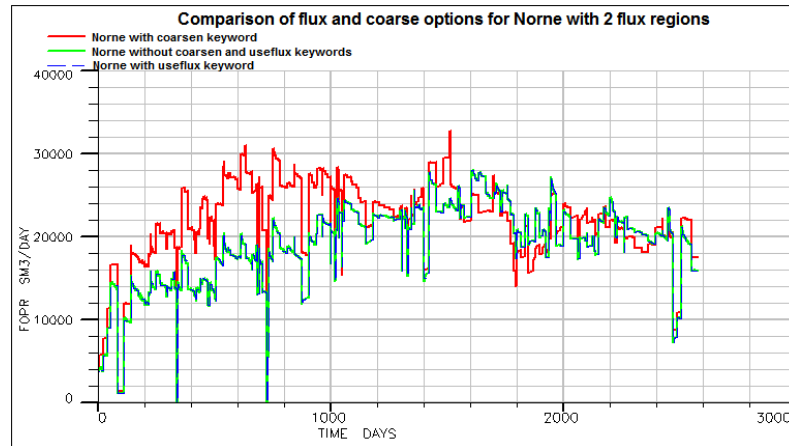


Figure 4.6: Difference in FOPR for the coarsened and flux-based simulation.

original results, when the grid size is not reduced (green line). The another benefit is that the grid in the flux-based simulation consist only of E-segment, therefore its size is smaller than the coarsened grid, however it requires one additional simulation in order to create the file with the boundary information. In history matching application it is aimless to perform full simulation after every update step for every ensemble member to create flux file. In results, the use of one flux file (for instance averaged over all ensemble members) created at the initial conditions brings the question about uncertainty on the boundaries for particular members.

The Figure 4.6 suggests the choice of flux option instead of coarse, however there is a major drawback for this method. The reservoir model can be divided into flux regions in order to distinguish local properties of the field, for instance the transmissibility multipliers between flux regions can be specified. When any of the wells is completed in more then one flux region, Eclipse returns an error message and the simulation is broken. Therefore to compare coarse and flux options 20 flux regions in Norne was replaced by 2 regions, as seen in the Figures 4.7 and 4.8.

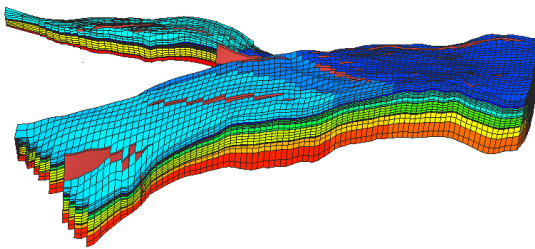


Figure 4.7: Norne with 20 flux regions

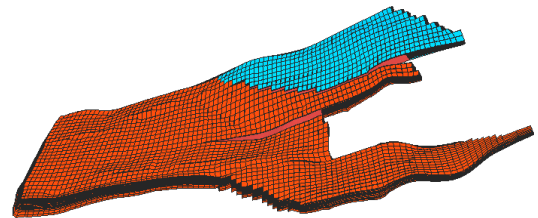


Figure 4.8: Nornw with 2 flux regions

This change, however, significantly change the field oil production response which can be visible comparing coarsen option in the Figure 4.6 where 2 region were used and the coarse model with 20 regions in the Figure 4.10 in the next section. This justifies the choice of the Norne Coarse model for the purpose of history matching in this thesis.

4.5 Discrepancies after Norne Coarse model import to Jewel Suite

Model imported to Jewel Suite differs from the original build in ECLIPSE due to the changes made in order to adjust it to Jewel Suite standards. The status of bottom hole pressure for well E-2H and oil production rate for the field are presented in Figure 4.9 and 4.10, respectively. There are three major factors expected to be responsible for the discrepancies.

First and also the most influential issue is set of edits made in original deck. Omission of keywords, especially commands controlling the well net properties (i.e. economic limits) influence the performance of the wells. For instance, after the production limit is reached the well is disabled. In addition, some keywords controls bottom hole pressure as an important factor used to maintenance the reservoir. The trouble keywords are explained in details in the Tables 4.2 and 4.3.

Using Darcy equation ECLIPSE calculates transmissibilities between neighbour cells based on cell shape permeability and net-to-gross. Although Jewel Suite computes transmissibilities also from Darcy equation, both methods differs. The detailed methodology can be found in software manuals [24] [25]. The default calculation of transmissibility in ECLIPSE is overwritten by calculations from Jewel Suite. In case when there is expected flow between non adjacent cells, for instance across the fault, then the non-neighbour connections and the corresponding transmissibilities are generated as well.

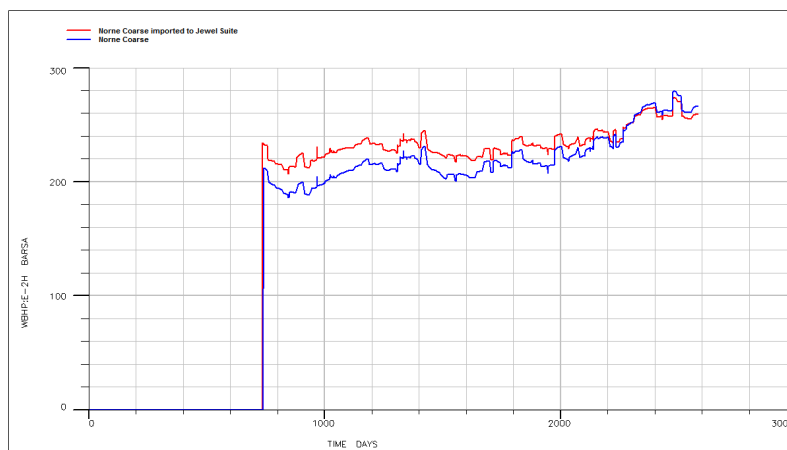


Figure 4.9: Difference in BHP in well E-2H for Norne models

In addition there is another change applied to the original Norne model. As it is explained in Appendix A, there are two possible grid treatments in ECLIPSE. The original Norne Model grid was created according to Corner Point Geometry (CP) which allows to build more irregular shapes of the cells than rectangles. However, Block Countered Geometry (BC) approach has advantage over CP since it requires less amount of data storage, therefore considering relatively large Norne Model CP has been switched in Jewel Suite output deck to BC approach. All the properties are assigned to the single cells and ECLIPSE does not use grid cell dimensions

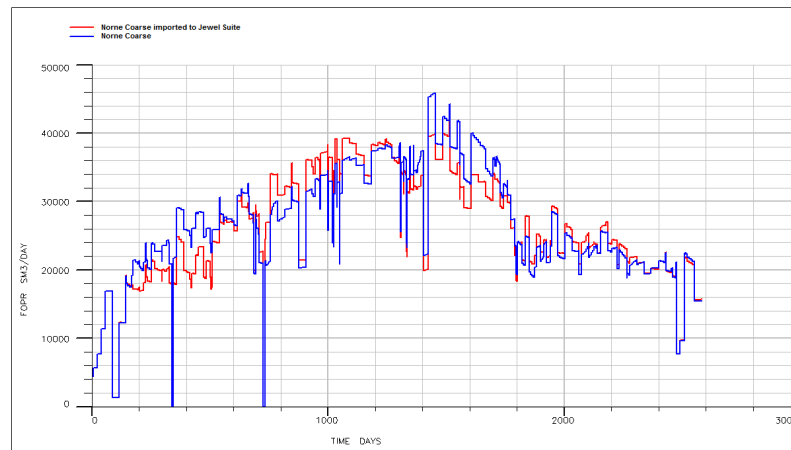


Figure 4.10: Difference in FOPR for Norne models

to calculate fluid flow, instead however, the pore volume and transmissibilities are calculated from the cell shape specifications. Transmissibility between cells depends in addition on their permeabilities whereas pore volume is calculated based on cell dimensions, porosity and net-to-gross ratio, $PORV = DX * DY * DZ * PORO * NTG$.

