Abstract
Well placement within a reservoir is a critical procedure in any field development plan. Determining the best well location is a complicated problem containing many factors such as geological uncertainty, reservoir and fluid properties, economic costs, and technical operations limitations. Applying pure engineering judgment to solve this complicated and nonlinear problem may not be enough to get the best result, leading to reservoirs underperformance. Hence, the use of automatic well placement optimization as a supporting tool has recently gained interest in the petroleum industry. The main objective of this thesis is to use stochastic optimization algorithm in order to explore a broader set of scenarios to identify optimum well locations. In this thesis, a model was created based on the Norne field reservoir model maintaining all the parameters apart from the fluid model. The well controls of all the wells were optimized to be used as the base case scenario for this work. Six scenarios were created, and in each scenario, the wells locations and the perforation intervals of the wells were optimized and the results obtained were compared with each other and the base case scenario. The results were analyzed by evaluating trends of average reservoir pressure, cumulative oil production, cumulative gas production and field water production to determine the best scenario. The net present value for each scenario was calculated over time to determine its consistency with the initial chart comparisons. Finally, the cases scenario of 5 spot regular and irregular well pattern are determined as the best cases, as both showed the highest net present value.

Keywords: automatic well placement optimization, Norne field, well controls, net present value, cumulative oil production.

1. Introduction
Locations of wells in oil reservoir field significantly affect the productivity and economic benefits of the subsurface reservoir. However, the determination of optimal well locations is challenging because it depends on geological and fluid properties as well as economic parameters. This tends to lead to a very large number of potential scenarios that have to be evaluated using numerical reservoir simulations. The high costs of simulation make their evaluation exhaustive and sometimes infeasible. As a result, the well locations are traditionally determined by analyzing only a few scenarios. However, this method may often lead to incorrect decisions which has high economic impact. Optimization algorithms gives the possibility for a systematic exploration of a wide set of scenarios to identify optimum locations with the given conditions. The use of these algorithms allow a superior assessment of uncertainty and significantly decrease the risk in decision-making. These have led to an increased interest in the use of optimization algorithms for finding the optimum well location in oil industry.
2. Well placement optimization

Well placement problem is extremely nonlinear problem, dependent on a lot of continuous and discrete decision variables. Further by adding constraints like subsurface geomechanics, well drilling and construction, and surface facilities, geological and economic uncertainty can add complexity to the problem. This problem can become more complicated where unconventional wells (horizontal, deviated or multilateral) are considered.

Also, a lot of runs may be needed to get good results that represent the optimal solution of the problem. The number of possible solution combinations to the well placement variables increases exponentially along the increase of decision variables. Finding the optimum solution for this problem by running a few case studies is not feasible. Using intuitive engineering judgment alone could not be enough and may bias results. For almost many decades, a lots of researchers have attempted to solve this problem through automatic optimization procedures. The optimization algorithms used for this type of problems need to be:

i) Efficient: it should not demand excessive computer time or storage
ii) robust: it has to perform well on a wide variety of problems in its class, for all reasonable values of the starting point

2.1 Particle Swarm Optimization

The algorithm tries to simulate social interactions showed in animal groups, e.g., schools of fish and flocks of birds. It is composed of a population of solutions, here referred to as particles rather than individuals. The position of each particle is settled according to its fitness and position respective to the other particles. The PSO algorithm has been shown to find optimal solutions in many different application areas such as in oil and gas industry.

At every iteration, every particle in the swarm moves to a new position in the search space. consider $X_i(k) = \{x_{i,1}(k), ..., x_{i,D}(k)\}$ is the position of particle i in a D-dimensional search space at iteration k.

consider $\tilde{y}_i(k) = \{\tilde{y}_{i,1}(k), ..., \tilde{y}_{i,D}(k)\}$ depict the best position (solution) found by particle i up to iteration k, and consider $y^*(k) = \{\tilde{y}_{i,1}(k), ..., \tilde{y}_{i,D}(k)\}$ be the best position found by any of the particles in the neighborhood of $X_i$ up to iteration k. The neighborhood topologies are mentioned in detail below. One option is for the neighborhood to contain the full swarm of particles, where $y^*(k) = y^*(k)$, along $y^*(k)$ indicates the global best particle position. The new position of particle i in iteration $k + 1$, $x_i(k+1)$, is calculated by compiling a velocity, $v_i(k+1) = \{v_{i,1}(k+1), ..., v_{i,D}(k+1)\}$, to the current position $x_i(k)$. (Eberhardt 1995).

