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# Uncertainty in multiphase flow estimates for a field development case

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# MASTER THESIS

For

Ingvil Bjørlo

Spring 2013

**Uncertainty in multiphase flow estimates for a field development case**
*Usikkerhetsanalyse av flerfasetransport for en feltutbygging*

**Background**
A commercial multiphase flow simulator will typically give one value for the required inlet pressure and accumulated liquid in the flowline for a given flow rate. There is, however, considerable uncertainty both in the flow model and input parameters. Field development project managers want to know the uncertainty in the predictions. Identifying uncertainty and its control has become a focus area in the oil and gas industry.

The basis for the work will be the OLGA simulator and the RMO module. With the RMO module input parameters and important model parameters may be given a probability distribution function. A Monte-Carlo simulation will draw randomly from these probability distributions and provide a probability distribution of the output variables such as liquid inventory and pipeline pressure drop.

**Objectives**
Development of a methodology for uncertainty estimation of multiphase simulation results

**The following tasks are to be considered**

1. A short literature study on internal work performed by subcontractor and Statoil
2. Familiarisation of OLGA and the RMO module
3. Construction of an OLGA model for two selected field cases
4. Evaluate input and model parameter uncertainty spans
5. Perform Monte-Carlo simulations, evaluate the results and iterate on point 4 if necessary
6. Present the results in a report with suggestions for further work

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☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 16 January 2013

For Zhilin

Olav Bolland
Department Head

Zhilin Yang
Academic Supervisor

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# Sammendrag

Kommersielle flerfasesimulatorer gir vanligvis én verdi for hver outputparameter som blir simulert i en rørledning. Prosjektledere for feltutbygging vil vite usikkerheten i disse prediksjonene for å vurdere risikoen. To feltstudier fra rørledningen P10 fra Troll plattformen ble undersøkt; ett tilfelle var tyngdekraftsdominert og det andre var friksjonsdominert. Dette ble gjennomført ved å bruke flerfasesimulatoren OLGA og funksjoner i den innebygde RMO (Risk Management and Optimization) modulen.

En sensitivitetsanalyse ble utført for å undersøke den lineære effekten av input- og modellparameterne på outputparameterne, og de mest betydningsfulle parameterne ble funnet. For å se simultane effekter ble en usikkerhetsanalyse utført. Latin Hypercube metoden ble brukt til å finne et utvalg ved å trekke input- og modellparametere i henhold til en sannsynlighetsfordeling, og deretter beregne outputverdier. Ut i fra dette ble usikkerhets-intervaller funnet for outputparameterne. Resultatene ble deretter sammenlignet med målinger fra Troll-feltet, for å se hvor godt OLGA klarte å simulere rørledningen. En tuning ble utført for å se om beregningene kom nærmere målingene ved å endre noen av modellparametere. Dette viste seg å være utfordrende ettersom rørledningen har lav væskelast og stiger i en veldig bratt vinkel mot land.

Som en metode for usikkerhetsestimering av resultater fra flerfasesimulering har RMO modulen potensial til å være et nyttig og praktisk verktøy. For øyeblikket har det imidlertid for mye uberegnelige oppførsel som fører til tap av data og tid. Generelt var denne typen metodikk for usikkerhetsestimering svært nyttig for å visualisere flerfasetransportrisiko i forbindelse med en feltutbygging, og representerer et betydelig skritt fremover i så måte.

# Abstract

Commercial multiphase flow simulators typically give one value for each output parameter simulated in a pipeline. Field development project managers want to know the uncertainty in these predictions in order to assess the risk. A study on two field cases, one gravity dominated case and one friction dominated, from the Troll P10 pipeline was conducted using the multiphase flow simulator OLGA and the functions in the embedded RMO (Risk Management and Optimization) module.

A sensitivity analysis was performed to investigate the linear effects of the input- and model parameters on the output, and the most influential parameters were found. To see simultaneous effects, an uncertainty analysis was executed, drawing input- and model parameter values using Latin Hypercube sampling according to a probability distribution, and calculating the output values. Thus, uncertainty ranges were found for the output parameters. The results were then compared to measurements from the Troll field, to see how well OLGA simulated the pipeline. A tuning session was performed to see if the calculations were closer to the measurements when altering some of the model parameters. This proved challenging, as the pipeline has low liquid loading and a high pipe inclination towards land.

As a methodology for uncertainty estimation of multiphase simulation results, the RMO module has potential to be a useful and practical tool. However, it currently has too much erratic behavior which causes loss of data and time. Generally, this sort of uncertainty estimation methodology was very useful to visualize flow assurance risk in connection with a field development project, and represents a significant step forward in this regard.

# Preface

This report is a result of cooperation between me, student technician Ingvil Bjørlo, writing a master thesis for the Norwegian University of Science and Technology and Statoil ASA. I came in contact with the Statoil Research Centre in Trondheim when I applied for a summer internship through professor Ole Jørgen Nydal and his multiphase flow course at NTNU. I continued working with Statoil after the internship, and completed my project thesis the following semester. This last semester has been spent on my master thesis, and I have enjoyed working almost a year with Statoil.

Multiphase flow is a complex and challenging field of study and it has been very rewarding for me to learn more about it from experienced people. With my background in computing and ICT, it has also been very interesting to work with multiphase flow simulators.

I would like to thank Peter Sassan Johansson, Bjørnar Hauknes Pettersen and Zhilin Yang at Statoil ASA and Ole Jørgen Nydal at NTNU for valuable help and guidance throughout this project. Especially Dr. Johansson has spent a lot of time with me, patiently answering questions and giving useful feedback, which I am very grateful for. I would also like to thank Statoil ASA for access to their offices at Rotvoll for the duration of the project and for providing licenses and software needed to complete the work for this thesis.

Ingvil Bjørlo, June 4, 2013. Trondheim

# Abbreviations and definitions

| | |
|---|---|
| Critical angle | The inclination angle at which transition between low and high holdup occurs for a given flow rate. The holdup solution is high above the critical angle, and low below. |
| Hysteresis effect | Phenomenon where different dynamic steady state solutions are obtained depending on history, or initial conditions. This can be due to multiple solutions to the equations solved in OLGA, numerical reasons, correlations and closure laws, and issues with slug regime effects. |
| Latin Hypercube Design | A statistical sampling method used to investigate the impact of parameter distributions. Samples of collections of parameter values are generated from a multidimensional distribution. |
| Monte Carlo simulations | A problem solving technique used to approximate the probability of certain outcomes by running multiple simulations using random variables. |
| $MSm^3/d$ | Unit of measurement for flow rate (mega standard cubic meters per day) |
| MEPO® | Software framework utilizing Experimental Design methods for optimization, sensitivity and uncertainty analysis. Can be coupled with OLGA. |
| OLGA® | Simulation software for multiphase pipe flow. |
| OLGA HD | The OLGA High Definition flow module, applicable for stratified two- and three-phase flow. |
| OLGA RMO | A Risk Management and Optimization module for OLGA with functions for sensitivity analysis, uncertainty analysis and data tuning. Powered by MEPO. |
| OLGAS | Steady-state multiphase model based on OLGA. |
| P10, P50 and P90 | Percentiles. The outcome for which the probability of occurrence of that value or less is 10%, 50% or 90%, respectively. E.g., if P10 is 20, there is a 10% chance, statistically, that the parameter value is 20 or below. |
| Sensitivity analysis | A set of simulations where each uncertainty parameter is individually set to minimum and maximum value while all other parameters are set to default values. Cheap with respect to number of simulation runs. |
| Uncertainty analysis | A set of simulations where all uncertainty parameters are varied simultaneously and randomly according to a probability distribution for each variable. Requires considerably more simulations than the sensitivity analysis. |

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# 1 Introduction

## 1.1 Background

A commercial multiphase flow simulator will typically give one value for the required inlet pressure and the accumulated liquid in the pipeline for a given flow rate. There is, however, considerable uncertainty both in the model parameters used in the flow model and in the input parameters given by the user, which can give considerable uncertainty for the output parameters. Field development project managers want to know the uncertainty in the predictions in order to assess the risk, i.e. the potential severity of impact. Identifying uncertainty and its control has become a focus area in the oil and gas industry. Two field cases from a Troll pipeline have been selected for the study; one is gravity dominated and the other is friction dominated.

The basis for the work will be the commercial flow simulator OLGA 7 with the Risk Management and Optimization (RMO) module. MEPO is a program currently used for uncertainty estimation, among other things, but it is quite extensive and requires its own license. The RMO module is a less extensive version of MEPO embedded in OLGA. It is therefore of interest to investigate the RMO module and whether or not it is an adequate alternative for uncertainty estimation. In the RMO module, input parameters and important model parameters may be given a probability distribution function with assigned upper and lower limits. A statistical sampling method can then randomly draw values between these limits, and the RMO module will then provide a probability distribution of the output variables such as inlet pressure and accumulated liquid. Thus, an uncertainty band for the output variables can be found, and the risk can be assessed.

## 1.2 Objective

A methodology for uncertainty estimation of multiphase simulation results is to be developed. The following tasks are to be considered:

1. A short literature study on internal work performed by subcontractor and Statoil
2. Familiarisation of the OLGA program and the use of the RMO module
3. Construction and modification of an OLGA model for two selected field cases
4. Evaluate input- and model parameter uncertainty spans and probability distributions
5. Perform uncertainty analyses, evaluate the results, and iterate on point 4 if necessary
6. Assess the performance of the RMO module
7. Present the results in a report with suggestions for further work

# 2 Literature review

Some internal work concerning uncertainty analysis of input- and model parameters has already been performed by subcontractor and Statoil ASA. These reports indicate which parameters are deemed important for the uncertainty estimation, and how the previous work has been executed. The work found most relevant for this study is summarized below.

## 2.1 Uncertainty estimates in multiphase flow simulation, SPT Group 2012

SPT Group did some work for Statoil looking for a universal and structured method to specify flow model uncertainties (Kirkedelen, 2012). An experimental matrix with 10 000 different combinations of input parameters was provided by Statoil, based on Statoil's database of laboratory measurements. The commercial flow simulator OLGAS (OLGA steady-state) with the High Definition (HD) model was used for the calculations. The model parameters were identified through discussions with the model development groups at SPT Group and IFE. An overview of the parameters used is found in Table 2-1, Table 2-2 and Table 2-3 (Kirkedelen, 2012, pp. ii - iii).

**Table 2-1: SPT Group 2012 - List of input parameters**

| Input parameter | Description | Unit | Comments |
|---|---|---|---|
| USG | Superficial velocity gas | [m/s] | Parameter ending = A: Absolute uncertainty (e.g. USGA, USHA, etc.)<br><br>Parameter ending = R: Relative uncertainty (e.g. USGR, USHR, etc.) |
| USH | Superficial velocity oil | [m/s] | |
| USW | Superficial velocity water | [m/s] | |
| ROG | Density oil | [kg/m$^3$] | |
| ROH | Density gas | [kg/m$^3$] | |
| ROW | Density water | [kg/m$^3$] | |
| MUG | Viscosity gas | [Pa·s] | |
| MUH | Viscosity oil | [Pa·s] | |
| MUW | Viscosity water | [Pa·s] | |
| SIGGH | Interfacial tension gas-oil | [N/m] | |
| SIGGW | Interfacial tension gas-water | [N/m] | |
| SIGHW | Interfacial tension oil-water | [N/m] | |
| DIAMA | Pipe diameter | [m] | Absolute uncertainty |
| PHI1A | Pipe inclination | [°] | Absolute uncertainty |
| EPSABSR | Pipe roughness | [m] | Relative uncertainty |

**Table 2-2: SPT Group 2012 - List of model parameters**

| Model parameter | Description |
|---|---|
| KTGSMTH | Scaled eddy viscosity on the gas side of the gas/liquid interface for a hydrodynamic smooth flow |
| KTGWAVY | Scaled eddy viscosity on the gas side of the gas/liquid interface for a hydrodynamic rough wavy flow |
| KTGGRAV | Scaled eddy viscosity on the gas side of the gas/liquid interface for a gravity dominated up-flow |
| KTLSMTH | Scaled eddy viscosity on the liquid side of the gas/liquid interface for a hydrodynamic smooth flow |
| KTLWAVY | Scaled eddy viscosity on the liquid side of the gas/liquid interface for a hydrodynamic rough wavy flow |
| KTBSMTH | Scaled eddy viscosity on the oil side of the oil/water interface for a hydrodynamic smooth flow |
| KTBWAVY | Scaled eddy viscosity on the oil side of the oil/water interface for a hydrodynamic rough wavy flow |
| KTASMTH | Scaled eddy viscosity on the water side of the oil/water interface for a hydrodynamic smooth flow |
| KTAWAVY | Scaled eddy viscosity on the water side of the oil/water interface for a hydrodynamic rough wavy flow |
| FF | Entrainment rate |
| FF_VOID | Onset of gas entrainment in liquid film |
| GG_VOID | Gas entrainment in liquid film |
| USLC | Critical liquid velocity for onset of droplet entrainment |
| OWCONST | Oil-water dispersion parameter |
| UB | Slug bubble velocity |
| VOIDINSLUG | Multiplier for the void fraction in slugs |
| DROPROUGH | Efficient wall roughness caused by liquid droplets at the wall |

**Table 2-3: SPT Group 2012 - List of output parameters**

| Output parameter | Variable description | Unit |
|---|---|---|
| HT | Total liquid volume fraction (including water and oil droplets in gas) | [-] |
| WAT | Total water volume fraction (continuous water film + water droplets in oil and gas) with respect to total liquid (water and oil in continuous liquid film and droplets in gas) | [%] |
| Pressure gradients | • Total pressure gradient (friction + gravity + acceleration)<br>• Frictional part (negative for positive flow)<br>• Acceleration part | [Pa/m] |
| IDGH | Gas-oil flow regime indicator | |
| IDWH | Oil-Water flow regime indicator | |

Uncertainties for the input parameters were defined by investigating the measurement uncertainties for the equipment used in the experiments done at the IFE, SINTEF and Porsgrunn laboratories. The range and distribution function for the model parameters were calculated using OLGA on a data set where holdup and pressure drop measurements were available. For each measured experiment, simulations using an uncertainty range for each model parameter were performed. The simulation best matched with the measurements was returned, and from this a distribution function was determined (Kirkedelen, 2012, pp. 14-18). The ranges and distribution functions for the different model parameters are found in Table 2-4 and Table 2-5 (Kirkedelen, 2012, pp. 18-19). The model parameters without ranges in the tables were discarded, as they had no significant impact on the results.

**Table 2-4: SPT Group 2012 - Range and distribution functions from tuning against two-phase measurements**

| Model parameter | | Lower limit | Default value | Upper limit | Distribution function |
|---|---|---|---|---|---|
| KTGGRAV | Multiplier | 0.001 | 1 | 2.0 | Truncated Normal |
| KTGWAVY | | 0.001 | 1 | 3.5 | Triangular |
| KTLWAVY | | - | - | - | |
| FF | Multiplier | 0.001 | 1 | 4.0 | Triangular |
| FF_VOID | Multiplier | 0.001 | 1 | 8.0 | Uniform |
| GG_VOID | Multiplier | 0.001 | 1 | 8.0 | Uniform |
| USLC | Multiplier | 0.001 | 1 | 2.0 | Truncated Normal |
| DROPROUGH | Multiplier | 0.001 | 1 | 4.5 | Truncated Normal |
| UB | Multiplier | 0.8 | 1 | 1.2 | Truncated Normal |
| VOIDINSLUG | Multiplier | 0.5 | 1 | 1.5 | Uniform |

**Table 2-5: SPT Group 2012 - Range and distribution functions from tuning against three-phase measurements**

| Model parameter | | Lower limit | Default value | Upper limit | Distribution function |
|---|---|---|---|---|---|
| KTGGRAV | Multiplier | 0.1 | 1 | 2 | Truncated Normal |
| KTGWAVY | Multiplier | 0.3 | 1 | 2.5 | Truncated Normal |
| FF | Multiplier | 0.1 | 1 | 3 | Truncated Normal |
| FF_VOID | Multiplier | 0.3 | 1 | 8 | Truncated Normal |
| GG_VOID | Multiplier | 0.2 | 1 | 8 | Truncated Normal |
| USLC | Multiplier | 0.2 | 1 | 2 | Truncated Normal |
| DROPROUGH | Multiplier | 0.5 | 1 | 6 | Truncated Normal |
| UB | Multiplier | 0.6 | 1 | 1.5 | Truncated Normal |
| VOIDINSLUG | Multiplier | 0.5 | 1 | 1.5 | Truncated Normal |
| OWCONST | Multiplier | 0.5 | | 8.5 | Truncated Normal |
| KTAWAVY | Multiplier | 0.3 | 1 | 3.5 | Truncated Normal |
| KTASMTH | Multiplier | - | - | - | Truncated Normal |
| KTBWAVY | Multiplier | 0.2 | 1 | 3.5 | Truncated Normal |

| **Model parameter** | | **Lower limit** | **Default value** | **Upper limit** | **Distribution function** |
|---|---|---|---|---|---|
| KTBSMTH | Multiplier | - | - | - | |
| KTLWAVY | Multiplier | - | - | - | |
| KTLSMTH | Multiplier | - | - | - | |
| KTGSMTH | Multiplier | - | - | - | |

A sensitivity analysis was performed in the analysis and optimization framework called MEPO to see the linear sensitivities of the output parameters to the input- and model parameters, thus finding the parameters which are most important. Then, an uncertainty analysis was performed in MEPO using the Latin Hypercube sampling method. The output parameters were calculated while each uncertainty parameter was randomly varied between the minimum and maximum values according to the given probability distribution function. Thus, an uncertainty span between P10 and P90 values could be found for the output parameters.

## 2.2 Shtokman flow assurance uncertainty analysis, SPT Group 2011

SPT Group has also performed a set of analyses for the Shtokman field in the Barents Sea. The first part was a core model evaluation, where the goal was to find the best OLGA model to use for the Shtokman flow assurance uncertainty analysis (Vanvik, 2011). A set of OLGA flow models at conditions relevant for two-phase transfer of gas and condensate from the Shtokman field to shore were evaluated. Comparisons with relevant laboratory- and field data were performed. The OLGA HD model was found to have the best overall match for both field- and experimental data. In addition, OLGA HD had no discontinuity in predicted critical angle versus flow rate, and the problems related to liquid holdup hysteresis during ramp-down/ramp-up were significantly reduced.