Chapter 5

EnKF simulation results

5.1 Study workflow

The complete work can be divided into two parts. In the first part the Norne model is imported to Jewel Suite. Because of the necessary manual modifications applied in the imported ECLIPSE deck the aim was to manually edit the output deck in order to match the model as close as possible with the original. The results of this procedure can be seen in Chapter 4. In the second part the focus is on the history matching of the model using EnKF plug-in available in Jewel Suite. The results of particular steps performed in order to achieve this goal are presented in the following chapter. Firstly the sensitivity of the production on reservoir parameters change is investigated then the initial ensemble is created and finally the EnKF simulation is performed.

5.2 Sensitivity analysis

Before the preparation of initial ensemble the decision of chosen parameters to update in EnKF procedure has to be made. The goal is to find reservoir parameters which are the most sensitive to the simulation results then create initial ensemble for selected properties. Sensitivity analysis was carried out for parameters listed below.

- porosity
- permeability
- net-to-gross
- transmissibility multipliers between regions

A base run received as an input initial properties defined in the Norne Model. Thereafter, a number of simulations for every change of the parameter had been carried out and compared with the base run. Values of the considered properties have been modified by shifting the distribution over a field by adding and subtracting constant value for every grid block. The

constant value 0.3 was added to transmissibility multipliers. The pattern that has been used is presented in the Table 5.1.

Property	Symbol	Mean\Value	Edit 1	Edit 2
Porosity	poro	0.219	0.5*poro	1.5*poro
PermeabilityX	kx	348.74	0.5*kx	2*kx
Net-to-gross	ntg	0.773	ntg-0.1	ntg+0.1
transmissibility multiplier	tran_i	0.01		tran_i + 0.2

Table 5.1: Sensitivity investigation pattern.

Porosity is usually the parameter that has a great impact on the performance of the reservoir production. This relation applies to Norne case as well.

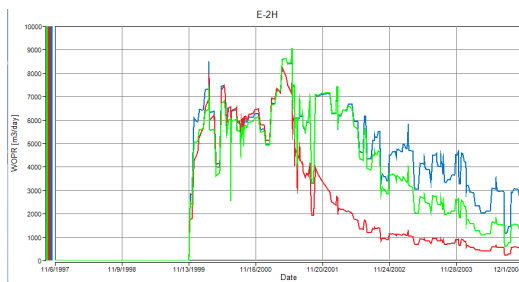


Figure 5.1: Sensitivity of oil production on porosity for well E-2H.

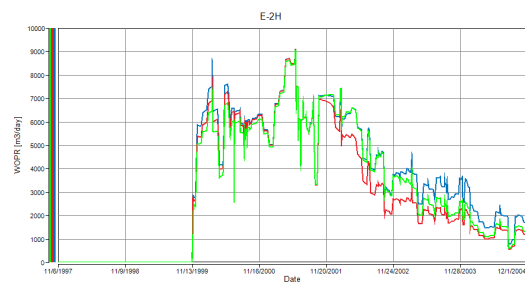


Figure 5.2: Sensitivity of oil production on permeability for well E-2H.

Among the investigated properties porosity and permeability show the most significant impact on the reservoir production in E-segment. The results of sensitivity analysis are presented in the Figures 5.1, 5.2, 5.3 and 5.4. Varying the transmissibility multipliers between the 5 regions in E-segment and the regions in remaining part of the field did not bring meaningful changes in the oil production. After one of the multipliers has changed, the very little change in oil production (see Figure 5.4) can be noticed in one of the wells in E-segment. It can be observed

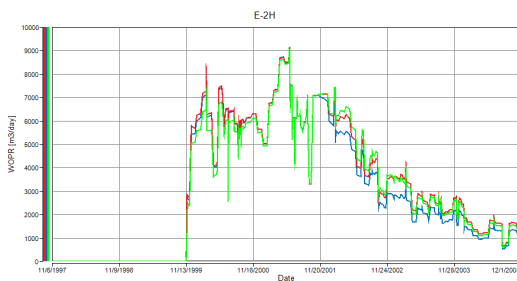


Figure 5.3: Sensitivity of oil production on net-to-gross for well E-2H.

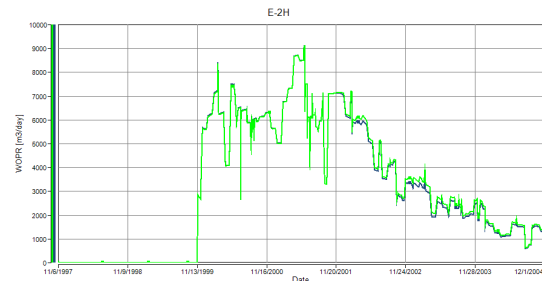


Figure 5.4: Sensitivity of oil production on transmissibility multiplier for well E-2H.

that uncertainty of the oil production rises around 1500 day. This can be caused by water breakthrough which occurs at that time. The water previously isolated from the production

(for instance, water injected into wells) gains access to the considered production well. The water production rate for the well E-2H can be seen in Figure B.5 in Appendix B.

5.3 History matching results

The initial ensemble was created via Sequential Gaussian Simulation which theory is explained in Chapter 2. According to sensitivity analysis the porosity and the permeability were chosen as parameters to update. There is 60 ensemble members involved in the simulation. During 2520 time steps (days) parameters are updated 4 times: at 900, 1620, 2160 and 2520 day. After every update simulation is restarted from time 0 with new parameters as an input. Restart option forbids updates of dynamic properties, however, it prevents possibility of appearance of non-physical values and thus it makes simulation more stable. The results in Figure 5.5