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (1)$$

The components of $v_i(k+1)$ are calculated as follows:

$$v_{ij}(k+1) = \omega v_{ij}(k) + c_1 r_{1,j} \left( \tilde{y}_{ij}(k) - x_{ij}(k) \right) + c_2 r_{2,j} \left( y^*(k) - x_{ij}(k) \right) \quad (2)$$

where j designates component in the search space; $\omega$, $c_1$ and $c_2$ are weights $r_{1,j}$ and $r_{2,j}$ are random numbers within the interval (0,1).
As mentioned in equation 2, the velocity includes three contributions, mention to as the inertia, cognitive, and social components (Eberhardt 1995). The inertia component $\omega v_i(k)$ let the particle to continue in the direction in which it was moving at iteration $k$. The cognitive term ($c_1$) captures the particle memory according to its previous best position and gives a velocity component in this direction. The social component ($c_2$) presents information regarding the best position of any particle in the neighborhood of particle $i$ and cause movement towards this particle. The velocity equation presents a random combination of these three components. Hence, each particle moves to a new position according to its existing trajectory, own memory, and the collective experience of other particles. The vectors $v_i(k)$ and $v_i(k)$ presents the difference between the current position of the particle, $x_i(k)$, and its previous best position $\bar{y}_i(k)$and global best position $y^\theta(k)$,respectively. The previous velocity $v_i(k)$ and vectors $v_i(k)$ and $v_i(k)$ are negred stochastically to obtain the new velocity $v_i(k + 1)$. The new velocity is then added to the previous position to obtain the new particle position, $x_i(k+1)$.

3. Methodology

The methodology adopted in this thesis can be basically divided into three major sections: the generation of the base case scenario, by changing the fluid system from the original Norne model scenario and optimizing its production wells’ rates; the generation of different scenarios considering the regularity and distances of different well patterns; and finally the optimization of the selected parameters. The base case scenario was created by changing the fluid system of the original model in other to be able to reduce the variables to be optimized hence the switching of all the gas injection wells from the original Norne field into water injection fields, with other reservoir parameters maintained. The production and injection rates were then optimized to obtain optimal results of the dynamic model as a base case scenario. Afterwards, six different well patterns scenarios, considering well distances and well perforations were optimized in order to maximize the oil recovery and reduce gas and water productions. The dynamic reservoir simulations ran in tNavigator® (Rock Flow Dynamics) and the optimization process was done using Raven (Epistemy). A simplified schematic representation of the workflow previously described is presented in the Figure 1 below:

![Figure 1 - Schematic representation of the methodology adopted under the development of this thesis](image-url)
3.1 Norne field overview

The Norne field is located in the southern part of the Nordland II area in the Norwegian Sea exactly on blocks 6607/10 and 6507/1. It is located 85 kilometers far from Heidrum and approximately 200 km distance from the north of the Norwegian coast (Statoil 2001).

This area has a water depth of 370 meters. Hydrocarbons in the Norne field are situated in the lower-to Middle-Jurassic sandstones, which are known to have good reservoir quality. Hydrocarbons in the Norne field are situated in the Lower- to Middle-Jurassic sandstones, which are known to have good reservoir quality (Statoil 2001).

The oil zone consists of 115 meters thick along an overlying gas cap, which makes the hydrocarbon column. The reservoir has a flat structure along crest about 2525m of depth. Reservoir pressure is near to hydrostatic, with a formation pressure of 273bar and a temperature of 98°C at a reference depth of 2639m below mean sea level. The oil/water contact is located at 2688m. Reserves in-place are estimated at 216 million mln.sm$^3$ of oil.

The whole reservoir thickness, from Top Åre to Top Garn Formations, varies over the Norne Field from 260 m in the southern parts to 120 m in the northern parts. Norne consists of two separate oil compartments; Norne Main Structure (Norne C-, D and E-segment, discovered in 1991), which contains 97% of the oil in place, and the North-East Segment (Norne G-segment).

3.2 Reservoir model description

The optimization procedure developed in this thesis was carried out on 3-D Norne reservoir model consisting of 46 x 112 x 22 grid blocks. The phases present in the reservoir are oil, water and gas. The model has 36 wells, with 4 producers and one injection wells drilled at the start, then gradually drilling more wells each year for a period of 9 years, from 1997 to 2006.

The basic geometry of the simulation grid and various rock properties (e.g., porosity, absolute permeability) in each grid cell are specified in the grid section. From these properties, the pore volumes of the grid blocks and the inter-block transmissibility are calculated by the simulator.