The second part consisted of developing and applying a methodology for a risk based uncertainty analysis of steady state prediction of pressure drop, capacity, minimum turndown and liquid content for the Shtokman long dry two-phase flow trunk lines to shore (Vanvik, Biberg, Holm, & Hoyer, 2011). The methodology proved to be successful, and the results seemed to be applicable. The Shtokman flow line was simulated using the OLGA HD 7.0.0 flow model coupled with MEPO. The uncertainty parameters considered in this study can be found in Table 2-6 and Table 2-7 (Vanvik, Biberg, Holm, & Hoyer, 2011, pp. 17, 21.).

**Table 2-6: SPT Group 2011 – List of input parameters with ranges**

| Input parameter | Description | Found in | Lower limit | Default value | Upper limit |
|---|---|---|---|---|---|
| LIQHCFAC | Liquid hydrocarbon fraction | TUNING | 0.4 | 1 | 1.76 |
| GASDENSITY | Gas density | TUNING | 0.95 | 1 | 1.05 |
| OILDENSITY | Oil density | TUNING | 0.9 | 1 | 1.1 |
| GASVISC | Gas viscosity | TUNING | 0.9 | 1 | 1.1 |
| OILVISC | Oil viscosity | TUNING | 0.7 | 1 | 1.3 |
| SIGGL | Gas/liquid surface tension | TUNING | 0.5 | 1 | 1.5 |
| ROUGHNESS | Hydraulic wall roughness (μm) | PIPE | 0 | 30 | 46 |
| XSTART | Flowline length (km) | GEOMETRY | 0 | 0 | +5 |
| DIAMETER | Internal diameter (mm) | PIPE | 862.4 | 863.4 | 864.4 |
| PRESSURE | Arrival pressure (bara) | NODE | 60 | 60 | 70 |
| UVALUE | Heat transfer coefficient ($W/m^2/K$) | HEATTRANSFER | 10 | 18 | 30 |
| OUTTAMBIENT and TAMBIENT | Seawater temperature (°C) | HEATTRANSFER | -2 | -1.8 | 4 |
| Trunk line geometry | Three different elevation profiles | (1=worst, 2=base, 3=best) | 1 | 2 | 3 |

**Table 2-7: SPT Group 2011 – List of model parameters with ranges**

| Model parameter | Description | Found in | Lower limit | Default value | Upper limit |
|---|---|---|---|---|---|
| DIAMPOWER | Diameter exponent | TUNING | 0.5 | 1 | 1.5 |
| ANGLESCALE | Inclination term factor | TUNING | 0 | 1 | 3 |
| ANGLEDIAMPOWER | Inclination term exponent | TUNING | 0 | 0 | 1.5 |
| GROUGHNESS | Roughness effect of droplets | TUNING | 0.7 | 1 | 1.3 |
| WETFRACTION | Scaling of droplet wetted wall | TUNING | 0.7 | 1 | 1.3 |
| KTGSMTHFAC | Smooth turbulence for gas | TUNING | 0.7 | 1 | 1.3 |
| KTGWAVYFAC | Wavy turbulence for gas | TUNING | 0.7 | 1 | 1.3 |
| KTGGRAVFAC | Gravity turbulence for gas | TUNING | 0.7 | 1 | 1.3 |
| KTALOWTFAC | Low turbulence for liquid | TUNING | 0.7 | 1 | 1.3 |
| KTAHIGHTFAC | High turbulence for liquid | TUNING | 0.7 | 1 | 1.3 |

A sensitivity analysis was then performed in MEPO to investigate which uncertainty parameters had the most influence on the liquid content at low flow rate, pressure drop at design flow rate, and arrival temperature at design flow rate. Parameters that had no effect at all were KTGSMTHFAC, GROUGHNESS and WETFRACTION. However, it was assumed that the effect could be present when varying all input- and model parameters simultaneously. In order to capture nonlinear dependence of the input- and model parameters, an uncertainty analysis was performed in MEPO using the Latin Hypercube sampling method. In this case, a triangular distribution was chosen for all parameters, ensuring that a significant fraction of the parameter values would be close to the upper and lower limits. In such a way, uncertainty spans for the liquid content, required inlet pressure and pressure drop were obtained.

The third part of SPT Group's analyses was developing and applying a methodology for a risk based uncertainty analysis of dynamic simulations of production ramp-up for the Shtokman long dry two-phase flow trunk lines to shore (Vanvik & Holm, 2011). However, the simulation cost associated with transient simulations of the Shtokman flowlines makes such an approach very challenging. The uncertainty parameters used were the same as for the previous steady-state from WPII, in addition to two new parameters, seen in Table 2-8.

**Table 2-8: SPT Group 2011 - Additional parameters for dynamic simulations**

| Uncertainty parameters | Description | Lower limit | Default value | Upper limit | Found in |
|---|---|---|---|---|---|
| Ramp-up time (TIME) | Time taken for the flow rate at inlet to be increased from initial to final value (h) | 1 | 6 | 24 | SOURCE |
| Drainage capacity | The maximum volumetric liquid flow rate that must be drained from the slug catcher ($m^3$/h) | - | 76 | - | Post-processing |

The methodology for the uncertainty analysis is much the same as for the steady-state study. As dynamic situations are not part of the scope for this work, the information from this report is not relevant in this case.

## 2.3 Conclusion

In both these sets of reports, OLGA HD 7.0.0 was used to perform the simulations. The scope of this project is for steady-state, and dynamic situations will not be taken into account. Hence, OLGA HD 7.1.4 (the latest version available in Statoil) with the steady-state option will be used for the simulation of the selected field cases in this project. More information about the field cases can be found in chapter 3.1.

The execution of the analyses was similar in the reports:

1. OLGA simulation of data
2. Sensitivity analysis by coupling OLGA with MEPO
3. Uncertainty analysis by coupling OLGA with MEPO
4. Analysis of the obtained results, and further tuning if necessary

The process can be used similarly in this study, except for the use of the MEPO software. After simulating the field cases in OLGA, the sensitivity and uncertainty analyses in this project will be performed using the RMO module embedded in OLGA 7.1.4. The RMO module does not have all the functions MEPO has, but it is powered by MEPO, and the analyses will thus be similar. More information about the RMO module can be found in chapter 3.2.

In the first report (Kirkedelen, 2012), the uncertainty analysis was based on experimental data from Statoil's laboratory database. The experimental data were entered into OLGA and simulated, and could then be analyzed by coupling OLGA with MEPO. The Shtokman uncertainty analysis (Vanvik, Biberg, Holm, & Hoyer, 2011), was based on an OLGA simulation of the Shtokman flowline, and was also done through MEPO. Both reports have their own list of input- and model parameters, with their respective upper and lower limits, and distribution functions. These parameters are the ones deemed important by the OLGA developers in SPT Group. The same input- and model parameters are tested in this project as well. Some of the parameters are not available for regular users of OLGA, i.e. they are not available from the commercial OLGA graphical user interface.

The field cases to be considered in this study are three-phase flows; hence the upper and lower limits used for analyses should essentially be taken from the three-phase results. The Shtokman flow line study assumed two-phase flow, but the limits from field data may be more relevant than the limits from experimental data. Therefore, if there are no three-phase parameter limits, the Shtokman parameter limits are used in this study.

The original idea was to use a Monte Carlo sampling method to generate samples for the uncertainty analysis. However, as seen in these reports, MEPO (and hence the RMO module) has Latin Hypercube sampling embedded. While Monte Carlo generates samples randomly, the Latin Hypercube method ensures that no sample can be selected twice. Thus, Latin Hypercube sampling will span the sample space with fewer samples. It was therefore decided that Latin Hypercube sampling should be used instead of the Monte Carlo simulations for this project. More information about Latin Hypercube sampling can be found in chapter 3.3.

# 3 Background theory

## 3.1 Field cases: Troll P10 pipeline

The Troll field is a natural gas and oil field in the northern part of the North Sea. It is primarily a gas field, but it also possesses significant amounts of oil. The field is operated by Statoil, and has three platforms: Troll A, B, and C (Berg & Johansen, 2002). As seen in Figure 3-1, Troll A is located in the east part (red) where gas production is the main focus. Troll B and C are in the west part, which is divided into two provinces, one for gas (green) and one for oil (blue).


**Figure 3-1: The Troll field with approximate locations of the platforms**

The platform of interest for the field cases is Troll A. Gas, condensate and MEG (water phase) from Troll A runs in two parallel pipelines, P10 and P11, to Kollsnes. Gas from Troll B and C can be directed on to either one or both pipelines. This is illustrated in Figure 3-2. It is the P10 pipeline for two different flow rates which has been considered in this study. The first case is friction dominated, with a flow rate of 34.9 $MSm^3/d$, while the second case is gravity dominated, with a flow rate of 24.6 $MSm^3/d$.

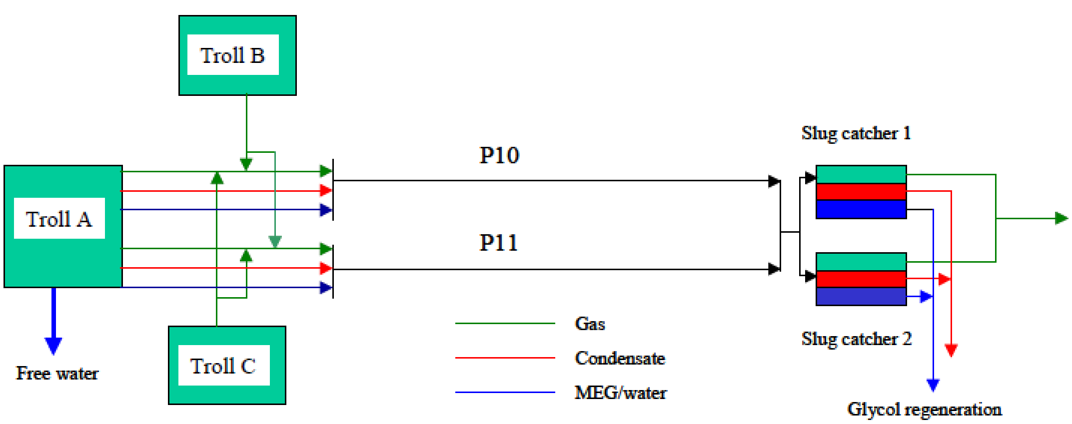


**Figure 3-2: Flow chart Troll A - Kollsnes**

**Table 3-1: Results from Troll tests by Statoil**

| | **Test 7 August 2002** | **Test 8 April 2004** |
|---|---|---|
| Gas flow rate | 24.61 $MSm^3/d$ | 34.94 $MSm^3/d$ |
| Condensate<br>• Flow rate<br>• Density | <br>2.87 $m^3/h$<br>700.3 $kg/m^3$ | <br>0 $m^3/h$<br>700.3 $kg/m^3$ |
| MEG<br>• Flow rate<br>• Density | <br>3.9 $m^3/h$<br>1086 $kg/m^3$ | <br>3.8 $m^3/h$<br>1086 $kg/m^3$ |
| Troll A gas<br>• Flow rate<br>• Temperature<br>• Density | <br>20.04 $MSm^3/d$<br>37.3 °C<br>0.739 $kg/m^3$ | <br>34.94 $MSm^3/d$<br>44.6 °C<br>0.739 $kg/m^3$ |
| Troll B gas<br>• Flow rate<br>• Temperature<br>• Density | <br>4.57 $MSm^3/d$<br>4.58 °C<br>0.789 $kg/m^3$ | <br>0 $MSm^3/d$<br>5 °C<br>0.789 $kg/m^3$ |
| Troll C gas<br>• Flow rate<br>• Temperature<br>• Density | <br>0 $MSm^3/d$<br>5 °C<br>0.776 $kg/m^3$ | <br>0 $MSm^3/d$<br>5 °C<br>0.776 $kg/m^3$ |
| ***Mass flow rate*** | | |
| Gas | 213.1 kg/s | 298.9 kg/s |
| Condensate | 0.558 kg/s | 0 kg/s |
| MEG | 1.18 kg/s | 1.15 kg/s |
| Total | 214.9 kg/s | 300.0 kg/s |
| ***Separator Troll*** | | |
| P_sep | 99.9 bara | 103.0 bara |
| T_sep | 36.0 °C | 44.6 °C |
| ***P10 pipeline*** | | |
| P_in | 101.7 bara | 105.5 bara |
| P_out | 89.7 bara | 92.8 bara |
| T_in | 32.2 °C | 44.6 °C |
| T_out | 6.3 °C | 6.6 °C |
| ***Kollsnes test data*** | | |
| Condensate acc. | 856 $m^3$ | 165 $m^3$ |
| Water acc. | 530 $m^3$ | 114 $m^3$ |
| Total liquid acc. | 1386 $m^3$ | 279 $m^3$ |
| Condensate frac. | 0.618 | 0.592 |
| Pressure drop | 12.0 bar | 12.7 bar |

Table 3-1 shows some measurements from selected tests done by Statoil in the Troll field. Test 7 is the gravity dominated case with a flow rate of 24.6 $MSm^3/d$ (Berg & Johansen, 2002). Test 8 is the friction dominated case with a flow rate of 34.9 $MSm^3/d$ (Borg & Torgersen, 2005).

The geometry of the P10 pipeline is shown in Figure 3-3. The y-axis shows the height and depth of the pipeline with respect to the sea level, which is located at 0 m, plotted against the pipeline length. The pipeline descends from the platform to the sea bed, and travels along the sea bed until it ascends and reaches Kollsnes at shore.

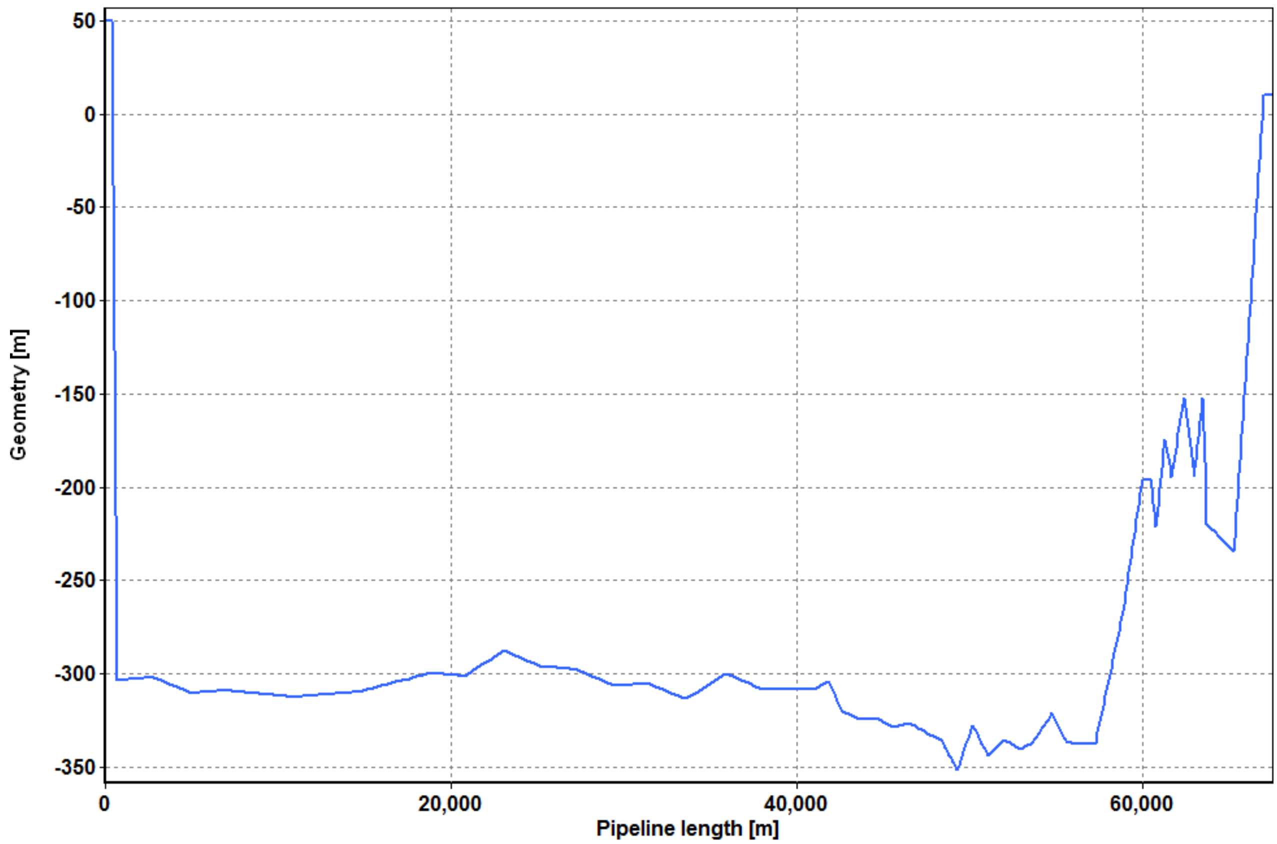


**Figure 3-3: Profile plot of the P10 pipeline geometry from OLGA**

## 3.2 OLGA Risk Management and Optimization module

OLGA is a commercial multiphase flow simulator used for flow assurance. In OLGA 7, a Risk Management and Optimization (RMO) module was added. The RMO module is powered by MEPO, which is used for RMO technology for reservoir simulators. It offers a systematic approach to identify the main contributors to uncertainties in flow assurance and study the risk picture. For an OLGA project, the effect of input- and model parameters on output parameters can be investigated further in the RMO module. When the parameters of interest are chosen, the module provides several tools to automatically run uncertainty studies. An overview of the workflow can be seen in Figure 3-4.