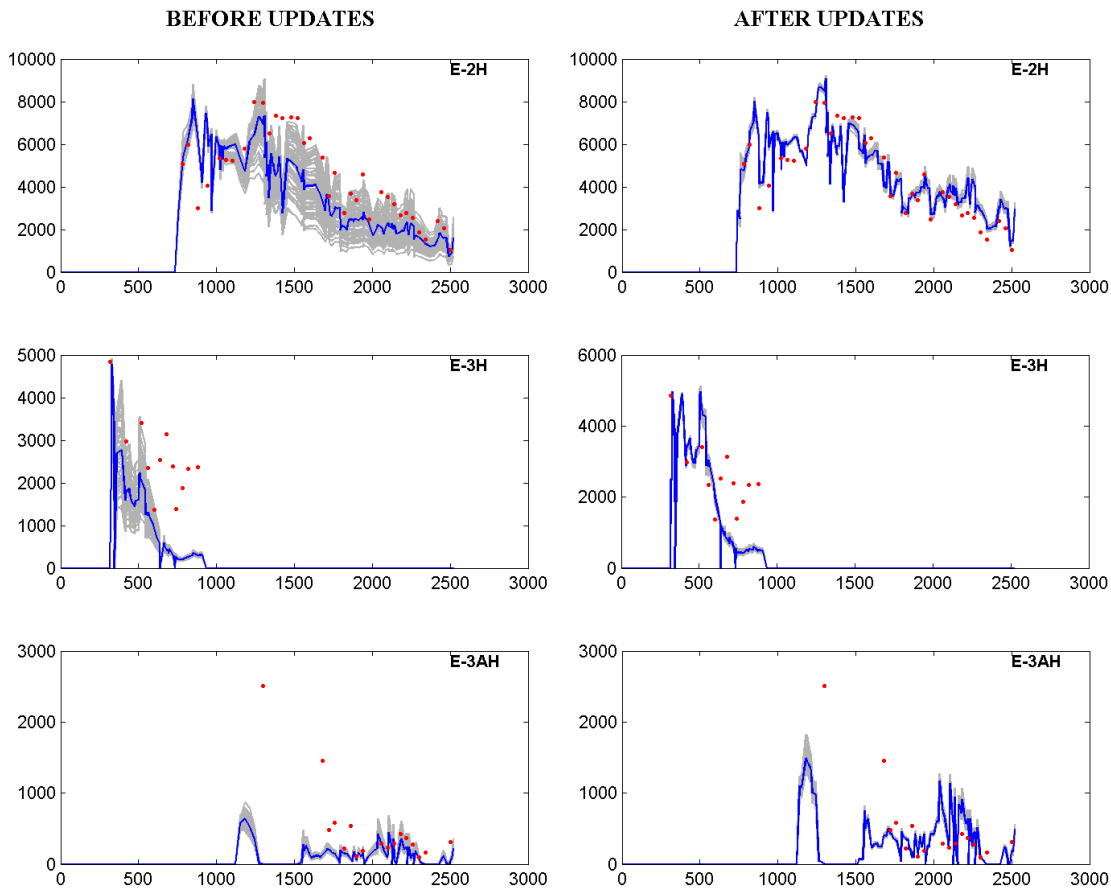


Figure 5.5: Initial behaviour of WOPR [sm³/day] on the left and after last update step on the right.

include the oil production per day in 3 production wells located in E-segment of Norne Field. Initial behaviour of the production can be seen on the left where the blue line represents the mean of initial ensemble and the red dots correspond to observations used in the assimilation. It is noticeable that the well E-2H is the most sensitive to the initial ensemble which form the best spread of the production among all 3 wells. Despite the ensembles with poor spread for

wells E-3H and E-3AH do not embrace the observations, the predicted production appears to approach the measurements. It is visible especially at the time with a major difference between ensemble and observations. The results of matching the gas and the water production rates can be found in Appendix B.

The log-permeability in X direction at the initial time and after every update is presented in Figure 5.6. The model consists of 22 layers and the results are presented for layer 1. The values represent the mean over the ensemble members. The updated permeability becomes

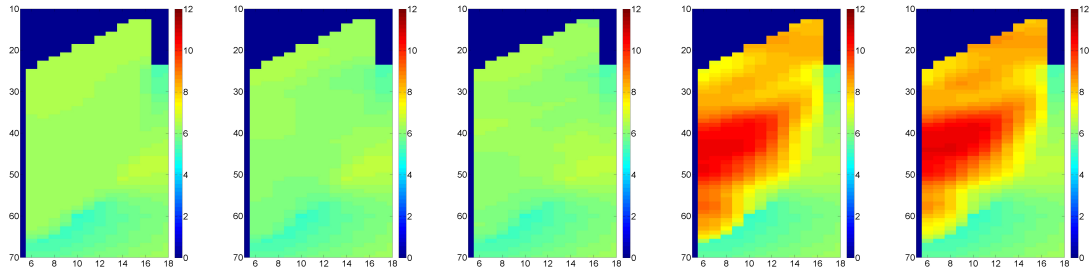


Figure 5.6: Mean of LogPermX, initial and after updates: 900, 1620, 2160 and 2520.
Location: E-segment, layer 1.

very convenient for the field development since the oil, gas and the production wells are located at a high permeability region. The next property assumed to be uncertain was porosity. The effect of the updates is demonstrated in Figure 5.7. The reservoir was assumed to be strongly

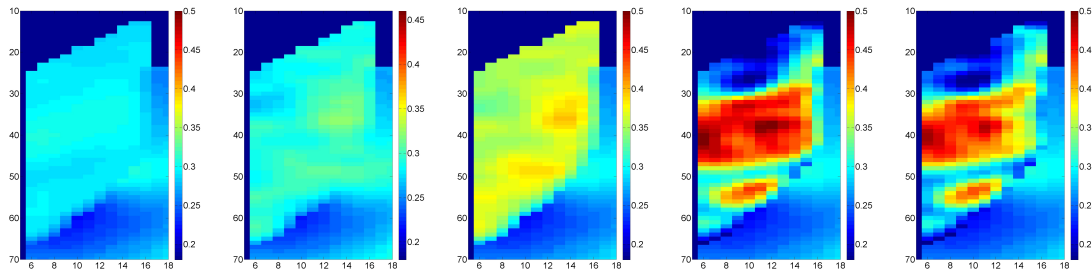


Figure 5.7: Mean of porosity, initial and after updates: 900, 1620, 2160 and 2520.
Location: E-segment, layer 1.

homogeneous at the first layer what is reflected in the mean of the properties in initial ensemble. However, already third update proofs more local variations. The values of the properties are rising since the model is being matched to the observations and most of them appear to be greater then the model prediction.

Chapter 6

Remarks and future improvements

The complete history matching workflow requires to focus on a variety of issues involved, i.e. when there is a need to adjust the model to different software conditions or the specification of the initial conditions is obligatory or the observations need to be prepared for the assimilation. Therefore, it is difficult to avoid contribution of the different science disciplines in application of mathematical procedure. Not only theoretical expertise but also programming skills and environmental knowledge (depended on application field) are often inevitable. There is several matters in Norne history matching workflow worth to investigate in order to improve final results.

One of the common issue in the Ensemble Kalman Filter is the creation of the initial ensemble. Usually the knowledge of geology is used to generate multiple stochastic reservoir realizations representing uncertainty in the model. Popular approach is to use sequential Gaussian simulation, which theory is explained in Chapter 2, to estimate parameters conditioned on the well data. How the initial ensemble, created this way, influences the EnKF results was investigated by Lorentzen [26]. For the Norne Field ensemble was create via sequential Gaussian simulation with well logs as an input, however, there is strong relation between Norne geological properties and the particular layer. Therefore, it is reasonable to involve this information in the creation of initial ensemble. Despite the model is history matched to the observations it does not mean that there is no error attached to the set of measurements. Therefore, this uncertainty need to be assessed.

Since often the measurements are acquired at the well locations, the data is not only sparse but in addition it is often available for a specific region of the field. To improve the experiment only such part of the field should be history matched since the updates in the wells have less impact on fluid flow in the long distance regions. It would be convenient to simply separate the area of interest, however, the question about the boundary conditions appears. The information about the fluid flow through the boundary of the isolated region should be included.

The ECLIPSE simulator allows to use FLUX or COARSEN approach described in Chapter 4 to deal with this issue, however, it does not completely neutralize uncertainty of the inflow of the fluid to the separated area and its outflow outside the boundary. Hence, it is important to asses uncertainty related to the fluid exchange.