The porosity distribution in the reservoir is assumed to be heterogeneous with mean value of 0.27, the permeability is heterogeneous also with an average value of 478 mD in X and Y direction, while it is 95 mD in Z direction. Net-to gross sand for in the geological model has a mean value of 0.97. The Norne field has 4 different segments with Gas-oil (GOC) and oil-water (OWC) contacts varying between 2581 to 2692 meter. The Characteristics of fluid Parameters for Norne Field is shown in the Table 1 below.

<table>
<thead>
<tr>
<th>Table 1-Characteristics of fluid Parameters for Norne Field</th>
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<tbody>
<tr>
<td><strong>Unit</strong></td>
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<tr>
<td>Bubble point</td>
</tr>
<tr>
<td>Gas Oil Ratio</td>
</tr>
<tr>
<td>Oil density at bubble point</td>
</tr>
<tr>
<td>Oil Viscosity at bubble point</td>
</tr>
</tbody>
</table>
3.3 Production Scheme
Different production schedule was implemented for the several scenarios and the scenarios are discussed below.

3.3.1 Base Case Scenario
The initial Norne field reservoir model consists of 36 wells. For our base case scenario, the initial total number of 36 wells was kept albeit all vertical wells and the gas injector turned to water injectors completely along different position of injection wells than the original version. The base case model was in production for 9 years with a total of 36 wells drilled sequentially within this period, 27 production wells and 9 injection wells.

3.3.2 5-spot well pattern
In this scenario, 2 options were tested. A regular 5-spot well pattern with well-defined well spacing and an irregular 5 spot well pattern with no well-defined well spacing. In the regular scheme, the wells were placed manually with a 60 acres well pattern size while for the irregular scheme, the wells pattern size was inconsequential. This case contains 27 wells drilled sequentially, because the well pattern size can only accommodate this amount on the reservoir, 18 of them are producer wells and 9 water injectors.

3.3.3 7-spot well pattern
In this scenario, 2 options also were tested. A regular 7-spot well pattern with well-defined well spacing and an irregular 7 spot well pattern with no well-defined well spacing. In the regular scheme, the wells were placed manually with a 60 acres well pattern size while for the irregular scheme, the wells pattern size was inconsequential.
This case consists of 34 wells drilled sequentially, because the well pattern size can only accommodate this amount on the reservoir, 27 of them are producer wells and 7 water injectors.

3.4 Optimization
Simultaneously optimizing was done for the production and injection wells in the Norne field reservoir model. The main optimization studies were focused on the placement of the wells and its perforations in order to maximize the oil recovery and reduce the gas and water production in the reservoir. The multi-objective functions for all the scenarios was the optimization of the oil recovery, and minimization of the gas and water production is presented in equation 3.

\[
\text{Multi-objective functions} = \min(\text{FOIP}); \min(\text{FGPT}); \min(\text{FWPT})
\]

\(\min(\text{FOIP})\) refers to minimization of field oil initially in place, \(\min(\text{FGPT})\) refers to the minimization of field gas production total, \(\min(\text{FWPT})\) set to minimize field water production total. All the functions considered, have the same weight which 33% each.

3.4.1 Rates Optimization of the base case scenario
Rates of production and injection in oil production are very important parameters in the wells, they determine the volume of fluids produced or injected and has a great effect on the life of the reservoir if not properly managed. Hence, in the base case scenario, the production and injection rates in the wells
were all optimized with the PSO algorithm by Raven software for 300 iterations, in order to obtain optimal results that would allow minimize our multi-objective functions.

3.4.2 Well pattern optimization
The optimization of large-scale multi-well field development projects is challenging because to the number of optimization variables and the size of the search space could be very large. This difficulty can be reduced by considering well patterns and then optimizing parameters associated with the pattern type. Two type of well pattern optimization were done in this thesis; they are discussed below.

3.4.2.1 Regular well pattern optimization
Regular well pattern optimization is a type of well pattern optimization in which a certain well pattern design is deployed in the reservoir taking into account equal well pattern size leading to an equal well distance.
In this study, the well pattern size considered was 60 acres for 3 different well pattern design. The well pattern design studied in this thesis were the 5-spot, 7-spot and 9 spot inverted well patterns meaning one injector in the middle, all within an equal well pattern size of 60 acres.
The deployment of a fixed pattern size and design are done manually, and only a stochastic optimization of perforation intervals of all the wells were carried out for the 5, 7 and 9-spot regular well pattern using PSO algorithm by Raven software for 300 iterations.

3.4.2.2 Irregular well pattern optimization
The irregular well pattern optimization is a type of well pattern optimization in which a certain well pattern design is deployed in the reservoir without taking into account equal well pattern size leading, thus distance between wells is not considered and production wells are allowed to be located anywhere. The well pattern design studied in this scenario were the 5, 7 and 9-spot inverted well patterns again. For these scenarios, the production wells location is considered as variables, hence they are optimized along the perforation interval of all the wells, using PSO algorithm by Raven software for 300 iterations.