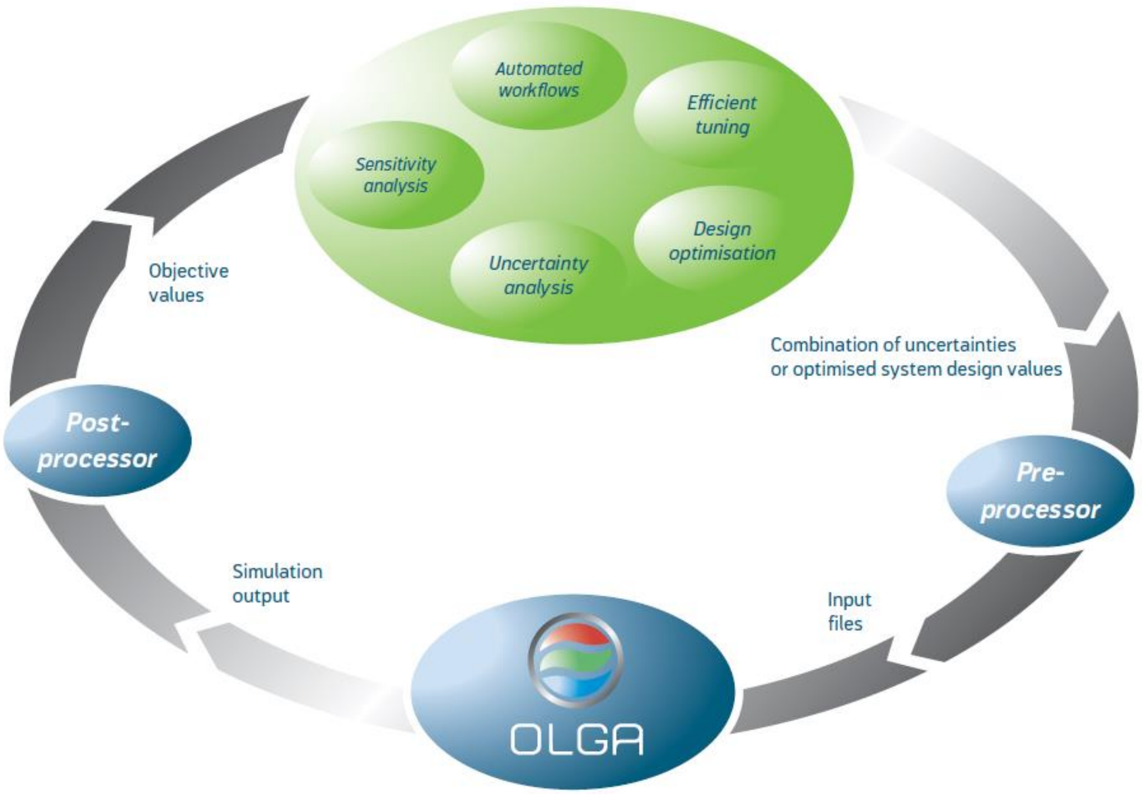


**Figure 3-4: Overview of the workflow in OLGA/RMO**[1]

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[1] The image is taken from the RMO brochure at http://www.sptgroup.com/en/Resources/Brochures/, 22.04.13

The following analyses can be done in the RMO module:

- Parametric studies and sensitivity analysis: analyze effects on the selected output parameters when input- and model parameters are changed to their minimum and maximum values one at a time, while the other parameters are kept at default values.
- Uncertainty analysis: analyze effects on the selected output parameters when input- and model parameters are drawn randomly and according to a given probability distribution. Then, uncertainty bands for the operational envelope can be derived, for instance with P10, P50 and P90 probabilities.
- Tuning/optimization: automatically change input parameters to either minimize or maximize the difference between specified measurements and simulation results.

## 3.3 Latin Hypercube Sampling

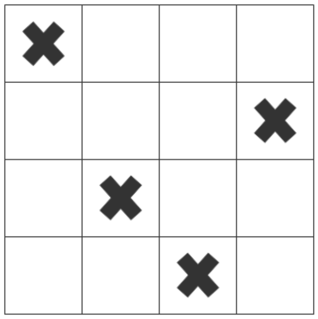

**Figure 3-5: Latin square example**

Latin Hypercube sampling is a statistical method often used in uncertainty analysis to generate a sample of parameter values from a multidimensional distribution (McKay, Beckman, & Conover, 1979). A Latin square is a square grid containing sample positions if there is only one sample in each column and each row (see Figure 3-5). Thus, one must first decide how many sample points are needed, and then, for each sample point, note the column and row is was located in. This ensures the same sample cannot be selected twice. This is opposed to random sampling, where new sample points are generated regardless of the sample points which have already been selected. The Latin square is a two-dimensional case, whereas the Latin hypercube is a generalization allowing an arbitrary number of dimensions.

In the RMO module, this sampling method is used for the uncertainty analysis. The cumulative distribution function defined by the user for each parameter is used, splitting the cumulative probability into compartments of equal size. The number of compartments is determined by the number of experiments to be run. As the analysis is run, for each experiment one value is randomly selected once from each compartment for each specified design parameter. By running more experiments, there will be more compartments, thus giving an increased number of samples and a more accurate result.

# 4 Methodology

Initially, some time was spent to get acquainted with the OLGA software and the field cases. After simulating some test cases in OLGA, the results could be opened in the RMO module and the functions available in the module could be investigated and tested. It must be noted that this project was completed without attending SPT Group's RMO course; the use of the program was self-learned. To begin the analyses, input-, model- and output parameters to be considered in the study had to be decided, together with an accompanying probability distribution function and lower and upper limits. This is more thoroughly discussed in chapter 5.

Originally, the intention was to use OLGA 7.2.0 for the field case simulations. However, the 7.2.0 version was not commercially released in Statoil at the time. An attempt was made to install it manually, but due to licensing issues and not getting the RMO module to work, OLGA 7.1.4 was used instead. The OLGA files of the field cases were given by Statoil as a basis. These OLGA files were then modified so that the desired input- and model parameters could be varied for the RMO analyses. The tuning parameters were added, and the required output parameters were set. Steady-state simulations were then run in OLGA to model the pipelines and calculate values for the output parameters. By launching the RMO module, the results from the simulations could be analyzed further.

In the RMO module, sensitivity analyses were run for both cases, using the ranges specified in Table 5-3 (34.9 $MSm^3/d$) and Table 5-5 (24.6 $MSm^3/d$). This analysis shows the linear effect of the input- and model parameters on the output parameters. The parameters are set to the upper and lower limits one at a time, while all other parameters are kept at their default values. The results are shown directly in Tornado plots which are automatically generated by the RMO module. In order to investigate nonlinear response of the output, uncertainty analyses where all the input- and model parameters varied simultaneously were performed. The ranges and probability distributions are specified in Table 5-3 (34.9 $MSm^3/d$) and Table 5-5 (24.6 $MSm^3/d$). Using Latin Hypercube sampling, parameter values in the appropriate range are chosen according to the probability distribution. In order to get a good representation of the output probability distribution, 1200 simulations were run.

Because the RMO module is not as extensive as MEPO, the data was exported to Microsoft Excel to be post-processed. The RMO module has some visualization tools to be able to view the results directly, but in order to obtain more customized graphs and statistics it was more convenient to use Excel. The results were plots showing the frequency distributions, cumulative frequencies and the percentile values P10, P50 and P90. These are found in chapter 6.

After analyzing the data, a tuning session was performed to see if altering some of the parameters could result in improved estimates of the OLGA simulations compared to the measured data from the Troll field. The intention was to use the tuning function in the RMO module, but it was not as intuitive to use as the other functions. It also seemed to be better suited for general tuning of data when there are several measurements for each parameter, and not trying to replicate one measurement as is the case for the P10 pipeline. Therefore, the uncertainty analysis function was used instead, by running the same analysis again and shifting the ranges of the relevant model parameters. This is more thoroughly discussed in chapters 6.1.3 and 6.2.3.

# 5 Parameter selection, ranges, and distribution functions

The parameters to be investigated (see Table 5-1) were chosen based on the conclusion from the literature review, and discussions with the project supervisor. Parameters that were not available were replaced with similar parameters, or removed. Some parameters which were not relevant for the field cases were also removed. Unfortunately, there were only tuning parameters available for the liquid-gas interface, and not for oil-water. Thus, for three-phase flow, these tuning parameters will only affect the gas layer and the liquid layer in contact with the gas (usually the liquid hydrocarbon layer).

**Table 5-1: Input-, model- and output parameters to be tested for the P10 pipeline**

| Parameter | Description | Found in |
|---|---|---|
| ***Input parameters:*** | | |
| GASDENSITY | Tuning coefficient for gas density | TUNING |
| OILDENSITY | Tuning coefficient for oil density | TUNING |
| WATERDENSITY | Tuning coefficient for water density | TUNING |
| GASVISC | Tuning coefficient for gas viscosity | TUNING |
| OILVISC | Tuning coefficient for oil viscosity | TUNING |
| WATERVISC | Tuning coefficient for water viscosity | TUNING |
| SIGGL | Tuning coefficient for gas/liquid surface tension | TUNING |
| ROUGHNESS | Tuning coefficient for inner wall roughness | TUNING |
| TAMBIENT | Tuning coefficient for ambient temperature | TUNING |
| MASSFLOWGAS | Total gas mass flow rate for the time series [kg/s] | SOURCE-1 |
| MASSFLOWLIQ | Total liquid mass flow rate for the time series [kg/s] | SOURCE-2 |
| TOTALWATERFRACTION | Mass fraction of total water in the total source flow mixture [-] | SOURCE-1 |
| UVALUE | Heat transfer coefficient [W/m$^2$/K] | HEATTRANSFER |
| ***Model parameters:*** | | |
| DIAMPOWER* | Diameter exponent in droplet entrainment scaling expression ($n_1$) | TUNING |
| ANGLESCALE* | Inclination term factor in droplet entrainment scaling expression ($K$) | TUNING |
| ANGLEDIAMPOWER* | Inclination term exponent in droplet entrainment scaling expression ($n_2$) | TUNING |
| GROUGHNESS | Tuning coefficient for roughness from droplets | TUNING |
| WETFRACTION | Scaling of droplet-wetted wall | TUNING |

| Parameter | Description | Found in |
|---|---|---|
| LAM_LGI | Tuning coefficient for interfacial friction factor liquid-gas | TUNING |
| LAM_WOI | Tuning coefficient for interfacial friction factor oil-water | TUNING |
| KTGGRAVFAC | Factor multiplied to the turbulence parameter correlation for gravity dominated flow, gas layer | TUNING |
| KTGSMTHFAC | Factor multiplied to the turbulence parameter correlation for smooth flow, gas layer | TUNING |
| KTGWAVYFAC | Factor multiplied to the turbulence parameter correlation for wavy flow, gas layer | TUNING |
| KTALOWTFAC | Factor multiplied to the turbulence parameter correlation for low turbulence flow, liquid layer at gas/liquid interface | TUNING |
| KTAHIGTFAC | Factor multiplied to the turbulence parameter correlation for high turbulence flow, liquid layer at gas/liquid interface | TUNING |
| ENTRAINMENT | Tuning coefficient for entrainment rate of liquid droplets in gas | TUNING |
| VOIDINSLUG | Tuning coefficient for void in horizontal slug | SLUGTUNING |
| VOIDINVERTSLUG | Tuning coefficient for void in vertical slug | SLUGTUNING |
| ***Output parameters:*** | | |
| PT | Pressure, chosen at inlet location (PIPE-1, section 1) [bara] | TRENDDATA |
| DPBR | Total pressure drop [bara] | TRENDDATA |
| LIQC | Total liquid content [$m^3$] | TRENDDATA |
| WATC | Total water content [$m^3$] | TRENDDATA |
| OILC | Total oil content [$m^3$] | TRENDDATA |

*The form of the droplet entrainment scaling expression is shown in equation (1).

$D$: Internal pipe diameter

$\theta$: Inclination angle

$K$, $n_1$, $n_2$: Tuning parameters

$f_1$, $f_2$, $f_3$: Functions confidential to SPT Group

$$f_1(D)^{n_1} + K \cdot f_2(\theta) \cdot f_3(D)^{n_2} \tag{1}$$

The variation ranges of the parameters were set by defining a default value, which is deemed the most likely value for the parameter, and upper and lower limits representing the maximum and minimum values. The ranges for the input parameters were typically set based on the Troll measurements with an approximate uncertainty from the field case. The model parameter ranges were mostly based on previous results found in the literature review. The parameters found in TUNING in OLGA are coefficients which are multiplied with the corresponding parameters, e.g. GASDENSITY is a coefficient for varying the gas density. The default value for the coefficient is 1, giving the set value for the parameter. The upper and lower value can for instance be 1.1 and 0.9 respectively, giving a ± 10% range. Other parameters, e.g. UVALUE found in HEATTRANSFER, must have the ranges set based on values, for instance 20, 30 and 40 W/m$^2$/K.

A probability distribution for each parameter was also set, defining the probability for picking a certain value in the specified range. A triangular distribution was chosen for all parameters due to its simplicity and the fact that it ensures a significant fraction of parameter values is close to the upper and lower limits (see Figure 5-1).

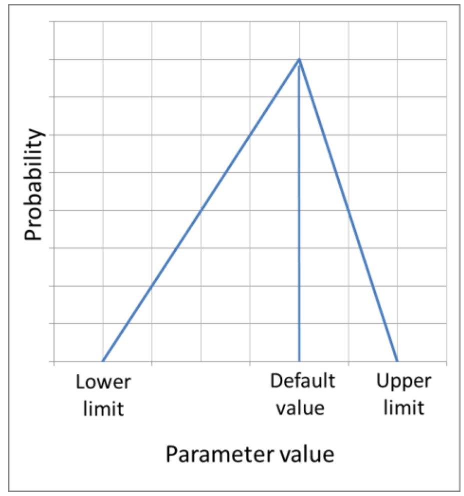


**Figure 5-1: Triangular distribution example**

## 5.1 Field case: Troll P10 pipeline, 34.9 MSm$^3$/d

The ranges and probability distribution functions for the Troll P10 34.9 MSm$^3$/d pipeline can be found in Table 5-3.

In order to vary the mass flows for gas and liquid separately, a second mass flow source was added to the pipeline in OLGA. Source-1 handles the gas mass flow with a water fraction, while Source-2 handles the liquid mass flow. The total mass flow from the original source was 300.0 kg/s, and in order to divide it between gas and liquid mass flow, the inlet conditions were examined. Inlet temperature and pressure were found from a profile plot of the pipeline. The gas mass fraction and total water fraction at the inlet could then be found by examining the fluid properties at these conditions. These fractions were used to divide the total mass flow. The results are seen in Table 5-2. For convenience, the two different mass flow variables have been named MASSFLOWGAS and MASSFLOWLIQ for the gas mass flow and the liquid mass flow, respectively.

**Table 5-2: Inlet conditions for the P10 pipeline, 34.9 MSm$^3$/d**

| | Value at inlet | Unit |
|---|---|---|
| Pressure | 107.9 | [bara] |
| Fluid temperature | 44.5 | [°C] |
| Gas mass fraction in gas/oil mixture | 0.991 | [-] |
| Total water fraction | 0.00462 | [-] |
| Gas mass flow | 297.28 | [kg/s] |
| Liquid mass flow | 2.72 | [kg/s] |

**Table 5-3: Ranges and distribution functions for input- and model parameters to be tested for the P10 pipeline, 34.9 MSm$^3$/d**

| Parameter | Lower limit | Default value | Upper limit | Distribution function |
|---|---|---|---|---|
| ANGLEDIAMPOWER | 0 | 0 | 1.5 | Triangular |
| ANGLESCALE | 0 | 1 | 3 | Triangular |
| DIAMPOWER | 0.5 | 1 | 1.5 | Triangular |
| ENTRAINMENT | 0.1 | 1 | 3 | Triangular |
| GASDENSITY | 0.9 | 1 | 1.1 | Triangular |
| GASVISC | 0.9 | 1 | 1.1 | Triangular |
| GROUGHNESS | 0.5 | 1 | 6 | Triangular |
| KTAHIGTFAC | 0.7 | 1 | 1.3 | Triangular |
| KTALOWTFAC | 0.7 | 1 | 1.3 | Triangular |
| KTGGRAVFAC | 0.1 | 1 | 2 | Triangular |
| KTGSMTHFAC | 0.7 | 1 | 1.3 | Triangular |
| KTGWAVYFAC | 0.3 | 1 | 2.5 | Triangular |
| LAM_LGI | 0.8 | 1 | 1.7 | Triangular |
| LAM_WOI | 0.5 | 1 | 2 | Triangular |
| MASSFLOWGAS | 291.4 | 297.3 | 303.2 | Triangular |
| MASSFLOWLIQ | 0 | 2.72 | 5.44 | Triangular |
| OILDENSITY | 0.9 | 1 | 1.1 | Triangular |
| OILVISC | 0.7 | 1 | 1.3 | Triangular |
| ROUGHNESS | 0.5 | 1 | 2 | Triangular |
| SIGGL | 0.5 | 1 | 1.5 | Triangular |
| TAMBIENT | 0.5 | 1 | 1.3 | Triangular |
| TOTALWATERFRACTION | 0.00231 | 0.00462 | 0.00693 | Triangular |
| UVALUE | 20 | 30 | 40 | Triangular |
| VOIDINSLUG | 0.5 | 1 | 1.5 | Triangular |
| VOIDINVERTSLUG | 0.5 | 1 | 1.5 | Triangular |
| WATERDENSITY | 0.9 | 1 | 1.1 | Triangular |
| WATERVISC | 0.7 | 1 | 1.3 | Triangular |
| WETFRACTION | 0.7 | 1 | 1.3 | Triangular |

## 5.2 Field case: Troll P10 pipeline, 24.6 MSm$^3$/d

The ranges and probability distribution functions for the Troll P10 24.6 MSm$^3$/d pipeline can be found in Table 5-5.

As for the friction dominated case, the mass flows for gas and liquid were varied separately by adding a second mass flow source the pipeline in OLGA. The total mass flow from the original source was 214.9 kg/s. In order to divide it between gas and liquid mass flow, the inlet conditions were examined the same way as for the previous case. The results are seen in Table 5-4.

**Table 5-4: Inlet conditions for the P10 pipeline, 24.6 MSm$^3$/d**

| | Value at inlet | Unit |
|---|---|---|
| Pressure | 102.8 | [bara] |
| Fluid temperature | 31.7 | [°C] |
| Gas mass fraction in gas/oil mixture | 0.983 | [-] |
| Total water fraction | 0.00564 | [-] |
| Gas mass flow | 211.2 | [kg/s] |
| Liquid mass flow | 3.65 | [kg/s] |

**Table 5-5: Ranges and distribution functions for input- and model parameters to be tested for the P10 pipeline, 24.6 MSm$^3$/d**

| Parameter | Lower limit | Default value | Upper limit | Distribution function |
|---|---|---|---|---|
| ANGLEDIAMPOWER | 0 | 0 | 1.5 | Triangular |
| ANGLESCALE | 0 | 1 | 3 | Triangular |
| DIAMPOWER | 0.5 | 1 | 1.5 | Triangular |
| ENTRAINMENT | 0.1 | 1 | 3 | Triangular |
| GASDENSITY | 0.9 | 1 | 1.1 | Triangular |
| GASVISC | 0.9 | 1 | 1.1 | Triangular |
| GROUGHNESS | 0.5 | 1 | 6 | Triangular |
| KTAHIGTFAC | 0.7 | 1 | 1.3 | Triangular |
| KTALOWTFAC | 0.7 | 1 | 1.3 | Triangular |
| KTGGRAVFAC | 0.1 | 1 | 2 | Triangular |
| KTGSMTHFAC | 0.7 | 1 | 1.3 | Triangular |
| KTGWAVYFAC | 0.3 | 1 | 2.5 | Triangular |
| LAM_LGI | 0.8 | 1 | 1.7 | Triangular |
| LAM_WOI | 0.5 | 1 | 2 | Triangular |
| MASSFLOWGAS | 206.9 | 211.2 | 215.4 | Triangular |
| MASSFLOWLIQ | 0 | 3.65 | 7.30 | Triangular |
| OILDENSITY | 0.9 | 1 | 1.1 | Triangular |

| Parameter | Lower limit | Default value | Upper limit | Distribution function |
|---|---|---|---|---|
| OILVISC | 0.7 | 1 | 1.3 | Triangular |
| ROUGHNESS | 0.5 | 1 | 2 | Triangular |
| SIGGL | 0.5 | 1 | 1.5 | Triangular |
| TAMBIENT | 0.5 | 1 | 1.3 | Triangular |
| TOTALWATERFRACTION | 0.00282 | 0.00564 | 0.00846 | Triangular |
| UVALUE | 20 | 30 | 40 | Triangular |
| VOIDINSLUG | 0.5 | 1 | 1.5 | Triangular |
| VOIDINVERTSLUG | 0.5 | 1 | 1.5 | Triangular |
| WATERDENSITY | 0.9 | 1 | 1.1 | Triangular |
| WATERVISC | 0.7 | 1 | 1.3 | Triangular |
| WETFRACTION | 0.7 | 1 | 1.3 | Triangular |

# 6 Results and analysis

The results from the steady-state OLGA simulations are shown in Table 6-1. These data are discussed later in this chapter.