The seismic data is dense comparing to the well observations and helps to investigate the layer structure in the reservoir. Therefore, recently the adjusting the EnKF method for seismic inclusion gain popularity. Several papers present Ensemble Kalman Filter adopted for use of the seismic data. Myrseth [27] presents Hierarchical Ensemble Kalman Filter (HEnKF) and Dong [28] propose the assimilation of seismic impedance in EnKF and test it on synthetic case. Moreover, if the seismic is available after history matching period it can be used as a validation source. For the Norne Field there are 3 available surveys for the years 2001, 2003, 2004 and 2006.

The size and complexity of the real reservoir model bring constraint on a number of simulations during the research. It is common to use from 40 to 100 ensemble members in the applications nowadays, however for the Norne reservoir the process becomes still time consuming, even with either FLUX or COARSE reduced grid. On the other hand, flow simulation for each of the ensemble can be performed simultaneously thus the method is ideal for parallel computing. According to time and memory constraints, several decisions have to be made. Except choosing a number of ensemble members and simulation length, also density of the set of observation and assimilation times need to be specified.

Appendices

Appendix A

Short Eclipse and Jewel Suite Guide

A.1 ECLIPSE from Schlumberger

There are five compulsory sections in *DATA file which is an input to ECLIPSE reservoir simulator: RUNSPEC, GRID, PROPS, SOLUTION and SCHEDULE together with three optional: EDIT, REGIONS and SUMMARY. Each section has particular meaning. It is important to acknowledge here that following chapter describes construction of ECLIPSE data with respect to Norne Field Model thus not all of possible keywords in ECLIPSE are mentioned. In fact there is much more commands that can be used to describe reality more accurate.

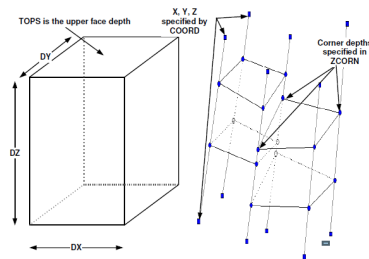


Figure A.1: Geometry types: Block Centred and Corner Point, ECLIPSE 100 user course, Schlumberger GeoQuest

The RUNSPEC section contains main characteristics of the model, i.e. unit system, dimensions of the reservoir and input tables dimensions necessary for ECLIPSE to allocate appropriate amount of memory. The most expensive in memory is a storage of grid information since the values is attached to every cell. Geometry properties, porosity, permeability and net-to-gross are converted by ECLIPSE after reading GRID section into a more convenient form for flow computations. It results in the calculation of pore volume, transmissibility in three directions and cell center depth for each single cell. Keyword DIMENS is use to specify reservoir dimensions, START is followed by start date of simulation. There are three units systems available in ECLIPSE: FIELD, METRIC and LAB but there can be only one defined for all data in the model. Five reservoir phases can be defined in RUNSPEC section: OIL, GAS, WATER,

DISGAS and VAPOIL.

The last two keywords states for dissolved gas and vapour oil, respectively. For history matching purpose it is worth to mention keywords UNIFIN and UNIFOUT, since the input, as well as the output files can be either unified or multiple these keywords indicates they are unified whereas the default option is multiple. When the Ensemble Kalman Filter is applied, after each assimilation step there is a need to have a new restart files thus this keywords supposed to be omitted.

The GRID section specifies static properties of the reservoir. In following section grid geometry, porosity, permeability, net-to-gross and aquifer are specified. Based on this informations ECLIPSE computes midpoint grid depths, pore volumes and block transmissibilities. There are two types of geometrical description in ECLIPSE. In Block Centred Geometry(BC) blocks are all rectangular and scheme requires a top depth and cell size in X, Y and Z direction. Corner Point Geometry (CP) is more complicated and comparing to BC requires much more data to describe each cell in the grid. A coordinate lines define columns of cells. It can be non vertical but it is always straight. Two points, one above and the second one below defines each line. The cells in the column are defined by elevation points as seen in Figure A.1. In results we need 4 lines and 8 points do describe each cell. This leads to larger data storage however this geometry allows to describe reality more accurately since grid blocks do not have to be rectangular any more. All data given for particular cells are read or write in the Universal Transverse Mercator(UTM) convention for Cartesian grid shown in the Figure A.2. The start cell read or written is numbered (1, 1, 1) and it is situated at the top, back, left of any display. The data is read or written in order of X cycling faster followed by Y and Z.

There are two types of cells in the model active and inactive. The second one are excluded from simulation and flow is not computed for those cells. Although, inputs as porosity, permeability etc. still have to be defined for inactive cells since ECLIPSE need to compute their pore volumes, depths and transmissibilities. To specify whether cell is active or inactive keyword ACTNUM is used followed by number 1 or 0 for each active or inactive cell, respectively. All cell parameters such as PORO (porosity), PERMX, PERMY, PERMZ (permeabilities in x, y and z directions respectively), NTG(net-to-gross ratio) are averages defined for the center of the grid block.

The Faults are defined using FAULTS keyword followed by name of the fault, upper and lower margins of the face and face name (X, Y or Z). The given values are positions of the grid blocks connected to the fault (see Figure A.3). Keywords MULTFLT can be used to set transmissibility multipliers for connected cells. Command EQUALS allows assigning values whereas MULTIPLY can be used to change these values for defined by user block of cells. Usually transmissibility multiplier value is between 0 and 1 when the small value refers to small trans-

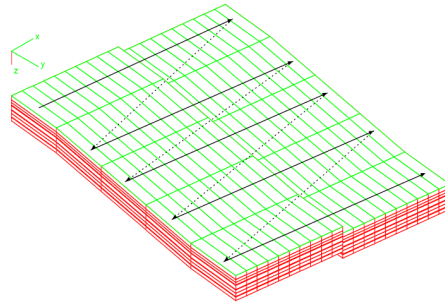


Figure A.2: Cycling scheme in read and written files, ECLIPSE 100 user course, Schlumberger GeoQuest

missibility. Except transmissibilities for grid blocks connected to faults there is a need to define this multipliers for the rest of the cells in particular zones according to horizontal barriers. This is done by use of MULTX, MULTY, MULTZ keywords which states for transmissibility in X, Y and Z direction, respectively.

The purpose of the GRID section is to calculate pore volumes, cell center depths, transmissibilities and non-neighbour connections. However after ECLIPSE have done its work user can modify these properties in EDIT section mainly by use of EQUAL and MULTIPLY keywords. Most of the keywords from GRID section apply to EDIT section.

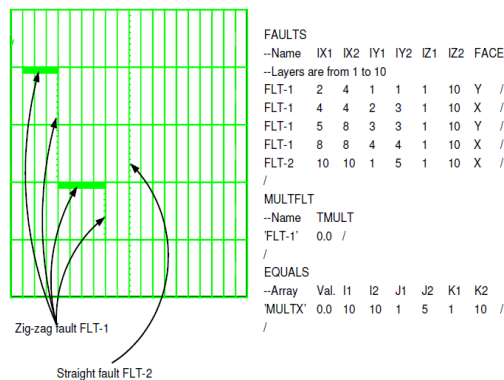


Figure A.3: Example of faults and transmissibilities definition, ECLIPSE 100 user course, Schlumberger GeoQuest

In the PROPS section tables for PVT data, rock properties, relative permeabilities and capillary pressures are defined. Keywords PVTG, PVTO and PVTW state for gas, oil and water PVT properties respectively required for material balance calculations at each time step. In case of PVTG first phase pressure is specified and then vaporized oil-gas ratio, formation volume factor and gas viscosity at according phase pressure is defined. The PVTO is followed by description of dissolved gas-oil ratio, the bubble point pressure, oil formation factor and oil viscosity at the specified bubble point. Finally properties for water are assign, reference pressure, formation volume factor, water compressibility and viscosity. In following section rock properties are included simply by using keyword ROCK i.e. compressibility at reference

pressure. For the purpose of flow calculation also saturation functions have to be described i.e. relative permeability and capillary pressure curves in the form of tables.