4. Results
After the optimization of the base case and the six case scenario, the best solution for well placement was picked as shown below in Figure 2, then simulation of 9 years was done, from 1997 to 2006 for all the optimized cases. The result of total oil, water and gas production along the field average pressure are then extracted and compared against each other. Further, the net present value of all cases were also computed and compared.
4.1 Field oil production total

In order to determine the best well pattern scheme, the best optimal results of each well pattern scheme are hereby compared against each other in terms of total oil, gas and water produced, and finally the net present value of each scheme. Figure 3 shows the comparisons between the best optimal result in each case in terms of the oil produced. It can be observed from the graph that the 5-spot well patterns both regular and irregular produced the highest volume of oil as compared to the others.

![Figure 3-Field oil production total vs time](image)

4.2 Field gas production total

Figure 4 shows the comparisons between the best optimal result in each case in terms of gas produced. It can be observed from the graph that the 5-spot well patterns with irregular well pattern, produced the
lowest volume of gas as compared to the others. As, our objective of the optimization at the beginning include the minimization of the gas production, Hence, the 5-spot irregular well pattern is the best scheme in terms reducing gas production. It can be also seen that all the cases performed better than base case in terms of minimization of the gas produced.

4.3 Field water production total

Figure 5 shows the comparisons between the best optimal result in each case in terms of water produced. It can be observed from the graph that almost all the cases have lower water production than the base case, except the 5-spot regular well pattern, which started to produce more water than the base case by the year 2003 to 2006. Also, the 9-spot regular well pattern has the lowest water produced comparing to all other cases.
4.4 Net present Value
The calculation of NPV is feasible after extracting results to Excel Spreadsheet program from the simulation output file. Annual oil production, summation of oil produced from the wells in a year for each case, represents a single value. Net present value takes more consideration of the economics of the project period, starting with the first year of production 1997 until the forecast production period to 2006. The base case will be compared with other Scenario cases under the NPV formula used is given below; Formula:

\[
NPV = \sum_{t=0}^{n} \left( \frac{c_f}{(1+d)^t} \right)
\]  

The NPV results summary for the base case and the six cases presented in Table 2.

<table>
<thead>
<tr>
<th>case</th>
<th>Net present value (billion usd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>73</td>
</tr>
<tr>
<td>5-spot regular well pattern</td>
<td>88</td>
</tr>
<tr>
<td>7-spot regular well pattern</td>
<td>75</td>
</tr>
<tr>
<td>9-spot regular well pattern</td>
<td>82</td>
</tr>
<tr>
<td>5-spot irregular well pattern</td>
<td>88</td>
</tr>
<tr>
<td>7-spot irregular well pattern</td>
<td>76</td>
</tr>
<tr>
<td>9-spot irregular well pattern</td>
<td>79</td>
</tr>
</tbody>
</table>

All cases are considered as there is no negative NPV. However, the NPV for the base case is less when compare to all other scenario cases. The best cases are both the 5-spot regular and irregular well pattern due to their highest NPV values of 88 billion dollars after 9 years’ production, from 1997 to 2006.

5. Conclusion
The stochastic well placement study was done on Norne field reservoir located about 85 km north of the Heidrun field in the Norwegian Sea. This field developed in the past from year 1997 to 2006, and in this study the same data and reservoir properties were used, except the production and injection rates for all wells were optimized, and the new model is the base case for this study. Then, six water flood cases were generated and optimized in order improve oil recovery, thus get a better field development scenario.

From the results of the optimization of the base case, it is concluded that not all wells have direct impact on the field performance. By, further studying the results, not all the wells seen converged entirely. Hence, an iteration with best solution was selected with their result and used base case for further study.

From the six cases scenarios, the results obtained showed that the 5-spot irregular well pattern, would likely maximize our objective functions. If analyzed individually, the 5-spot irregular well pattern showed
a slightly higher oil production, low gas production and decent water production in comparison to other cases. But, by the analysis of the net present value, we can observe that this is not the case. The net present value analysis showed a high return in monetary investment from 5-spot both regular and irregular well pattern. Even though the irregular well pattern showed promise when the objective functions are analyzed individually, but for a multi objective point of view, the 5-spot regular and irregular well pattern both performed good. Hence, we can conclude that If we properly design the 5-spot both regular and irregular well pattern scheme, we stand a chance of obtaining great value for our investment.

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