**Table 6-1: Results from OLGA simulations**

| Output parameter | Friction dominated (34.9 $MSm^3/d$) | Gravity dominated (24.6 $MSm^3/d$) |
|---|---|---|
| Inlet pressure (PT) [bara] | 107.9 | 102.8 |
| Total pressure drop (DPBR) [bar] | 15.1 | 13.1 |
| Total liquid content (LIQC) [$m^3$] | 546 | 1217 |
| Total oil content (OILC) [$m^3$] | 457 | 994 |
| Total water content (WATC) [$m^3$] | 89.2 | 222 |

The results from the sensitivity analyses, uncertainty analyses and tuning are presented below. The friction dominated field case is found in chapter 6.1 and the gravity dominated field case is found in chapter 6.2.

## 6.1 Field case: Troll P10 pipeline, 34.9 $MSm^3/d$

### 6.1.1 Sensitivity analysis

After having run the sensitivity analysis in the RMO module, the results were plotted in Tornado plots showing the effects on the inlet pressure, total pressure drop, total liquid content, oil content and water content. The blue and red bars in the Tornado plots show the parameter effect relative to the default value when using the upper and lower limit, respectively, as specified in Table 5-3. The results of the sensitivity analysis only show linear variations, i.e. the parameters are varied one at a time. Results when varying the parameters simultaneously are further discussed in the uncertainty analysis.

### *Total pressure drop*

The Tornado plot for the sensitivity analysis of the total pressure drop can be found in Figure 6-1. The inner wall roughness and the turbulence parameter for gravity dominated flow have the largest effect; the maximum roughness will give an 8.6% increase in the pressure drop and the maximum turbulence parameter for gravity dominated flow (KTGGRAVFAC) will give a 7.9% decrease.

It is expected that the inner wall roughness would have a large impact, because the case is friction dominated. The higher the flow rate and the rougher the surface, the more energy is lost as friction, leading to an increased pressure drop. Other parameters with some effect are the gas density and the turbulence parameter for wavy flow. Compared to the liquid content plots further down having differences up to 30-40%, variations in pressure drop of 8% is not very much.

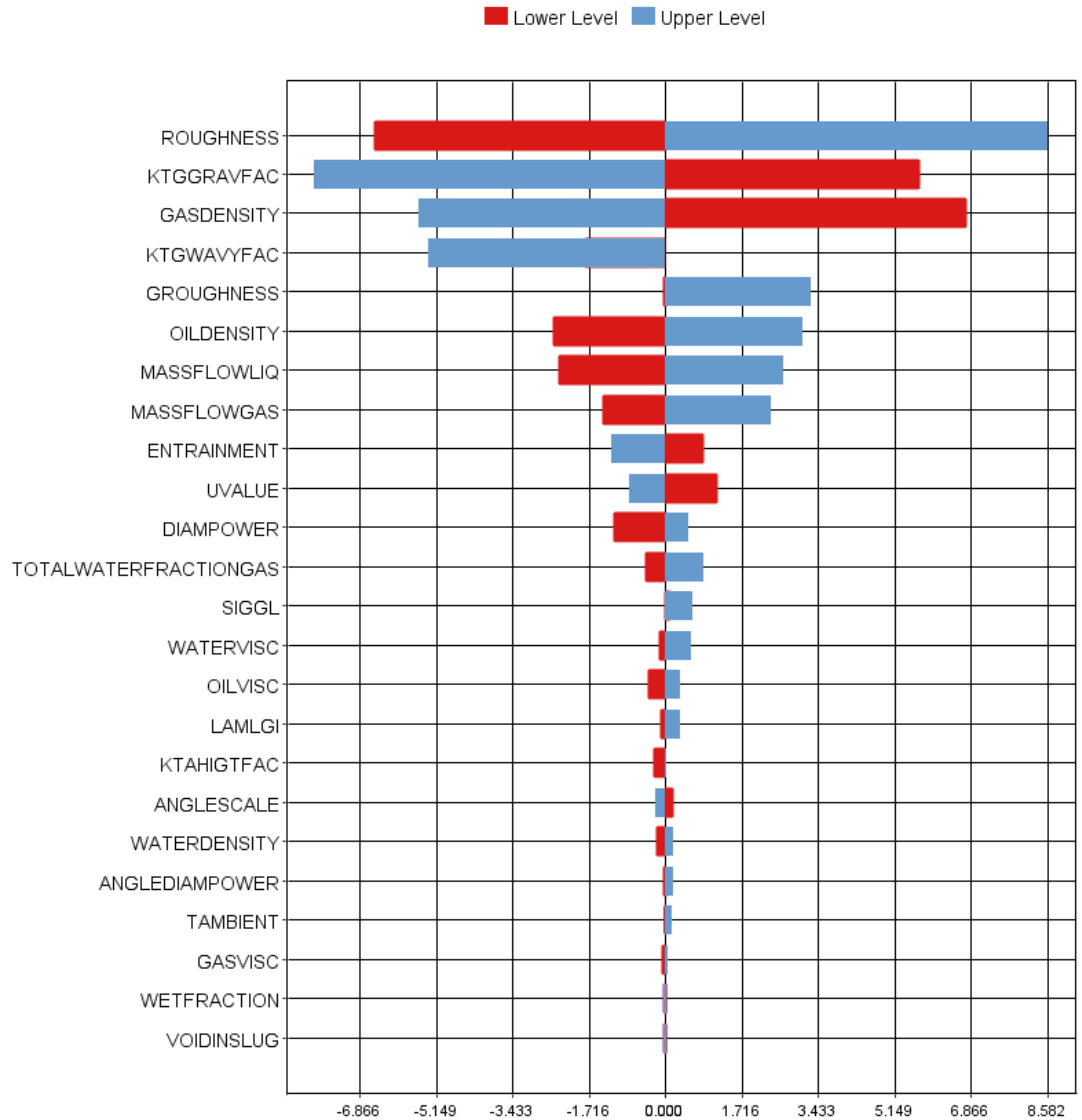


**Figure 6-1: Tornado plot for total pressure drop P10 pipeline, 34.9 MSm$^3$/d**

### *Inlet pressure*

The Tornado plot for the sensitivity analysis of the inlet pressure can be found in Figure 6-2. The most influential parameters affecting the inlet pressure are the same as for the total pressure drop: inner wall roughness, turbulence parameters for gravity dominated flow and wavy flow, and gas density. The change in pressure drop varies from -1% to 1.2%.

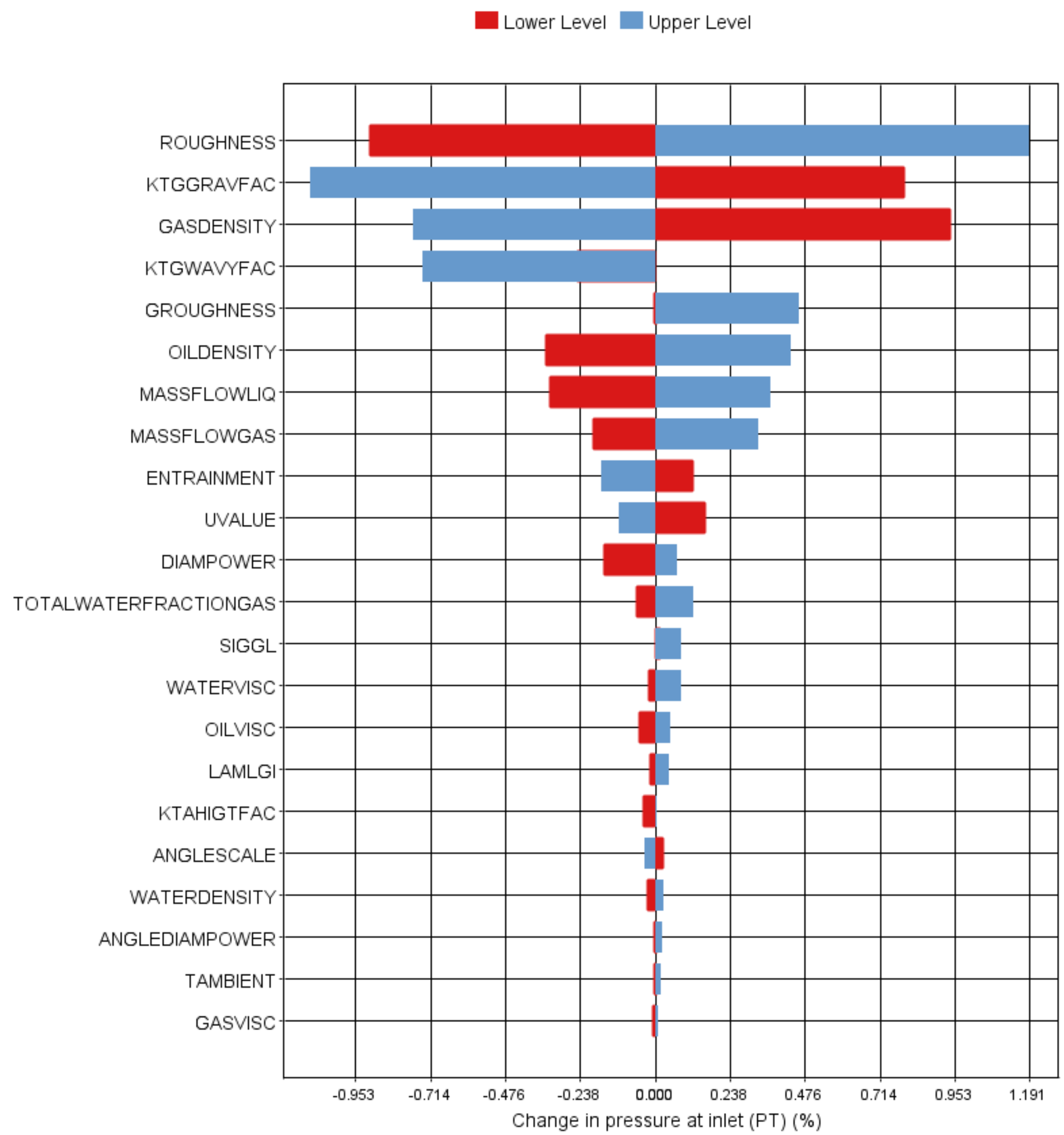


**Figure 6-2: Tornado plot for pressure at inlet P10 pipeline, 34.9 MSm$^3$/d**

***Total liquid content***

The Tornado plot for the sensitivity analysis of the total liquid content can be found in Figure 6-3. The most influential parameter for the total liquid content is the liquid mass flow, giving a change of -27.9% to 28.9% for the lower and upper limit, respectively. The high impact of the liquid mass flow is expected, as increased mass flow gives an increased liquid content.

Other important parameters are the turbulence parameters for wavy flow and gravity dominated flow, gas density, and ambient temperature. The liquid content is decreasing with increasing turbulence parameters since the interfacial friction increases, making the liquid transport more efficient.

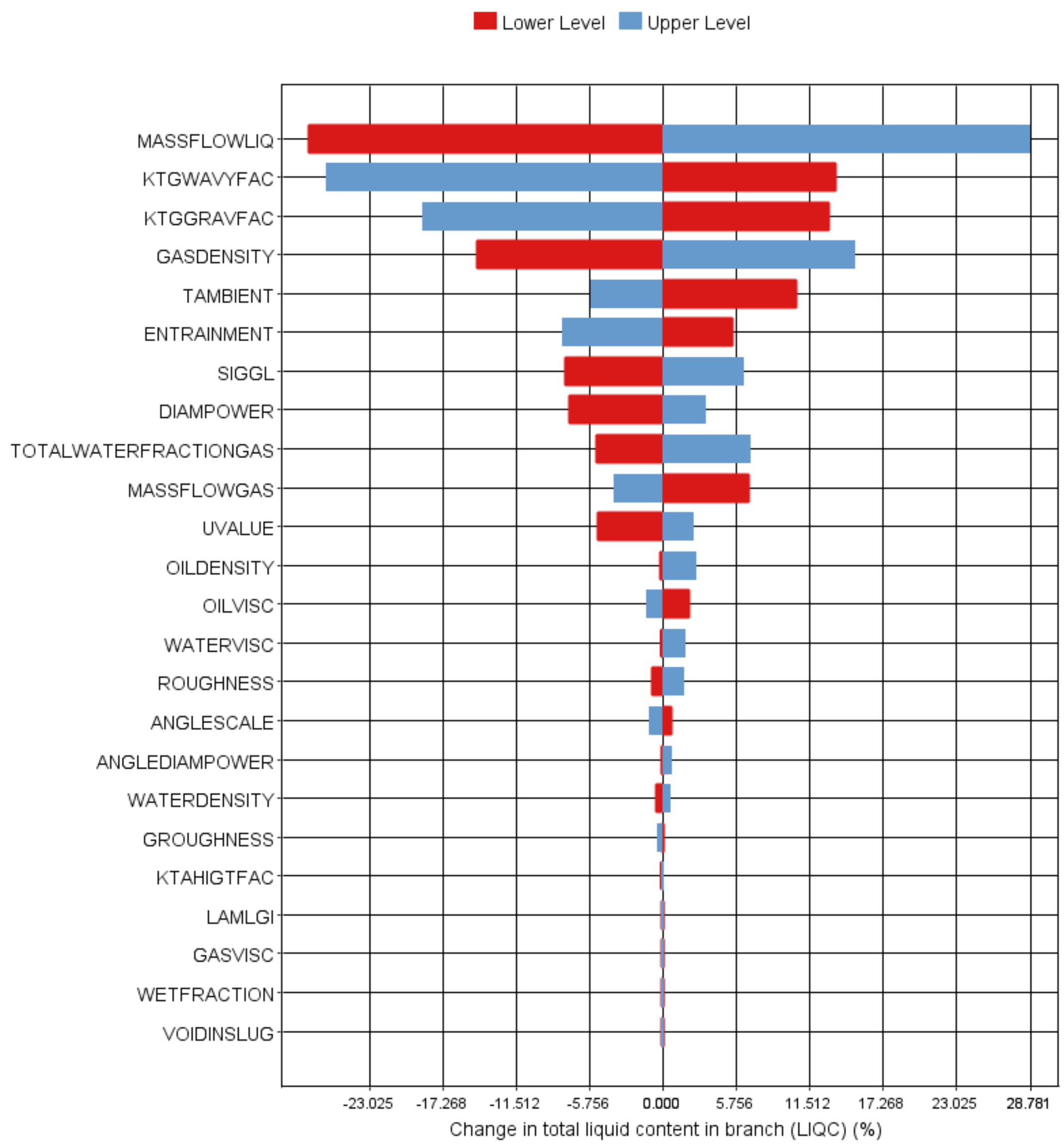


**Figure 6-3: Tornado plot for total liquid content P10 pipeline, 34.9 MSm$^3$/d**

***Total oil content***

The Tornado plot for the sensitivity analysis of the total oil content can be found in Figure 6-4. As for the total liquid content, the liquid mass flow has the largest effect, giving a change from -34% to 35% in the oil content. Other important parameters are the turbulence parameters for wavy flow and gravity dominated flow, gas density, and ambient temperature.

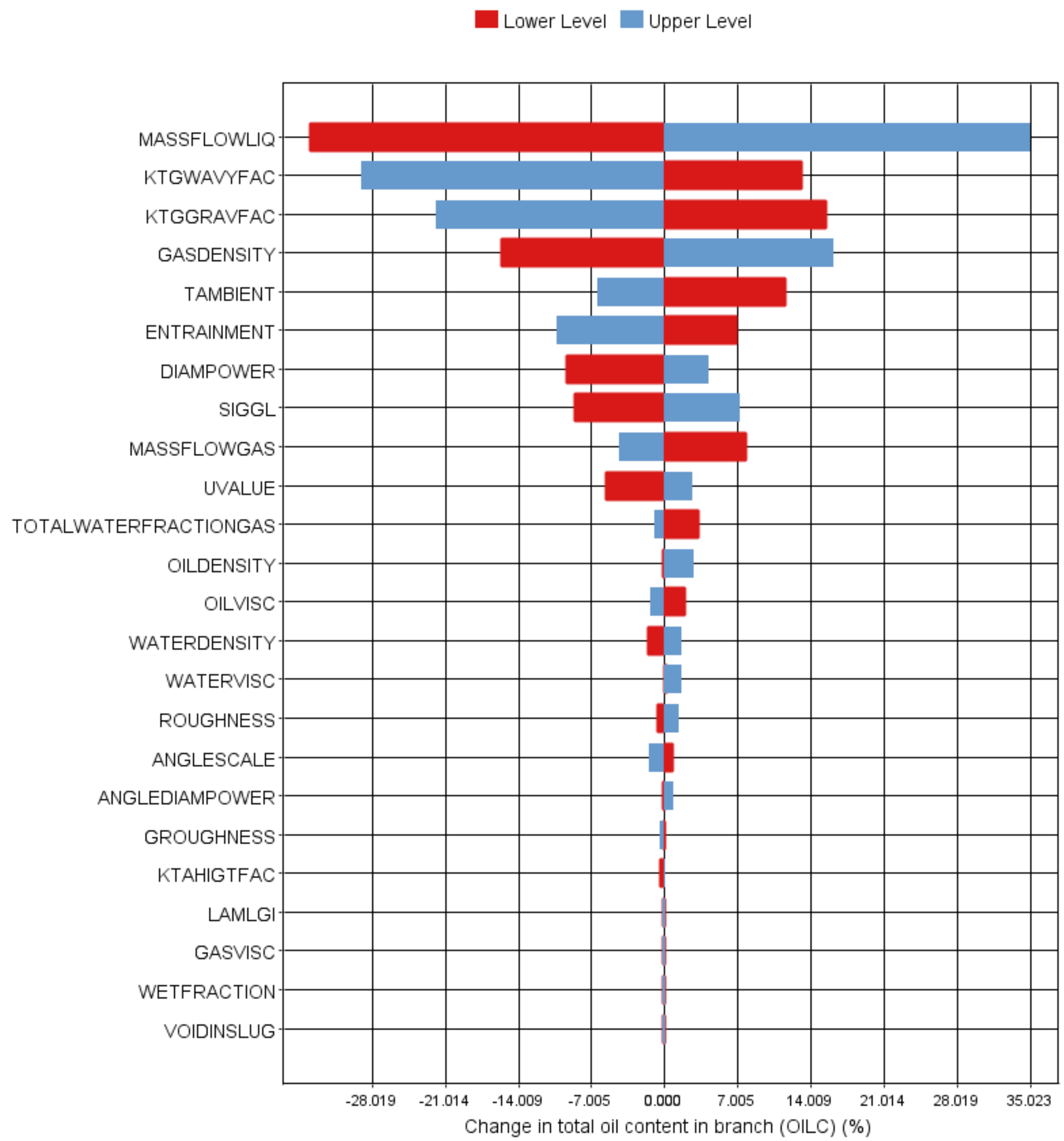


**Figure 6-4: Tornado plot for total oil content P10 pipeline, 34.9 MSm$^3$/d**

### *Total water content*

The Tornado plot for the sensitivity analysis of the total water content can be found in Figure 6-5. The total water fraction has a significant impact on the water content compared to the other parameters, giving a change from -46% to 44%. This is expected, as the total water fraction decides how much water is present in the pipeline. The turbulence parameter for wavy flow and the gas density also have a significant effect.