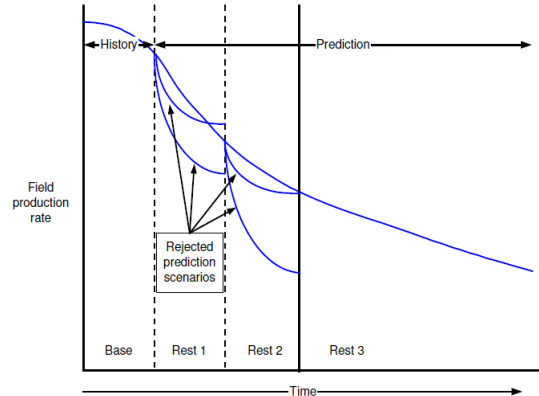


Figure A.4: Restart methodology, ECLIPSE 100 user course, Schlumberger GeoQuest

In reality parameters in reservoir vary due to the regional geology. In the REGIONS section reservoir can be subdivide in such areas in order to edit rock and fluid properties i.e. fluids in place, relative permeability, capillary pressure or fluid contacts. If the focus is only on the small part of the reservoir, it can be used for reporting purposes as well. Each cell receives a number of region it is assign to. This number can be between 0 and the maximum number of regions specified in RUNSPEC section. Commonly used keywords are EQLNUM, PVTNUM, FLUXNUM and SATNUM to associate different equilibration, PVT properties and saturations functions for different regions. Fluid-in-place regions are defined by the FIPNUM keyword.

Before simulation begins there is a need to specify initial conditions in the reservoir. This is done in the SOLUTION section. Initial pressure, phase saturation, oil and gas rates and analytical aquifer conditions are defined in one of three possible ways: equilibration, enumeration or restart. In the first case ECLIPSE describes gas-oil, oil-water contacts and pressures automatically base on information in saturation functions from the previous PROPS section. However, having the sufficient data it is possible to assign initial conditions explicitly for every cell. This is called enumeration. For the purpose of history matching initial conditions can be defined in useful RESTART way. After each so called base simulation results are written to restart file (values are assigned to every cell) and then read as a initial solution for so called restart run. It is illustrated in the Figure A.4.

Specification of the data output necessary to further plotting procedures is located in SUMMARY section. Name construction is explained in the Table A.1. For instance FOPR states for Field Oil Production Rate or WGIT is Well Gas Injection Total, however, there are exceptions to this rule, i.e. Well Bottom Hole Pressure is behind WBHP or FWCT is simply Field Water Cut.

First character		Second character		Third character		Fourth character	
F	Field	O	Oil	P	Production	R	Rate
G	Group	W	Water	I	Injection	T	Total
R	Region	G	Gas	F	Flow		
W	Well	V	Volume				
B	Block	T	Tracer				
C	Connection	L	Liquid				

Table A.1: Construction of abbreviations in ECLIPSE.

Finally the SCHEDULE section contains well data, i.e. well completion, rate data, well control and flow correlations for specified time steps. Basically this is the section where the production and injection of the wells can be managed. The fact that wells are drilled, shut, closed and opened in different times justifies the purpose of this section. It is very important to honour the right order of the keywords. Generally this must be consistent with the reality i.e. before the start of the production of particular well it has to be completed first. Each action at the certain time step has to be implemented between the specification of the date using DATES keyword followed by the day description in DAY MONTH YEAR format, for instance 14 AUG 2008 or equally 14 'AUG' 2008, and before the next date. There is about sixty keywords available in this section, albeit only the commonly used will be described in this paragraph. The keyword WELLSPECS is used to specify the location of the well in the grid and among other properties, BHP reference depth, flowing phase or fluid PVT table can be described. It is necessary for each well and has to precede any other action taken on this well and can be located at the beginning of the schedule section or at any time of the simulation. Using COMPDAT command all connections between the well and grid block can be defined. Their status is set to either OPEN or SHUT. However, two keywords WCONPROD and WCONINJE can be used to change well status to SHUT or OPEN and to set properties such control mode, fluid rate limits and bottom hole pressure limits. An alternative is to use WCONHIST for production wells and WCONINJH for injectors which declares the well as special history matching well. Defined measured fluid rates can be written to summary files to compare with simulated values. In case of Norne Filed control mode for producers is set to RESV for most of the wells what means that ECLIPSE calculate fluid pore volume rates using reservoir pressure and set the well to produce at that target.

The way how ECLIPSE deals with the flow boundary conditions deserve separate paragraph attention. If there is a need to isolate part of the field because it is a region of interest it is possible to reduce simulation time by using USEFLUX keyword. First, the maximum number of flux regions need to be specified in REGDIMS command in RUNSPEC section, then the regions are defined in keyword FLUXNUM in the GRID section, where the number of region to which the cell belongs is assigned to every gridblock. The FLUXNUM regions can be simply COPY from SATNUM or FIPNUM property. Now the full grid simulation need to be

performed once with keyword DUMPFLUX in the grid section what indicates that ECLIPSE saves the file with the record of the flow moving through the boundary. After the full field run is finished the DUMPFLUX need to be replaced with the USEFLUX keyword followed by the name of the flux file. Every time the simulation with USEFLUX is performed it refers to reduced run. However, in the reduced run the regions of interest need to be set active. It is done by use of FLUXREG in the grid section followed by the number of active region. Keywords DUMPFLUX and USEFLUX cannot be used in the same run. The wells outside the active region are simply omitted in the reduced run, however their rates are read from flux file and added to the group and field totals. There are two treatments of boundary conditions in ECLIPSE. As a default flow for each phase is stored in the flux file. However, as an alternative pressures, saturations, solution gas-oil ratio and vapour oil-gas ratio in the so called halo cells surrounding the boundary can be saved to flux file. Base on these information in the reduced run ECLIPSE calculates flows through the flux boundary. To switch between these options keyword FLUXTYPE in the GRID section can be used followed by either FLUX or PRESSURE.

There is an alternate approach to separate any area from the full field. It involves more manual edits but does not require creation of the additional files. In the GRID section user must enter COARSE keyword and specifies not overlapping "boxes" of cells to consolidate and the number of output cells. Reserved memory is specified in RUNSPEC section in the LGR keyword where the number of new cells are entered. After the method is applied, number of active cells in the model is reduced. Upscaled properties values are assigned to the center cell in the box and all other cells are set inactive. However, size of this cell is set to the size of the box thus appropriate transmissibility multipliers can be calculated. All the wells are moved to the center cell and multilayer connections are reduced to only one. Non neighbour connections between coarsened grid blocks and between original cells and coarsened are calculated.

A.2 Jewel Suite

JOA Oil & Gas Jewel Suite is a full workflow-integration framework which allows to build and design from the seismic interpretation, the grid representation to static and dynamic programming and the wells structure. It has a user friendly interface guiding step by step through preparation of the model and its workflow. Reservoir simulators such SENSOR, ECLIPSE and IMEX can be plugged in and the results of the simulation can be imported and viewed in the Jewel Suite.

It is obvious that each cell in the three dimensional grid can be represented by eight corner points. By contrast, Jewel Suite allows cell to have any number of corner points. Large reduction of storage data is gained because for the cells having the same vertical indexes only one cell is created. The K value is then stored in the cell and single depth value at the edges. Data necessary to build a grid can be either created or imported . Data Creation tools allows

to create or edit already imported data. In the process of creation tables can be entered manually or easily copied from formats as Excel files *.xls. If the model already exists but is created in different application it can be imported. Except previously exported files from Jewel Suite other formats including ASCII files, grid files, seismic SegY files and well data files are available. Because of a choice of the simulator in this thesis the focus is on the cooperation between ECLIPSE and Jewel Suite which can be seen in the Figure NUMBER. It is allowed to read different type of the data stored in separate files, i.e. *.inc, *.ecl or *.GRDECL. It is however more convenient to import the ECLIPSE deck described in the previous subsection containing full set of information required for creation of the model and a simulation.

While the model is created or imported there is a variety of tools in Jewel Suite for eventual modifications and analysis. Property Modelling allows to edit existing property of the field or create a new one. Property Calculator contains a number of functions required such basic mathematical functions, distribution, interpolation, filtering or upscaling functions. Using Property Analysis tool user can easily create statistical plots such variograms and histograms of the particular properties in order to validate quality of data. Wells can be placed in Well Planning tool and well logs can be imported from file.

Appendix B

Figures

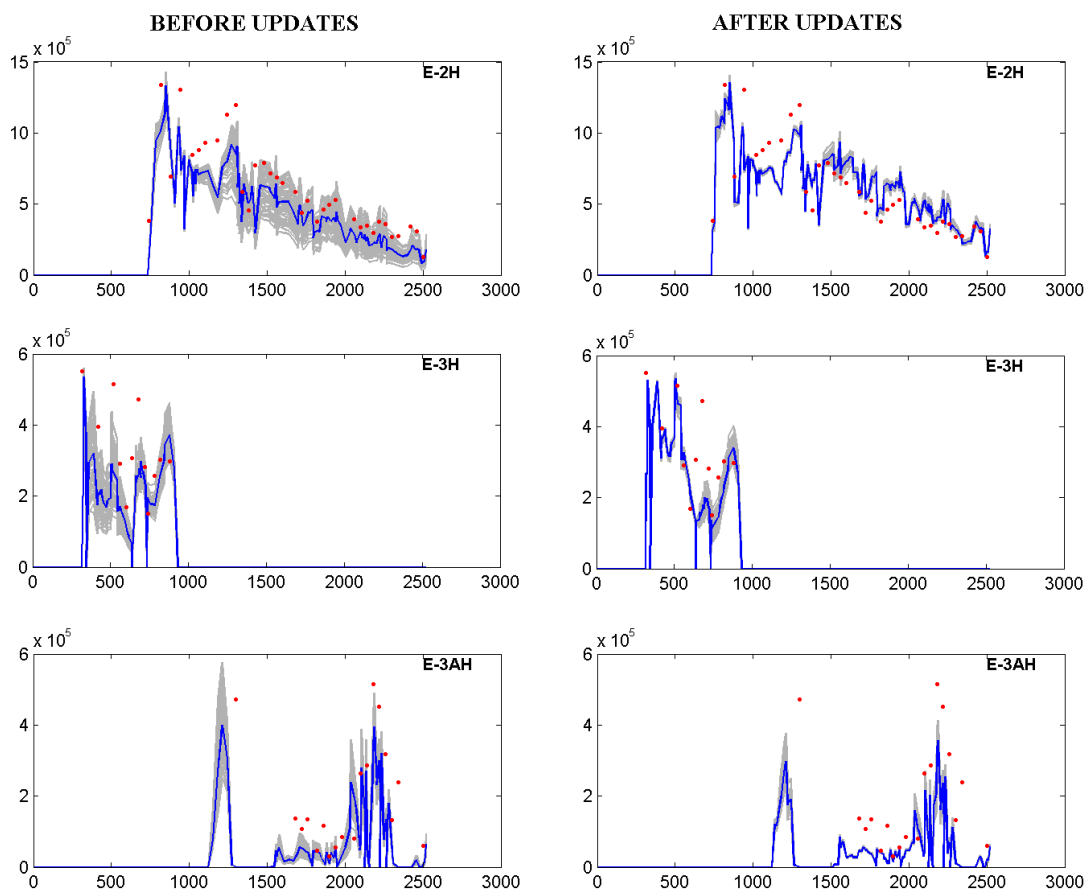


Figure B.1: Initial behaviour of WGPR [sm³/day] on the left and after last update step on the right.

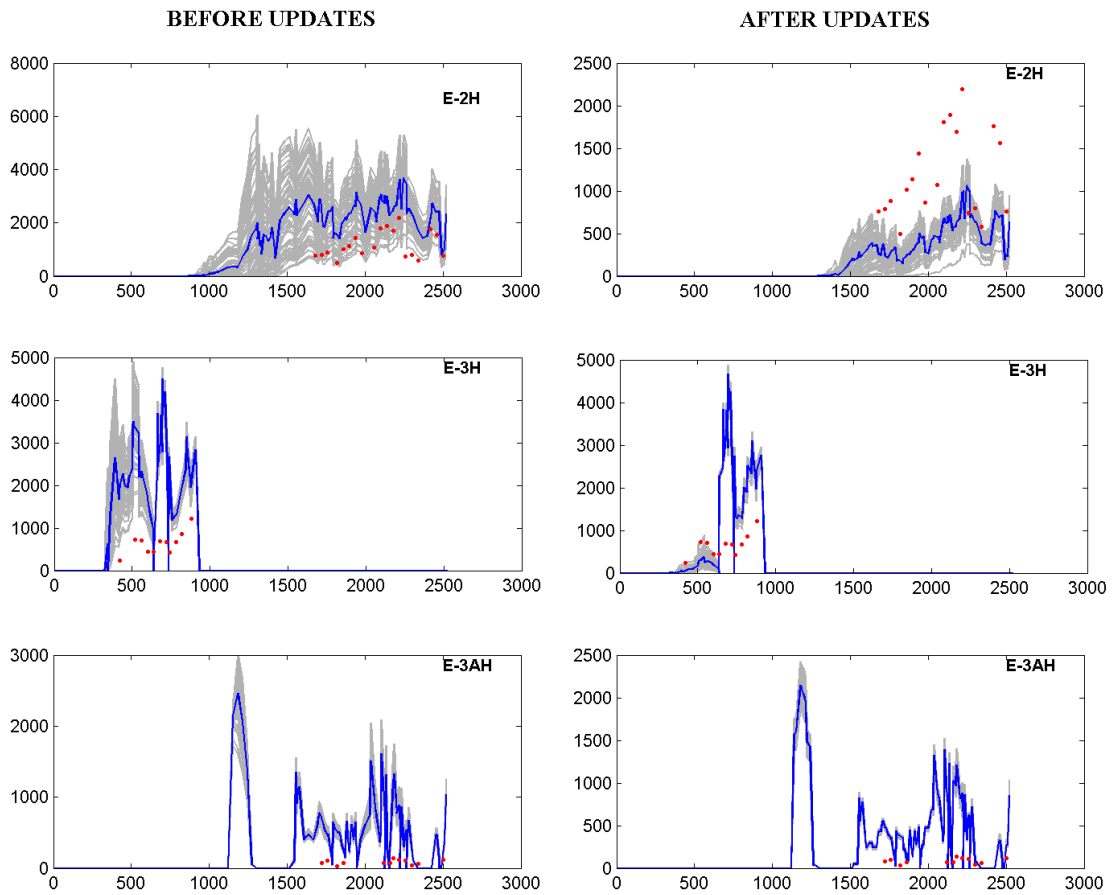


Figure B.2: Initial behaviour of WWPR [sm³/day] on the left and after last update step on the right.