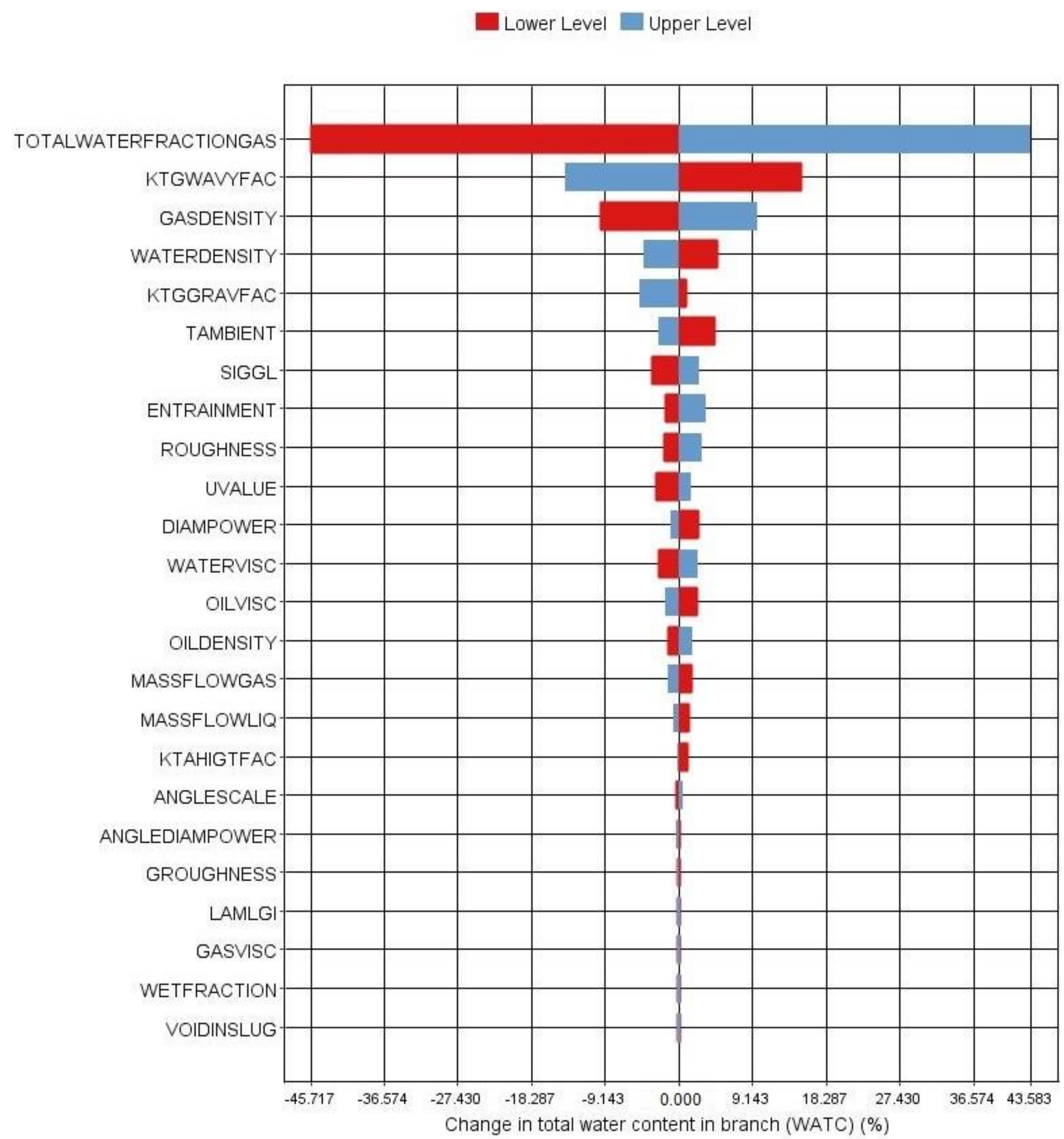


**Figure 6-5: Tornado plot for total water content P10 pipeline, 34.9 MSm$^3$/d**

***Summary***

The most influential input- and model parameters are summarized in Table 6-2. The most influential parameters are naturally the same for the inlet pressure and the pressure drop. Other parameters which are influential for most output parameters are the mass flows of liquid and gas, gas density, heat transfer coefficient, entrainment rate of droplets, and the turbulence parameters for wavy flow and gravity dominated flow.

**Table 6-2: Summary of results from sensitivity analysis, 34.9 MSm$^3$/d**

<table>
<tr><th>Output parameter</th><th>Input parameters with the largest effect</th><th>Model parameters with the largest effect</th></tr>
<tr><td>PT</td><td rowspan="2">ROUGHNESS<br>GASDENSITY<br>OILDENSITY<br>MASSFLOWLIQ<br>MASSFLOWGAS<br>UVALUE</td><td rowspan="2">KTGGRAVFAC<br>KTGWAVYFAC<br>GROUGHNESS<br>ENTRAINMENT</td></tr>
<tr><td>DPBR</td></tr>
<tr><td>LIQC</td><td>MASSFLOWLIQ<br>GASDENSITY<br>TAMBIENT<br>SIGGL<br>TOTALWATERFRACTION<br>MASSFLOWGAS<br>UVALUE</td><td>KTGWAVYFAC<br>KTGGRAVFAC<br>ENTRAINMENT<br>DIAMPOWER</td></tr>
<tr><td>OILC</td><td>MASSFLOWLIQ<br>GASDENSITY<br>TAMBIENT<br>SIGGL<br>MASSFLOWGAS<br>UVALUE</td><td>KTGWAVYFAC<br>KTGGRAVFAC<br>ENTRAINMENT<br>DIAMPOWER</td></tr>
<tr><td>WATC</td><td>TOTALWATERFRACTION<br>GASDENSITY<br>WATERDENSITY<br>TAMBIENT</td><td>KTGWAVYFAC<br>KTGGRAVFAC</td></tr>
</table>

Parameters that do not appear at all in any of the Tornado plots i.e. have zero or near zero contribution are:

- KTGSMTHFAC: This is probably because the smooth turbulence parameter is only applicable for very low gas Reynolds numbers, mostly laboratory conditions.
- KTALOWTFAC: Similarly, this parameter is only applicable in cases of low turbulence flow, which is not the case in the P10 pipeline.
- VOIDINVERTSLUG and VOIDINSLUG: This indicates that there is no slug flow present in the pipeline. This is verified by a profile plot of the flow regime indicator in OLGA.
- WETFRACTION
- GASVISC
- LAM_WOI

### 6.1.2 Uncertainty analysis

The results from the uncertainty analysis were shown using plots showing the distribution of the inlet pressure, pressure drop, liquid content, oil content and water content when varying the input- and model parameters. The blue columns represent the density distribution, the three red columns show where the percentiles P10, P50 and P90 are located, and the light red columns connected with a red line show the cumulative distribution.

Scatter plots of the data can be found in Appendix A.

### *Total pressure drop*

The distribution plot from the uncertainty analysis of the total pressure drop can be found in Figure 6-6. The rise and decline of the probability frequencies are quite steep, and there are several pressure drop values with a high frequency around the P50 value. There are two points outside the general band of values which are quite far off. This is due to having high values for inner wall roughness and droplet roughness, and simultaneously having low values for the turbulence parameter for gravity dominated flow and the gas density.

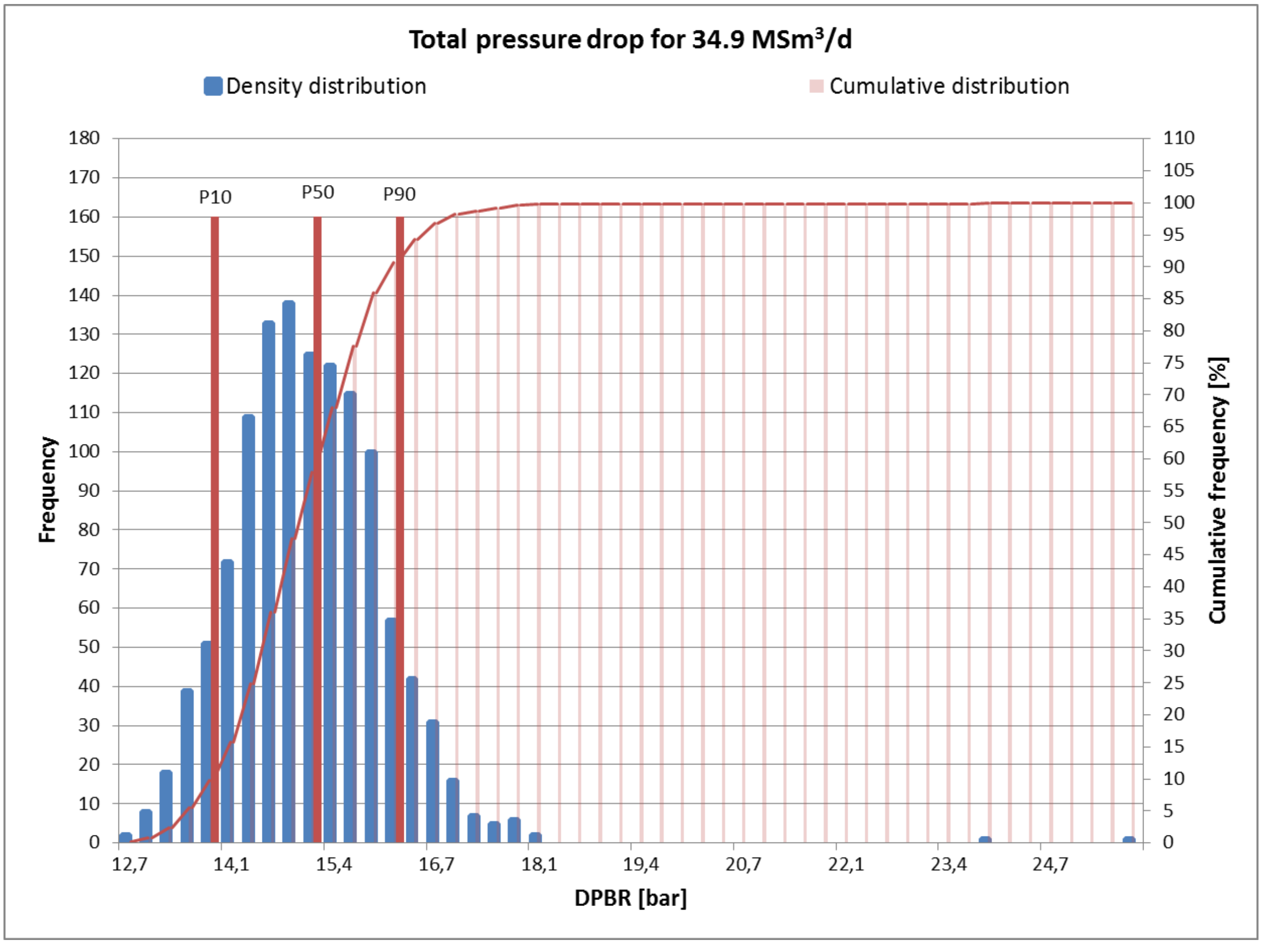


**Figure 6-6: Distribution plot for total pressure drop, P10 pipeline, 34.9 MSm$^3$/d**

### *Inlet pressure*

The distribution plot from the uncertainty analysis of the inlet pressure can be found in Figure 6-7. Similarly as for the pressure drop, the rise and decline of the probability frequencies are quite steep, and there are several inlet pressure values with a high frequency around the P50 value.

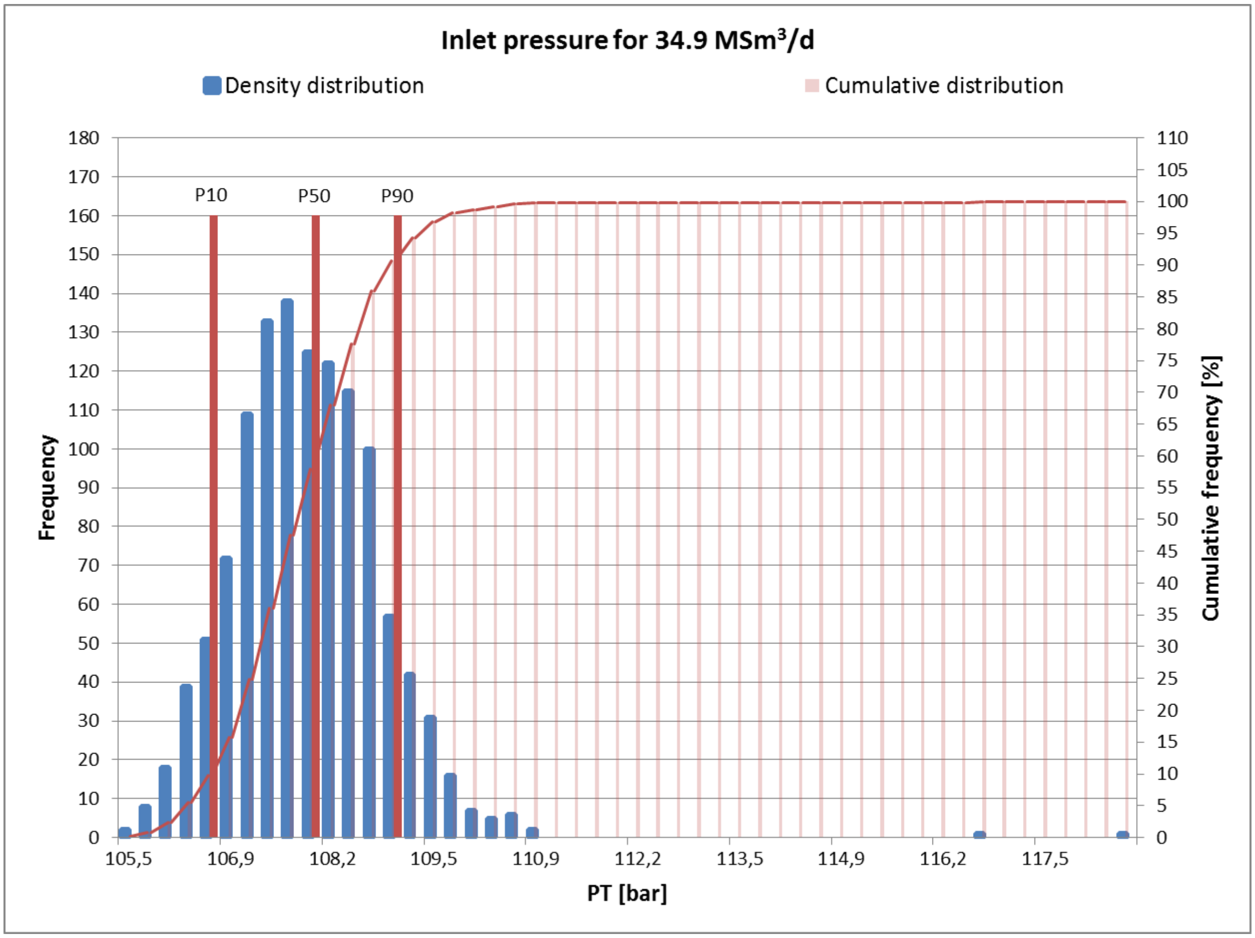


**Figure 6-7: Distribution plot for inlet pressure, P10 pipeline, 34.9 MSm$^3$/d**

***Total liquid content***

The distribution plot from the uncertainty analysis of the total liquid content can be found in Figure 6-8. Here, the distribution is much wider compared to the pressure drop probability distribution. This results in a more gradual slope of the cumulative distribution. There are more points for the higher liquid content values, having low frequencies. Two points are quite far away from the others, due to low values for the turbulence parameters for gravity dominated flow and wavy flow, and the ambient temperature. For a wet gas such as the Troll gas, the uncertainty in the liquid content is much higher than for the pressure drop.