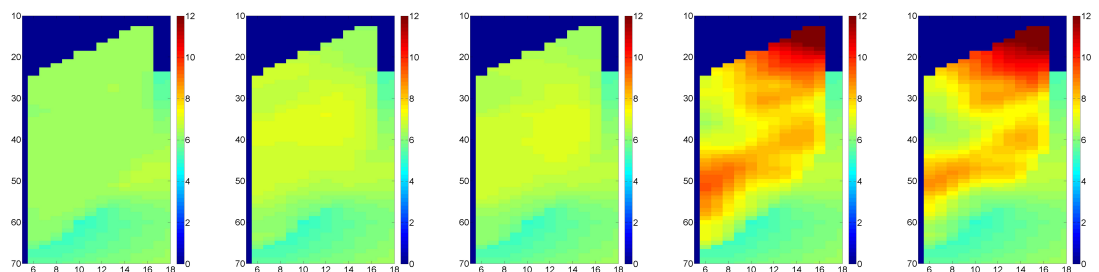


Figure B.3: Mean of LogPermY, initial and after updates: 900, 1620, 2160 and 2520.
Location: E-segment, layer 1.

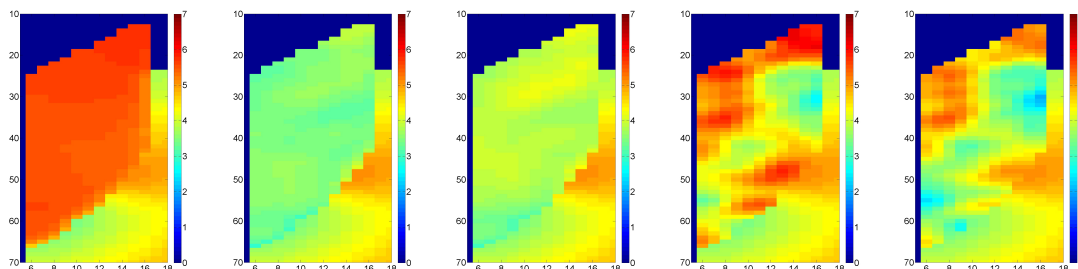


Figure B.4: Mean of LogPermZ, initial and after updates: 900, 1620, 2160 and 2520.
Location: E-segment, layer 1.

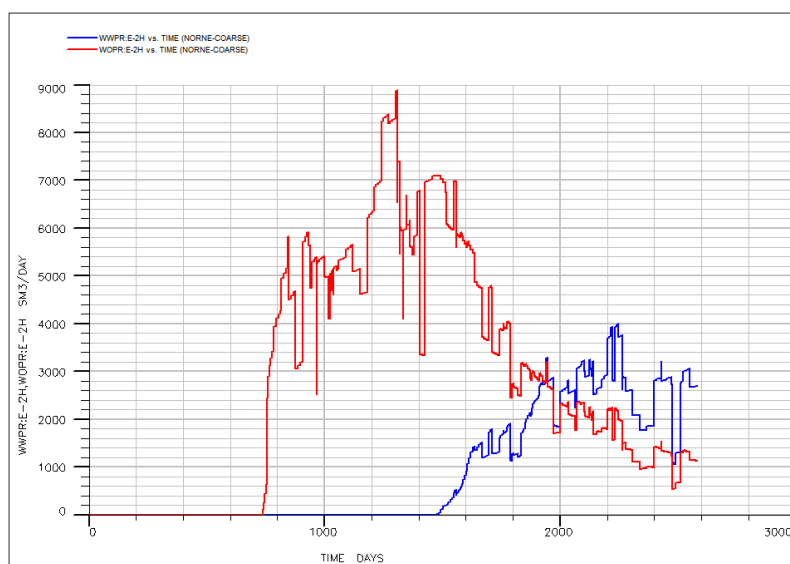


Figure B.5: Water and oil production rates for the well E-2H

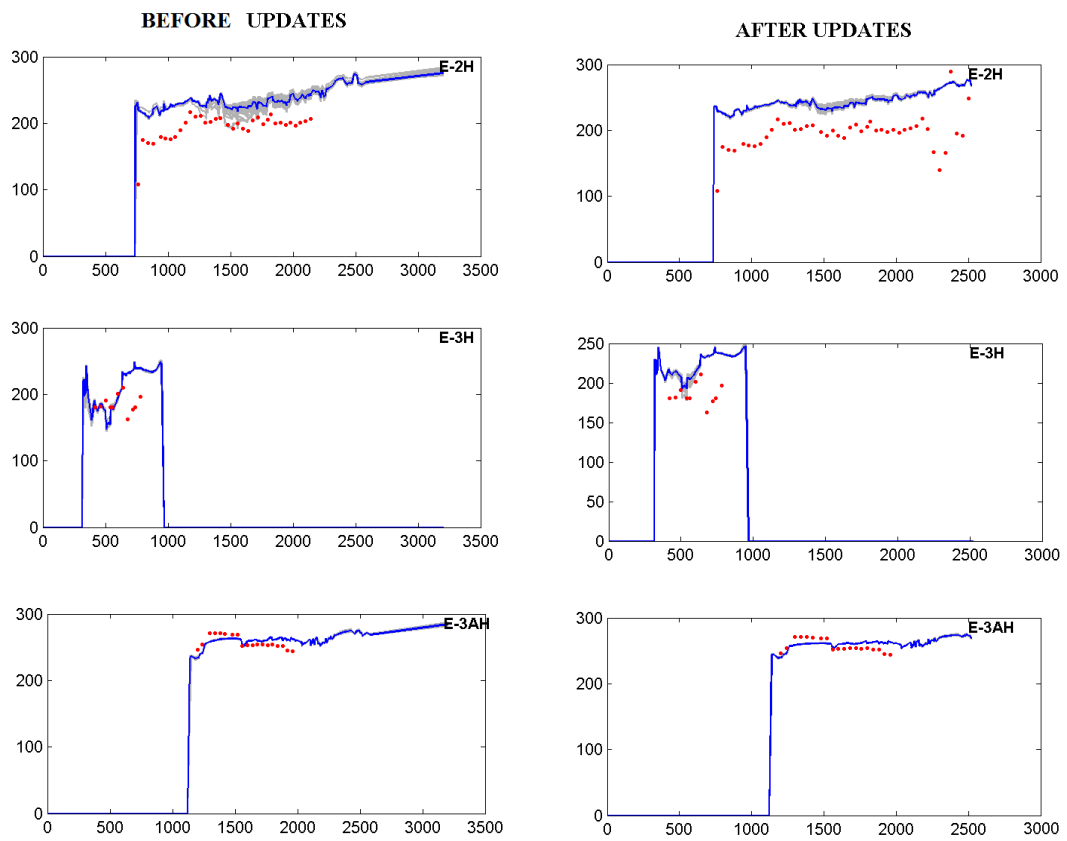


Figure B.6: Initial behaviour of BHP [Bar] on the left and after last update step on the right.

Appendix C

Basic statistics

This section covers the statistical background information required to understand the theory included in this thesis, however it can be omitted by readers familiar with basic statistics theory. The purpose of this section is rather to explain the basics than to formulate strict technical definitions.

Random Variable

It is very convenient to start with the explanation of the term *random variable*. It is a function assigning real values to the outcomes of some random experiment called *event*, $X : \Omega \rightarrow \mathbb{R}$ with a property that for all $x \in \mathbb{R}$ we can assign probability for the event $X \leq x$. The Ω is called *sample space* or *probability space*. Usually random variables are denoted as capital letters i.e. X, Y etc. and their values as an according small letters x, y etc, respectively. Thus expression $X = x$ means that random variable X takes value x .

Cumulative Distribution and Density Function

The *cumulative distribution function* (cdf) of a random variable X is a function $F_X : \mathbb{R} \rightarrow [0, 1]$ with relation

$$F_X(x) = P(X \leq x) \tag{C.1}$$

which gives the probability that X takes values smaller or equal to x . If the cdf is differentiable then the derivative

$$f_X(x) = \frac{dF_X(x)}{dx} \tag{C.2}$$

is called the *probability density function* (pdf). It is required for pdf to satisfy conditions $f_X(x) > 0$ for all x and $\int_{-\infty}^{\infty} f_X(x)dx = 1$. The pdf is used to describe the likelihood of a given random variable. It specifies the probability that the random variable takes a particular value. If X is a continuous random variable i.e. probability that X takes x at any point x is

zero,

$$P(X = x) = 0 \quad \text{for } x \in \mathbb{R} \quad (\text{C.3})$$

and if corresponding density f_X exists then probability that X lies between a and b is

$$P(a \leq X < b) = \int_a^b f_X(x) dx \quad (\text{C.4})$$

The definitions can be extended for several random variables and the *joint distribution function* of X_1, \dots, X_n is the function

$$F_{X_1, \dots, X_n}(x_1, \dots, x_n) = P(X_1 \leq x_1, \dots, X_n \leq x_n) \quad (\text{C.5})$$

and the corresponding *joint density function* is expressed as

$$f_{X_1, \dots, X_n}(x_1, \dots, x_n) = \frac{d}{dx_1} \dots \frac{d}{dx_n} F_{X_1, \dots, X_n}(x_1, \dots, x_n) \quad (\text{C.6})$$

Conditional probability density is then described as

$$f_{X|Y}(x|y) = \frac{f_{XY}(x, y)}{f_X(x)} \quad (\text{C.7})$$

Independence

Two random variables X_1 and X_2 are independent if and only if for any numbers a, b, c, d

$$P(a < X_1 \leq b, c < X_2 \leq d) = P(a < X_1 \leq b)P(c < X_2 \leq d) \quad (\text{C.8})$$

or equivalently

$$F_{X_1, X_2}(x_1, x_2) = F_{X_1}(x_1)F_{X_2}(x_2) \quad (\text{C.9})$$

or if the densities exist then analogically

$$f_{x_1, x_2}(x_1, x_2) = f_{X_1}(x_1)f_{X_2}(x_2) \quad (\text{C.10})$$

Independence of random variables is an important property in statistics. When the joint probability of two random variables $\{X_1, X_2\}$ is specified then, usually, knowing the value of one of them gives us some information what the value of the another one can be. If it is not a case then considering random variables are said to be independent.

Mean and Covariance

One of the most useful tools in statistics are *expectation* and *covariance*. The expected value for a random variable X for the continuous case is given by

$$E[X] = \int_{-\infty}^{\infty} x f_X(x) dx \quad (\text{C.11})$$

and for the discrete random variable by

$$E[X] = \sum_{i=1}^n x_i P(X = x_i) \quad (\text{C.12})$$

Intuitively expectation or mean can be interpreted as an average over many independent repetitions of an experiment in a long-run. The μ is used very often to denote mean instead of $E[X]$. Variance of the random variable is defined by

$$VAR(X) = E[(X - E[X])^2] \quad (C.13)$$

Variance measures the dispersion of a random variable around its mean. The *standard deviation* of a random variable is used very often instead of variance. It is defined as a square root of the variance

$$\sigma = \sqrt{VAR(X)} \quad (C.14)$$

Covariance of the two random variables X, Y is defined using their expected values. Namely,

$$COV[X, Y] = E[(X - E[X])(Y - E[Y])] \quad (C.15)$$

The *covariance matrix* in the case of a set of random variables X_1, X_2, \dots, X_n is defined as

$$\Sigma = \begin{bmatrix} COV(X_1, X_1) & COV(X_1, X_2) & \dots & COV(X_1, X_n) \\ COV(X_2, X_1) & COV(X_2, X_2) & \dots & COV(X_2, X_n) \\ \vdots & \vdots & \ddots & \vdots \\ COV(X_n, X_1) & COV(X_n, X_2) & \dots & COV(X_n, X_n) \end{bmatrix} \quad (C.16)$$

Covariance describes the dependency of two random variables. If they are independent then $COV(X, Y) = 0$. In the covariance matrix, elements on the main diagonal reduce to simple variances since

$$COV(X, X) = VAR(X) \quad (C.17)$$

For practical purposes basic statistical characteristics are approximated using sample method. Given a sample of N realizations of a random variable X , mean, variance and covariance are assessed by

$$E[X] \simeq \bar{x} = \frac{1}{N} \sum_{i=1}^N x_i \quad (C.18)$$

$$VAR[X] \simeq \frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2 \quad (C.19)$$

$$COV[X, Y] \simeq \frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y}) \quad (C.20)$$

Gaussian Distribution

The distribution of a random variable is given by its pdf. There are many known distributions. One of the most common is *Gaussian distribution* or *normal distribution*. Probability density of a Gaussian distribution of random variable X is given by

$$f_X(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (C.21)$$

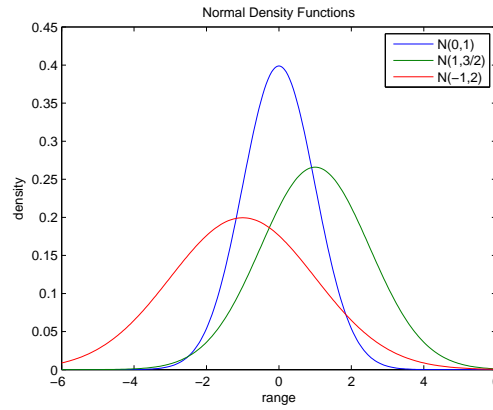


Figure C.1: Gaussian probability density function

where σ is standard deviation and μ is the mean of the variable X . Normal distribution of a random variable X can be announced by notation $X \sim N(\mu, \sigma^2)$ or in case when X is a vector of random variables with mean μ then $X \sim N(\mu, \Sigma)$ where Σ is covariance matrix. Probability density functions of a Gaussian distribution for different mean and standard deviations are presented in Figure C.1.

An important Gaussian property states that

$$\text{if } X_i \sim N(\mu_i, \sigma_i^2) \text{ then } \sum_{i=1}^n a_i X_i \sim N\left(\sum_{i=1}^n a_i \mu_i, \sum_{i=1}^n a_i^2 \sigma_i^2\right). \quad (\text{C.22})$$

In other words, the sum of normal random variables is again a normal random variable.

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