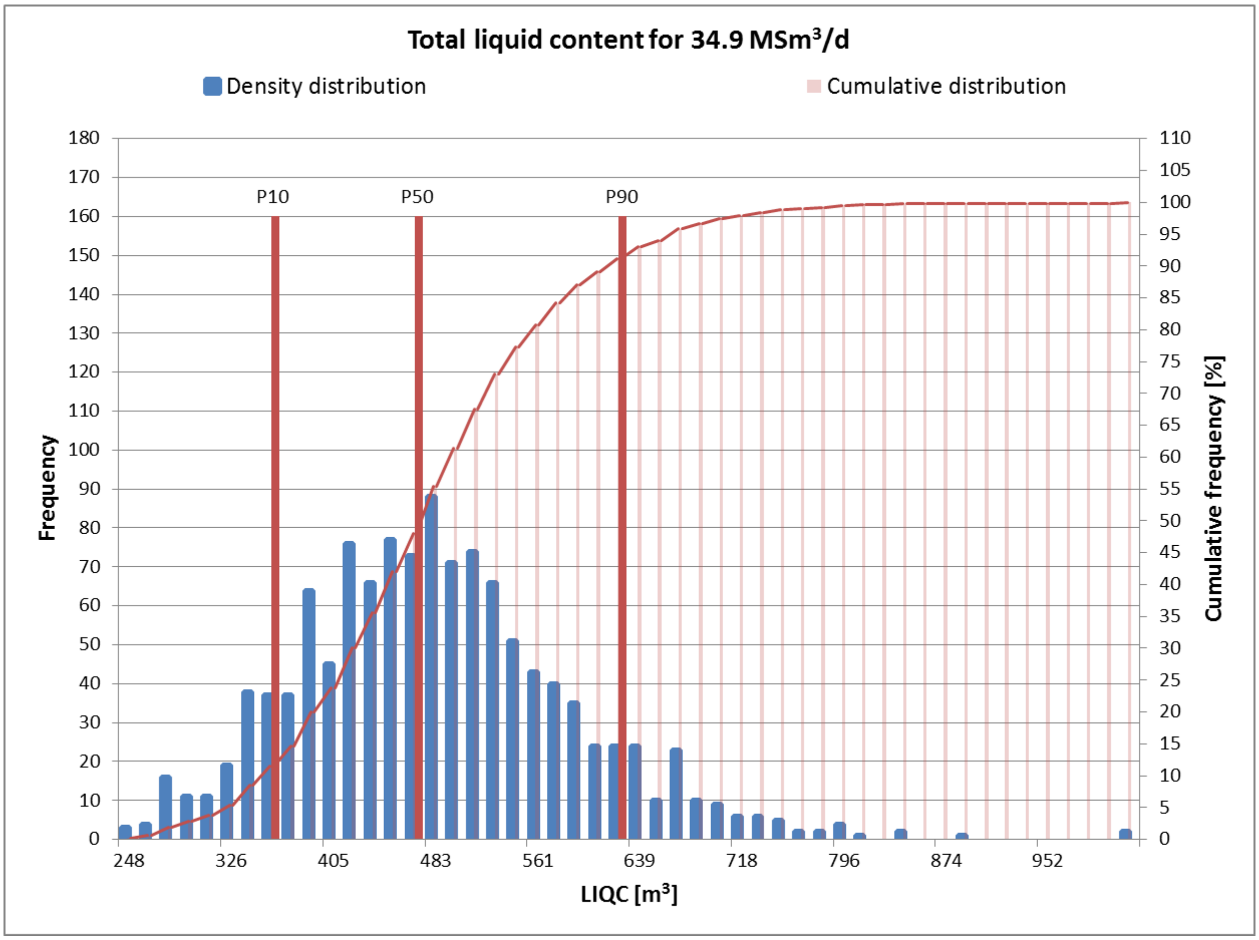


**Figure 6-8: Distribution plot for total liquid content, P10 pipeline, 34.9 MSm$^3$/d**

***Total oil content***

The distribution plot from the uncertainty analysis of the total oil content can be found in Figure 6-9. Here, the distribution is even more widespread than for the liquid content, with a very gradual rise and decline of probability frequencies. The distribution is quite symmetric, with P10 and P90 approximately the same distance from P50. One point is further away from the general band of values, due to high values for the liquid mass flow and the gas density, and a low value for the ambient temperature.

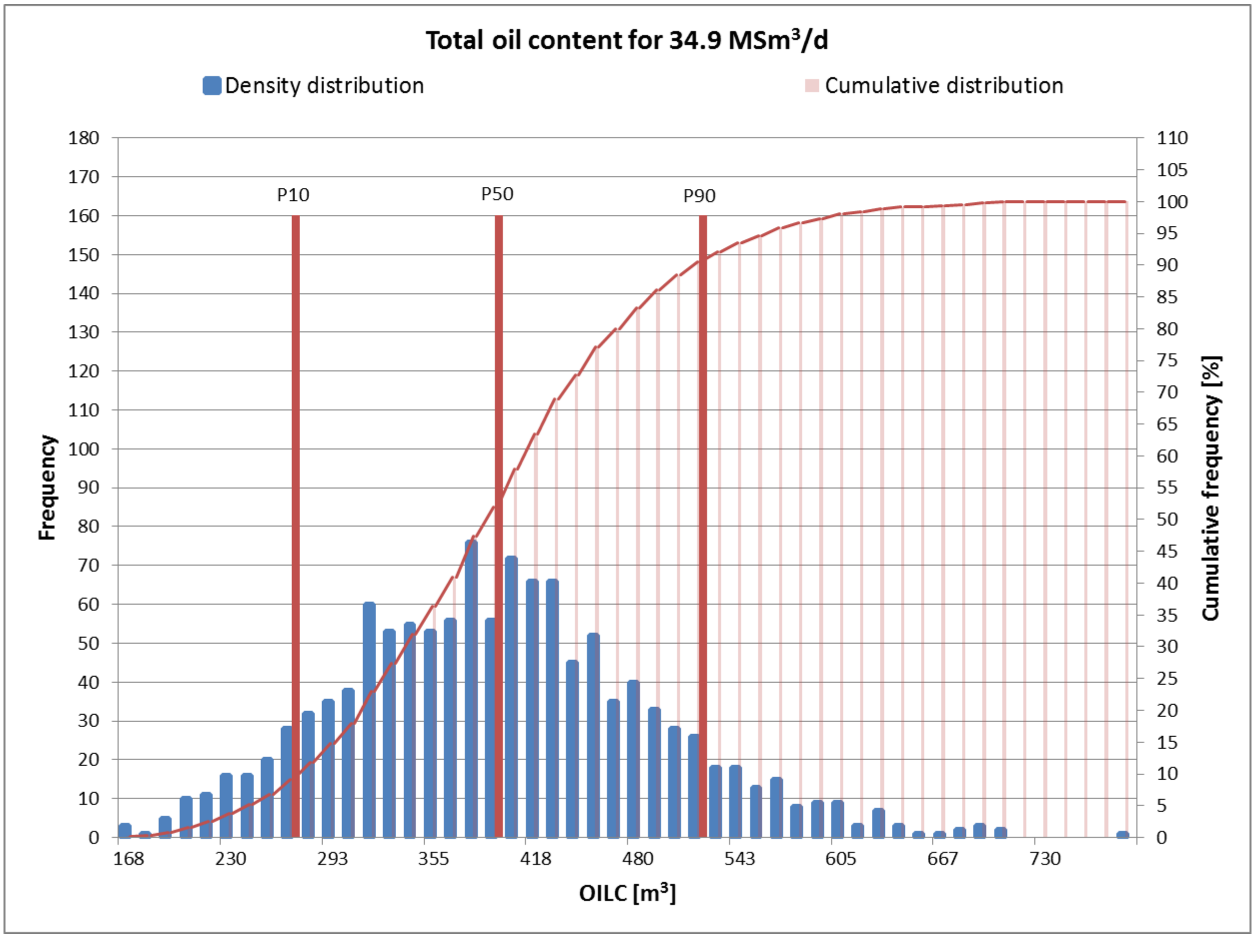


**Figure 6-9: Distribution plot for total oil content, P10 pipeline, 34.9 MSm$^3$/d**

***Total water content***

The distribution plot from the uncertainty analysis of the total water content can be found in Figure 6-10. The distribution is quite narrow with high probability frequencies for the lower water content values, followed by a tail of values with very low frequencies. There are also two extreme values far away from the others. This is due to a somewhat high total water fraction, and low values for the turbulence parameter for gravity dominated flow and ambient temperature.

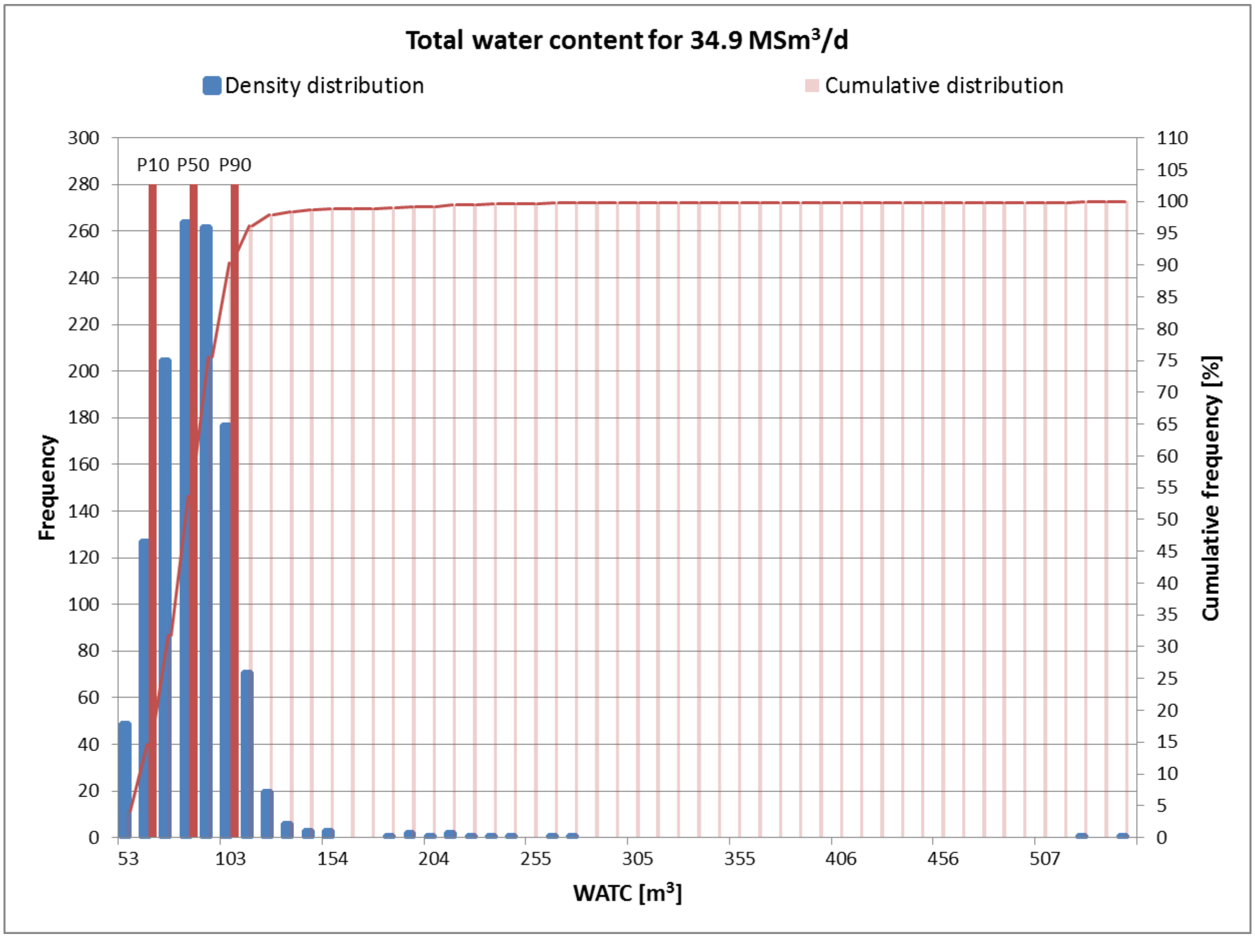


**Figure 6-10: Distribution plot for total water content, P10 pipeline, 34.9 MSm$^3$/d**

***Summary***

In Table 6-3 is a summary of the key data in the distribution plots. The minimum and maximum values for the output parameters are the minimum and maximum values of the general band containing the output values, i.e. none of the extreme values. The default value is the one value OLGA calculates for the output parameter. Two different kinds of uncertainties are also stated; one showing the difference between P10 and P50 (-), and between P50 and P90 (+), and the other showing the difference between the minimum and default value (-), and the default and maximum value (+). A comparison of these results with the measurement data from the Troll P10 pipeline can be found in Table 6-4.

**Table 6-3: Summary of results from uncertainty analysis, 34.9 MSm$^3$/d**

| Output variable | P10 | P50 | P90 | Min. | Default | Max. | Uncertainty P10-P50-P90 | Uncertainty Min-Default-Max |
|---|---|---|---|---|---|---|---|---|
| PT [bar] | 106.8 | 107.9 | 109.1 | 105.4 | 107.9 | 111.0 | -1.0% / +1.1% | -2.3% / +2.9% |
| DPBR [bar] | 14.0 | 15.1 | 16.3 | 12.6 | 15.1 | 18.2 | -7.4% / +8.0% | -16.5% / +20.5% |
| LIQC [m$^3$] | 359 | 479 | 624 | 240 | 546 | 891 | -25.1% / +30.3% | -56.0% / +63.2% |
| OILC [m$^3$] | 278 | 394 | 521 | 162 | 457 | 786 | -29.4% / +32.3% | -64.6% / +72.1% |
| WATC [m$^3$] | 64.1 | 86.7 | 108 | 48.0 | 89.2 | 278 | -26.1% / +24.4% | -46.2% / +212% |

The uncertainties for the liquid, oil and water content are quite high compared to the inlet pressure and pressure drop. When comparing the two different uncertainties, the Min-Default-Max uncertainty is significantly larger than the P10-P50-P90 uncertainty for most cases. This shows that some calculations can be quite high or low, even though they do not occur as frequent.

**Table 6-4: Comparison with Troll measurement data, 34.9 MSm$^3$/d**

| | Troll measurement | OLGA calculation | Within P10-P90 | Within Min-Max | P- value the measurement represents |
|---|---|---|---|---|---|
| Inlet pressure [bara] | 105.5 | 107.9 | No | Yes | P0.3 |
| Pressure drop [bar] | 12.7 | 15.1 | No | Yes | P0.3 |
| Total liquid accumulation [m$^3$] | 279 | 546 | No | Yes | P1.2 |
| Condensate accumulation [m$^3$] | 165 | 457 | No | Yes | P0.1 |
| Water accumulation [m$^3$] | 114 | 89.2 | No | Yes | P94 |

From this it is seen that none of the measurements fall inside the P10-P90 uncertainty range, and all are barely within the Min-Max range. For all output parameters except the water content, the measurement value is just above the minimum value, indicating that OLGA tends to over-predict the output parameters.

### 6.1.3 Tuning

For this friction dominated case, there was an over-prediction of the output parameters compared to the field measurements, with the exception of the water content. However, the under-prediction of the water content is a known weakness of the OLGA HD 7.1.4 model (Nygård, 2012) (Valle & Johansson, 2011). This is supposed to be improved in OLGA 7.2.0., and because the water content prediction is so uncertain, it was not worthwhile to take it into account. Thus, it was of interest to tune some of the most influential model parameters to shift the OLGA predictions towards lower values in order to get closer to the measurements. As of today, there are few model parameters available for tuning the oil-water interfacial friction in OLGA. It was therefore necessary to accept what was available. As seen in the sensitivity analysis, two model parameters which were quite influential on all the output parameters were KTGGRAVFAC and KTGWAVYFAC. A higher value for these gave a lower value for the pressure drop and liquid content. Consequently, a new uncertainty analysis with a shifted range (Table 6-5) for these model parameters was performed, while all other parameter ranges were set as before.

**Table 6-5: Tuned parameters, 34.9 MSm$^3$/d**

| Model parameter | Lower limit | Default value | Upper limit |
|---|---|---|---|
| KTGGRAVFAC | 1 | 2 | 3 |
| KTGWAVYFAC | 1 | 2 | 3 |

The results from the tuning are summarized in Table 6-6. A comparison with Troll data is shown in Table 6-7. Scatter plots and distribution plots can be found in Appendix B.

**Table 6-6: Summary of results from tuning, 34.9 MSm³/d**

| Output variable | P10 | P50 | P90 | Min. | Default | Max. | Uncertainty P10-P50-P90 | Uncertainty Min-Default-Max |
|---|---|---|---|---|---|---|---|---|
| PT [bar] | 106.2 | 107.2 | 108.2 | 104.9 | 106.9 | 110.1 | -0.9% / +0.9% | -1.9% / +3.0% |
| DPBR [bar] | 13.4 | 14.4 | 15.4 | 12.1 | 14.1 | 17.3 | -7.0% / +6.7% | -14.2% / +22.9% |
| LIQC [$m^3$] | 309 | 385 | 471 | 224 | 394 | 592 | -20.0% / +22.4% | -43.0% / +50.2% |
| OILC [$m^3$] | 226 | 306 | 394 | 154 | 314 | 506 | -26.2% / +28.6% | -50.9% / +60.9% |
| WATC [$m^3$] | 61.1 | 80.4 | 102 | 44.3 | 79.9 | 126 | -23.9% / +26.4% | -44.5% / +58% |

Compared to the uncertainty analysis, all the tuned results are lower in value. Especially for the liquid content, the P90 and maximum values are significantly reduced. The P10-P50-P90 uncertainties are generally smaller for the tuned values. The Min-Default uncertainties (-) are slightly smaller and the Default-Max uncertainties (+) are slightly larger for the inlet pressure and pressure drop. For the liquid and oil content the Min-Default-Max uncertainties are significantly smaller.

**Table 6-7: Comparison of tuning with Troll measurement data, 34.9 MSm³/d**

| | Troll measurement | OLGA calculation | Within P10-P90 | Within Min-Max | P- value the measurement represents |
|---|---|---|---|---|---|
| Inlet pressure [bara] | 105.5 | 106.9 | No | Yes | P1 |
| Pressure drop [bar] | 12.7 | 14.1 | No | Yes | P1 |
| Total liquid accumulation [$m^3$] | 279 | 394 | No | Yes | P4 |
| Condensate accumulation [$m^3$] | 165 | 314 | No | Yes | P0.4 |
| Water accumulation [$m^3$] | 114 | 79.9 | No | Yes | P99 |

The OLGA predictions are closer to the Troll measurements after the tuning, but they are still higher than the measured values. The percentile values the measurement values represent in the OLGA output distributions are higher than before the tuning. However, they are still very low in value, meaning that the measurements are close to the minimum values obtained from the analysis. The exception again is the water content which is under-predicted, with a percentile value close to the maximum. All the measurements are still within the minimum and maximum values, but none are within P10 and P90.

## 6.2 Field case: Troll P10 pipeline, 24.6 MSm$^3$/d

### 6.2.1 Sensitivity analysis

After having run the sensitivity analysis in the RMO module, the results were plotted in Tornado plots showing the effects on the inlet pressure, total pressure drop, total liquid content, oil content and water content. The blue and red bars in the Tornado plots show the parameter effect relative to the default value when using the upper and lower limit, respectively, as specified in Table 5-5. The results of the sensitivity analysis only show linear variations, i.e. the parameters are varied one at a time. Results when varying the parameters simultaneously are further discussed in the uncertainty analysis.

### *Total pressure drop*

The Tornado plot for the sensitivity analysis of the total pressure drop can be found in Figure 6-11. The most influential parameter is the turbulence parameter for gravity dominated flow, giving a range in pressure drop from -21% to 11%. This parameter has a large effect because the flow is gravity dominated and many of the pipe sections have high liquid holdup values.

Other parameters with some effect are the oil density, the turbulence parameter for wavy flow, void in slug and the inner wall roughness. The fact that the void in slug parameter appears in the list shows that OLGA predicts slug flow in the high inclined sections towards the landfall.

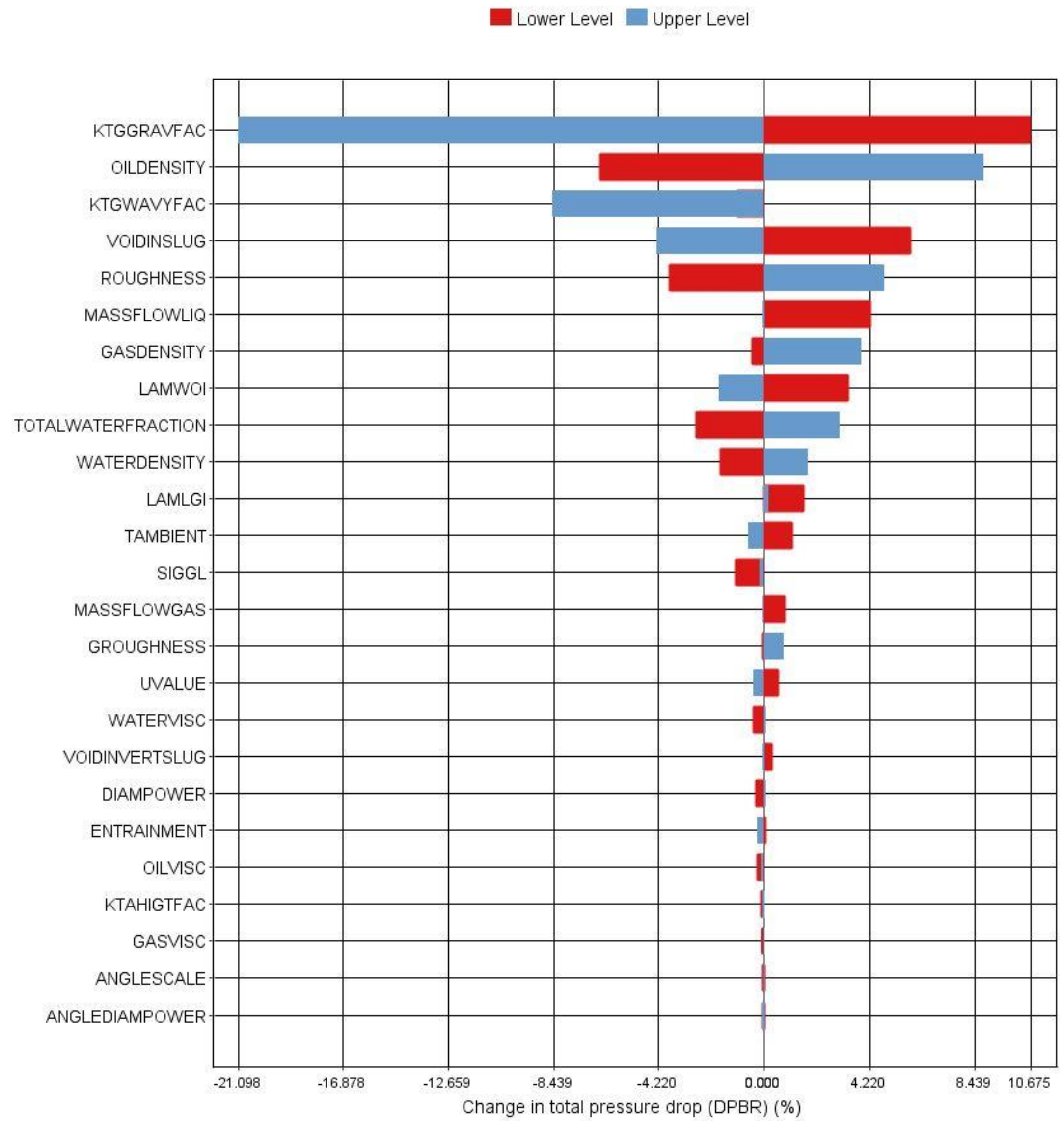


**Figure 6-11: Tornado plot for total pressure drop P10 pipeline, 24.6 MSm$^3$/d**

### *Inlet pressure*

The Tornado plot for the sensitivity analysis of the inlet pressure can be found in Figure 6-12. The most influential parameters affecting the inlet pressure are the same as for the pressure drop: the turbulence parameters for gravity dominated flow and wavy flow, oil density, void in slug and the inner wall roughness. The range in inlet pressure is from -2.7% to 1.4%. Compared to the liquid content plots further down having much larger differences, variations in inlet pressure of 2% is not very much. However, in relation to the pressure drop, 2% change at the inlet is more significant.

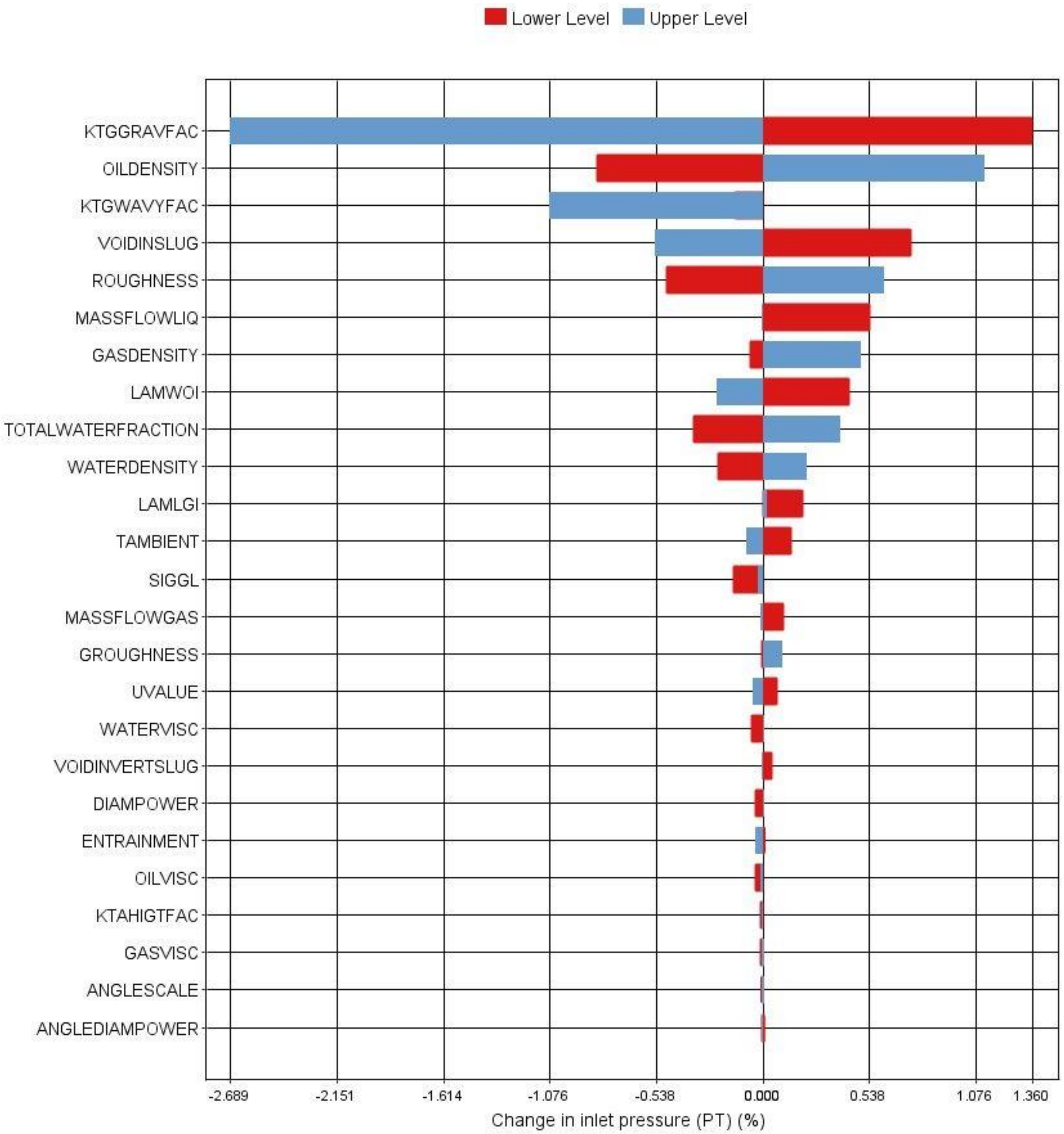


**Figure 6-12: Tornado plot for pressure at inlet P10 pipeline, 24.6 MSm$^3$/d**

### *Total liquid content*

The Tornado plot for the sensitivity analysis of the total liquid content can be found in Figure 6-13. The most influential parameters are the turbulence parameters for gravity dominated flow and wavy flow, and the liquid mass flow. The variation in liquid content is from -29% to 22%. Other significant parameters are the gas density, void in slug and the total water fraction.

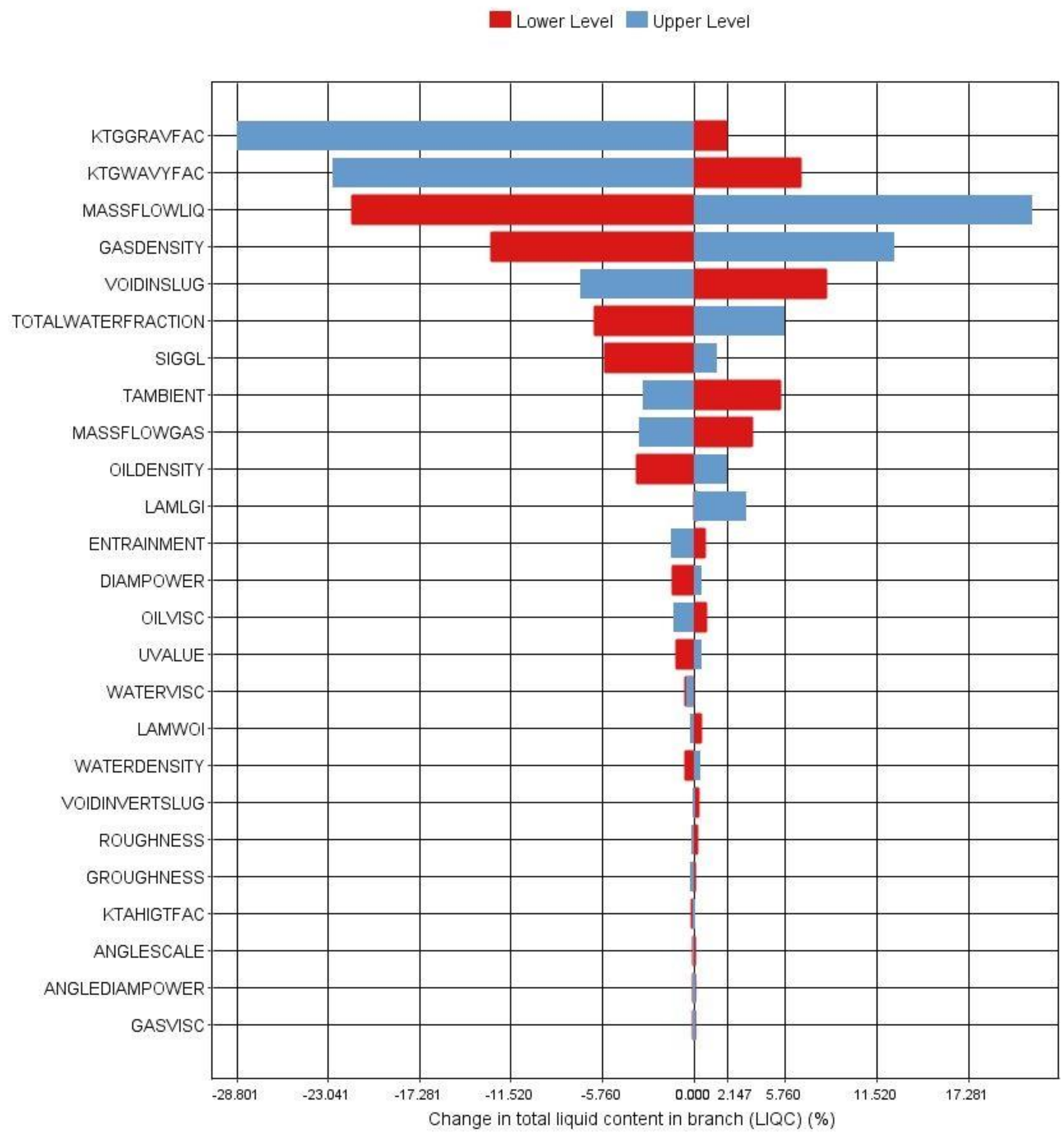


**Figure 6-13: Tornado plot for total liquid content P10 pipeline, 24.6 MSm$^3$/d**

### *Total oil content*

The Tornado plot for the sensitivity analysis of the total oil content can be found in Figure 6-14. The most influential parameter is the liquid mass flow, giving a range in oil content from -36% to 30%. Other significant parameters are the turbulence parameters for gravity dominated flow and wavy flow, void in slug, oil and gas densities and the tuning coefficient for interfacial friction factor (liquid-gas).

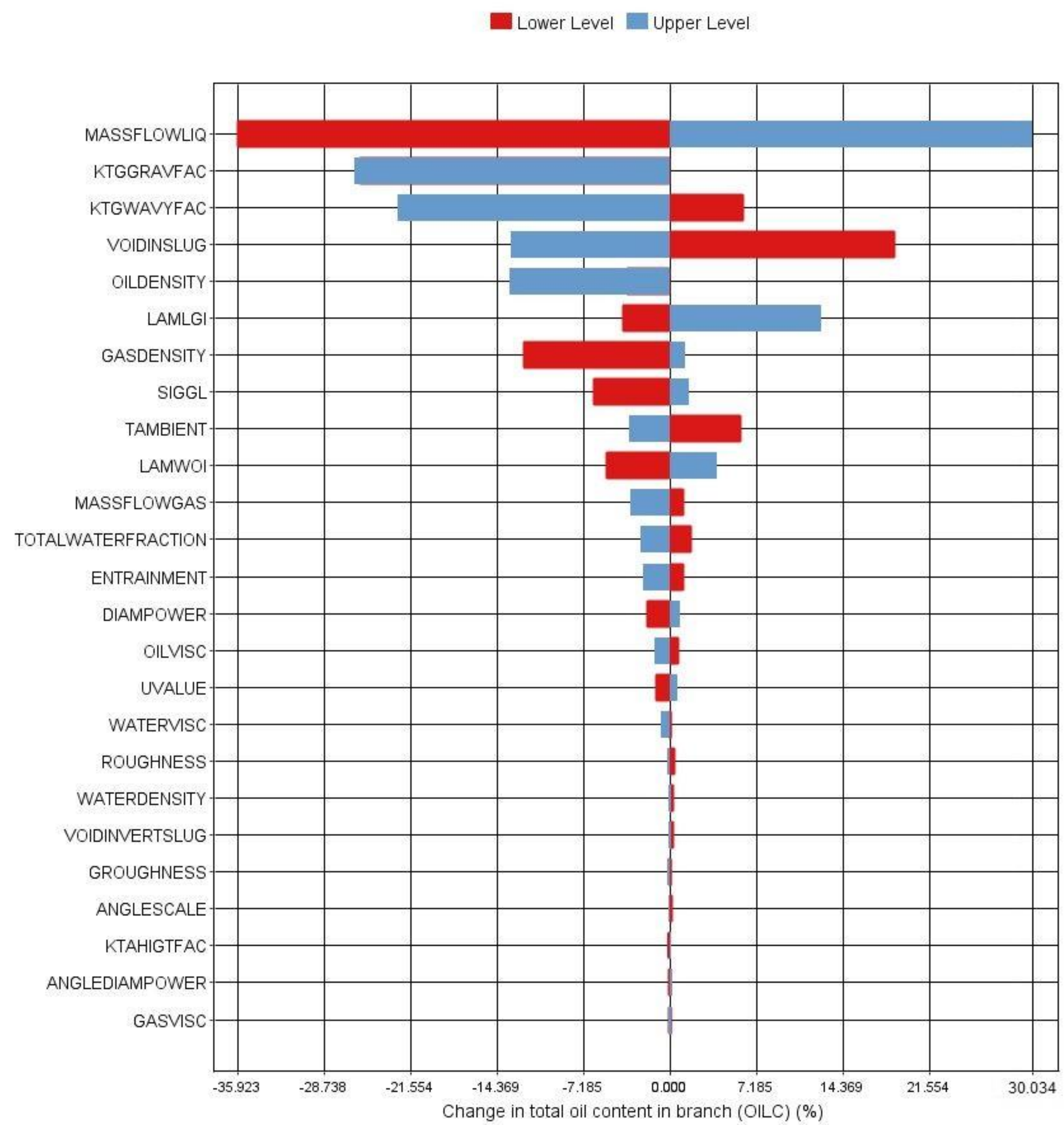


**Figure 6-14: Tornado plot for total oil content P10 pipeline, 24.6 MSm$^3$/d**

***Total water content***

The Tornado plot for the sensitivity analysis of the total water content can be found in Figure 6-15. The most influential parameter is the turbulence parameter for gravity dominated flow giving a range of the water content from -40% to 124%. Other significant parameters are the oil and gas densities, the total water fraction, the liquid mass flow, void in slug, and the tuning coefficients for interfacial friction factors for gas/liquid and oil/water in the slug model (LAMLGI and LAMWOI).

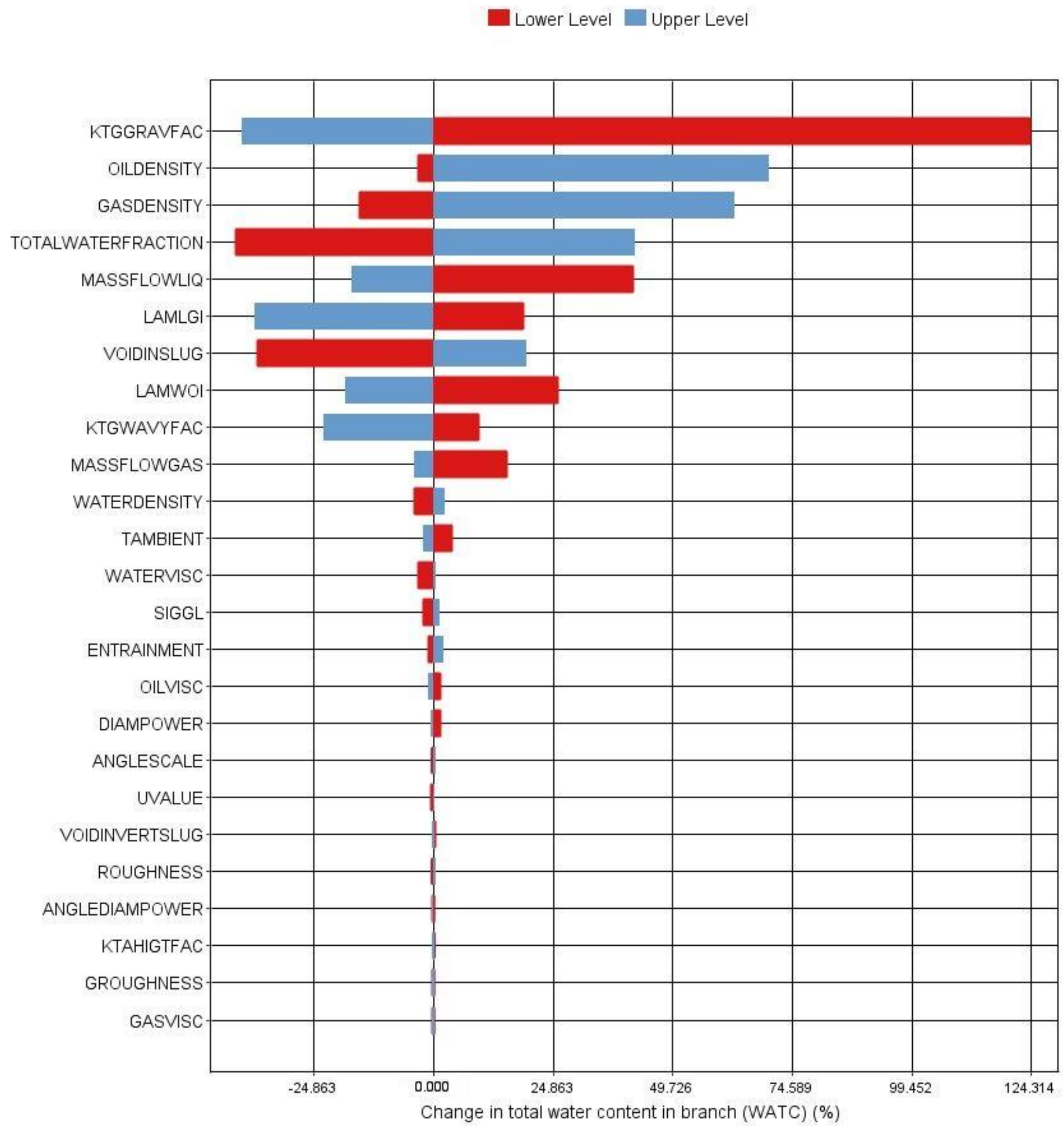


**Figure 6-15: Tornado plot for total water content P10 pipeline, 24.6 MSm$^3$/d**

### *Summary*

The most influential input- and model parameters are summarized in Table 6-8. The most influential parameters are naturally the same for the inlet pressure and the pressure drop. Other parameters which are influential for most output parameters are the mass flows of liquid and gas, oil and gas densities, total water fraction, the tuning coefficient for void in slug, and the turbulence parameters for wavy flow and gravity dominated flow.

**Table 6-8: Summary of results from sensitivity analysis, 24.6 MSm$^3$/d**

<table>
<tr><th>Output parameter</th><th>Input parameters with the largest effect</th><th>Model parameters with the largest effect</th></tr>
<tr><td>PT</td><td rowspan="2">OILDENSITY<br>TOTALWATERFRACTION<br>MASSFLOWLIQ<br>ROUGHNESS<br>GASDENSITY</td><td rowspan="2">KTGGRAVFAC<br>KTGWAVYFAC<br>VOIDINSLUG<br>LAM_WOI</td></tr>
<tr><td>DPBR</td></tr>
<tr><td>LIQC</td><td>MASSFLOWLIQ<br>GASDENSITY<br>TOTALWATERFRACTION<br>SIGGL<br>TAMBIENT<br>MASSFLOWGAS<br>OILDENSITY</td><td>KTGGRAVFAC<br>KTGWAVYFAC<br>VOIDINSLUG</td></tr>
<tr><td>OILC</td><td>MASSFLOWLIQ<br>OILDENSITY<br>GASDENSITY<br>TOTALWATERFRACTION<br>SIGGL<br>TAMBIENT</td><td>KTGGRAVFAC<br>LAM_LGI<br>KTGWAVYFAC<br>VOIDINSLUG<br>LAM_WOI</td></tr>
<tr><td>WATC</td><td>TOTALWATERFRACTION<br>OILDENSITY<br>GASDENSITY<br>MASSFLOWLIQ<br>MASSFLOWGAS</td><td>KTGGRAVFAC<br>LAM_LGI<br>VOIDINSLUG<br>LAM_WOI<br>KTGWAVYFAC</td></tr>
</table>

Parameters that do not appear at all in any of the Tornado plots i.e. have zero or near zero contribution are:

- KTGSMTHFAC: This is probably because the smooth turbulence parameter is only applicable for very low gas Reynolds numbers, mostly laboratory conditions
- KTALOWTFAC: Similarly, this parameter is only applicable in cases of low turbulence flow, which is not the case in the P10 pipeline.
- KTAHIGHTFAC
- WETFRACTION
- GASVISC
- ANGLESCALE
- ANGLEDIAMPOWER

### 6.2.2 Uncertainty analysis

The results from the uncertainty analysis were shown using plots showing the distribution of the inlet pressure, pressure drop, liquid content, oil content and water content when varying the input- and model parameters. The blue columns represent the density distribution, the three red columns show where the percentiles P10, P50 and P90 are located, and the light red columns connected with a red line show the cumulative distribution.

Scatter plots of the data can be found in Appendix A.

### *Total pressure drop*

The distribution plot from the uncertainty analysis of the total pressure drop can be found in Figure 6-16. The distribution rises and declines gradually and there are several points beyond P90 with low probability frequencies, making the distribution slightly skewed.

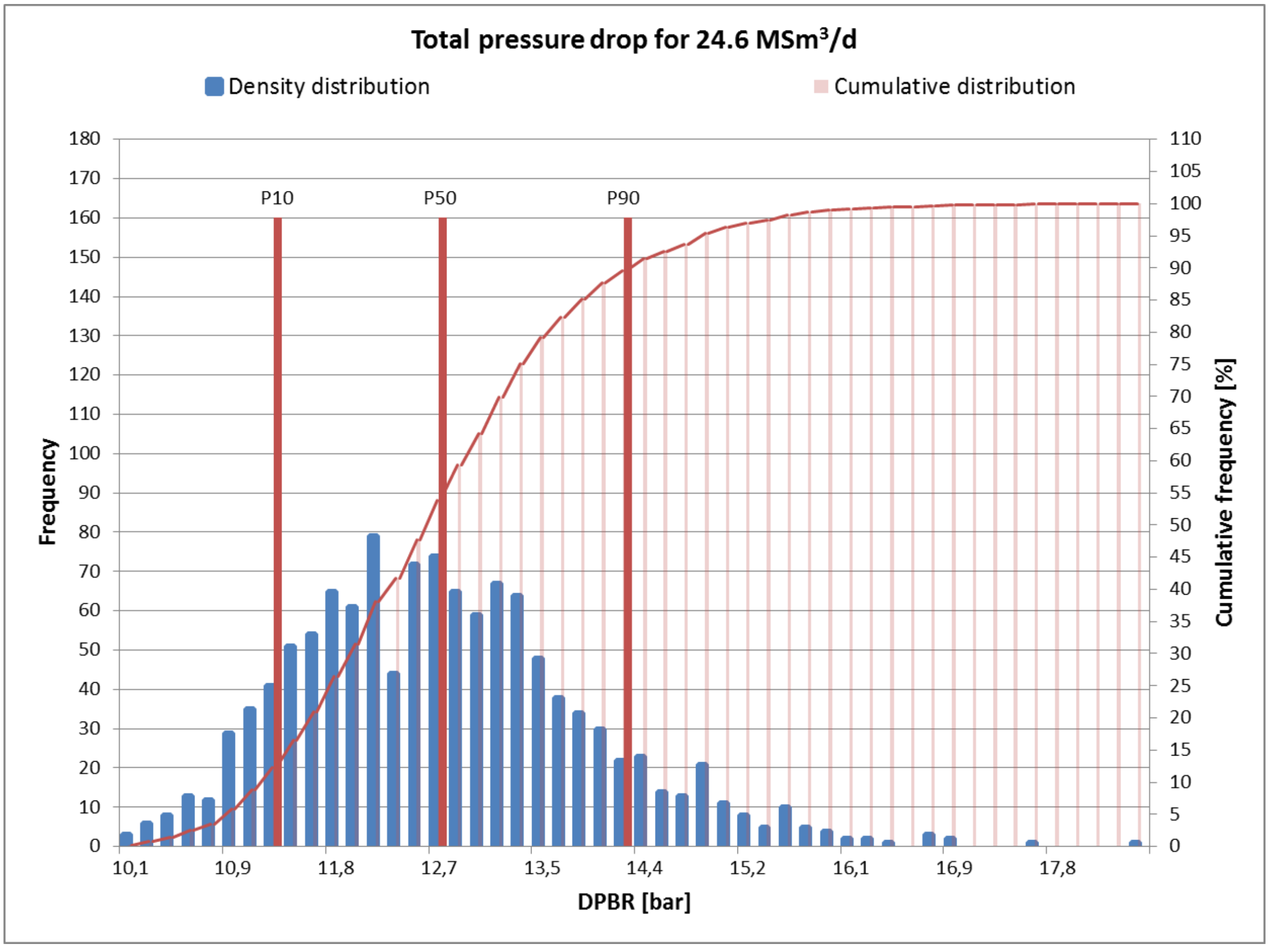


**Figure 6-16: Distribution plot for total pressure drop, P10 pipeline, 24.6 MSm$^3$/d**

### *Inlet pressure*

The distribution plot from the uncertainty analysis of the inlet pressure can be found in Figure 6-17. Similarly as for the pressure drop, the distribution rises and declines gradually and there are several points beyond P90 with low frequencies.

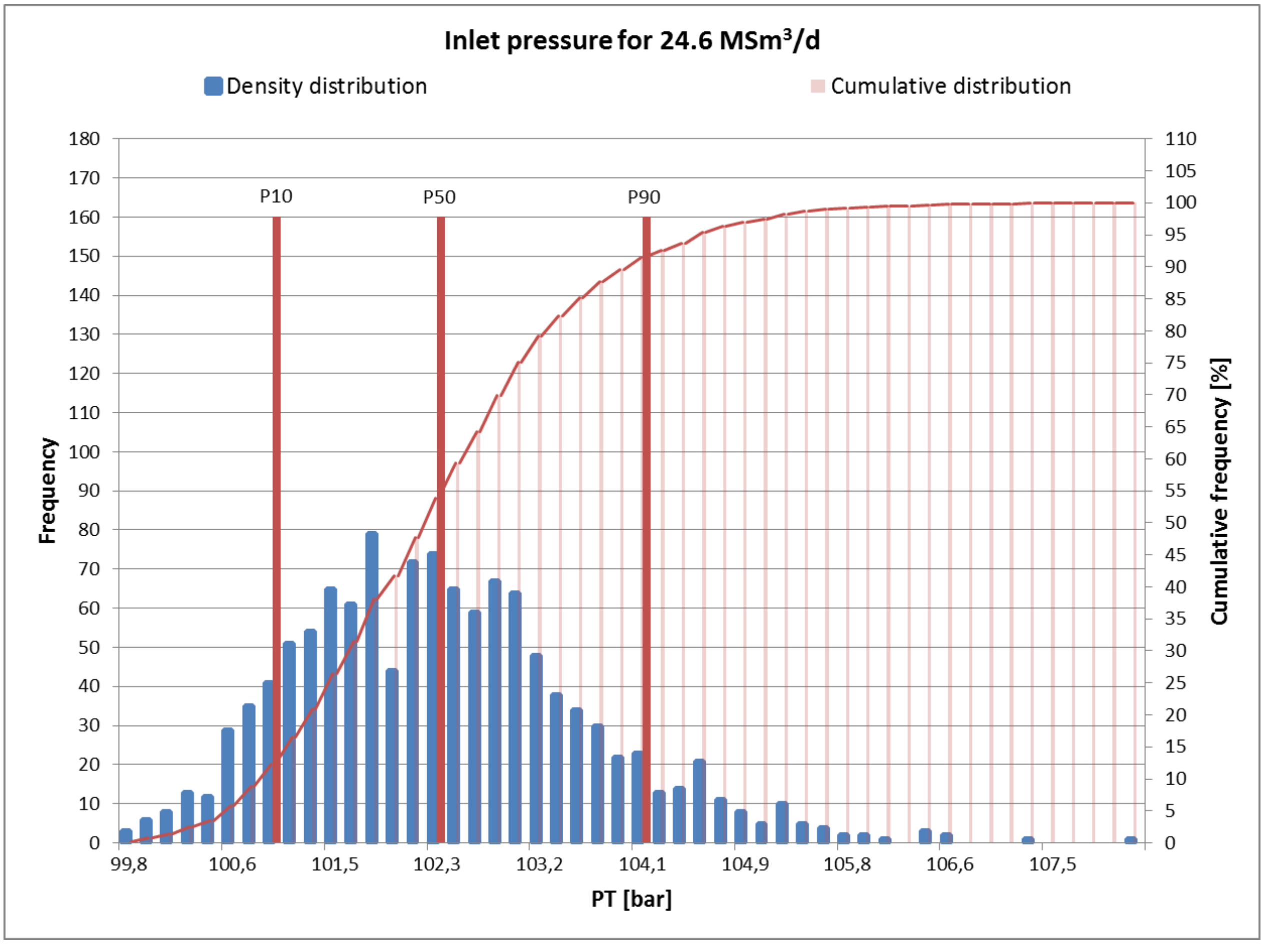


**Figure 6-17: Distribution plot for inlet pressure, P10 pipeline, 24.6 MSm$^3$/d**

### *Total liquid content*

The distribution plot from the uncertainty analysis of the total liquid content can be found in Figure 6-18. The probability distribution is rather flat and widespread. There is a band of values near P50 which have similar probability frequencies.

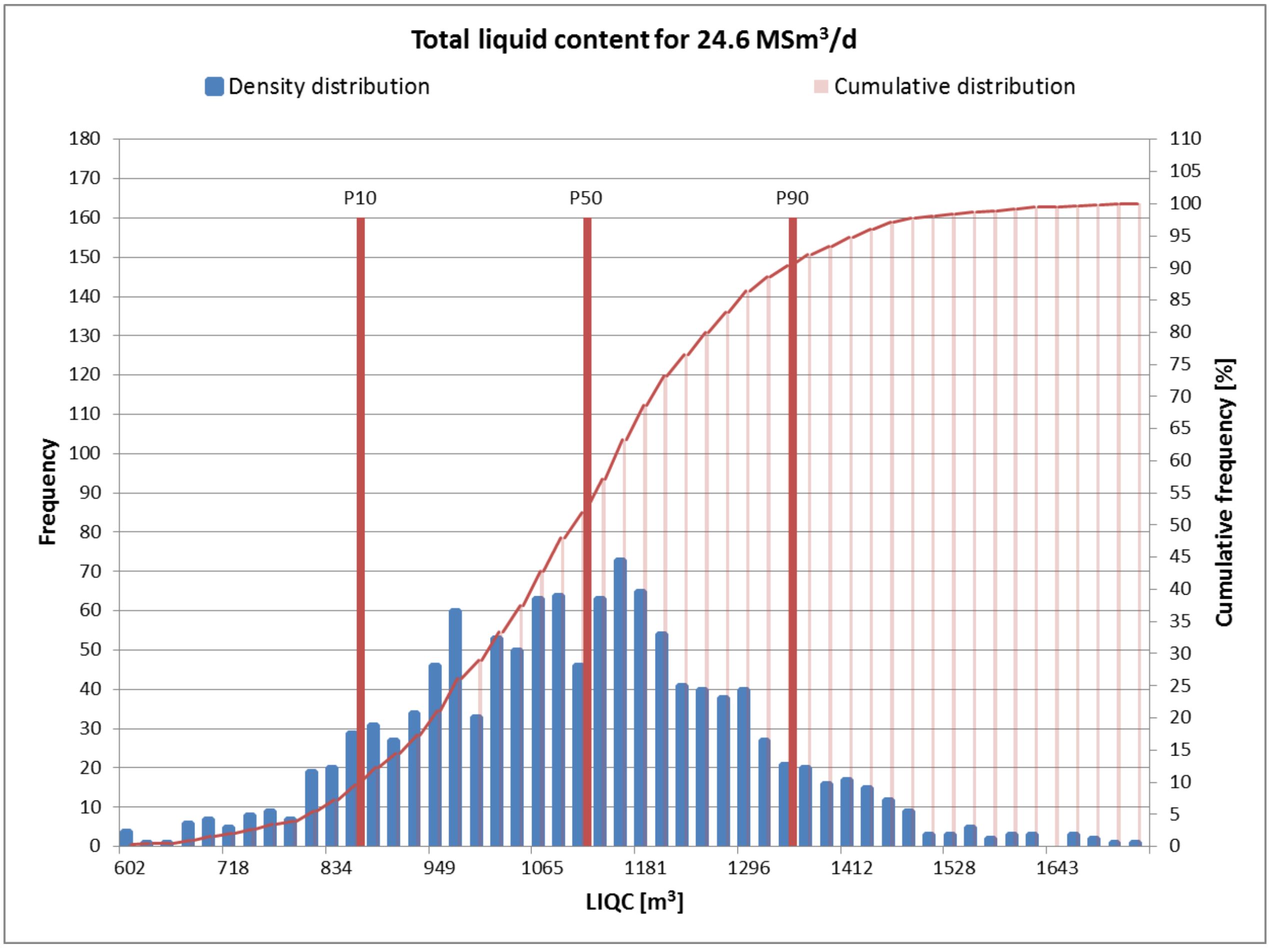


**Figure 6-18: Distribution plot for total liquid content, P10 pipeline, 24.6 MSm$^3$/d**

### *Total oil content*

The distribution plot from the uncertainty analysis of the total oil content can be found in Figure 6-19. The distribution is quite widespread and gradual. There is a band of values near P50 which have similar probability frequencies; there is no definite peak. There are some high values with low frequencies, resulting in P90 being further away from P50.

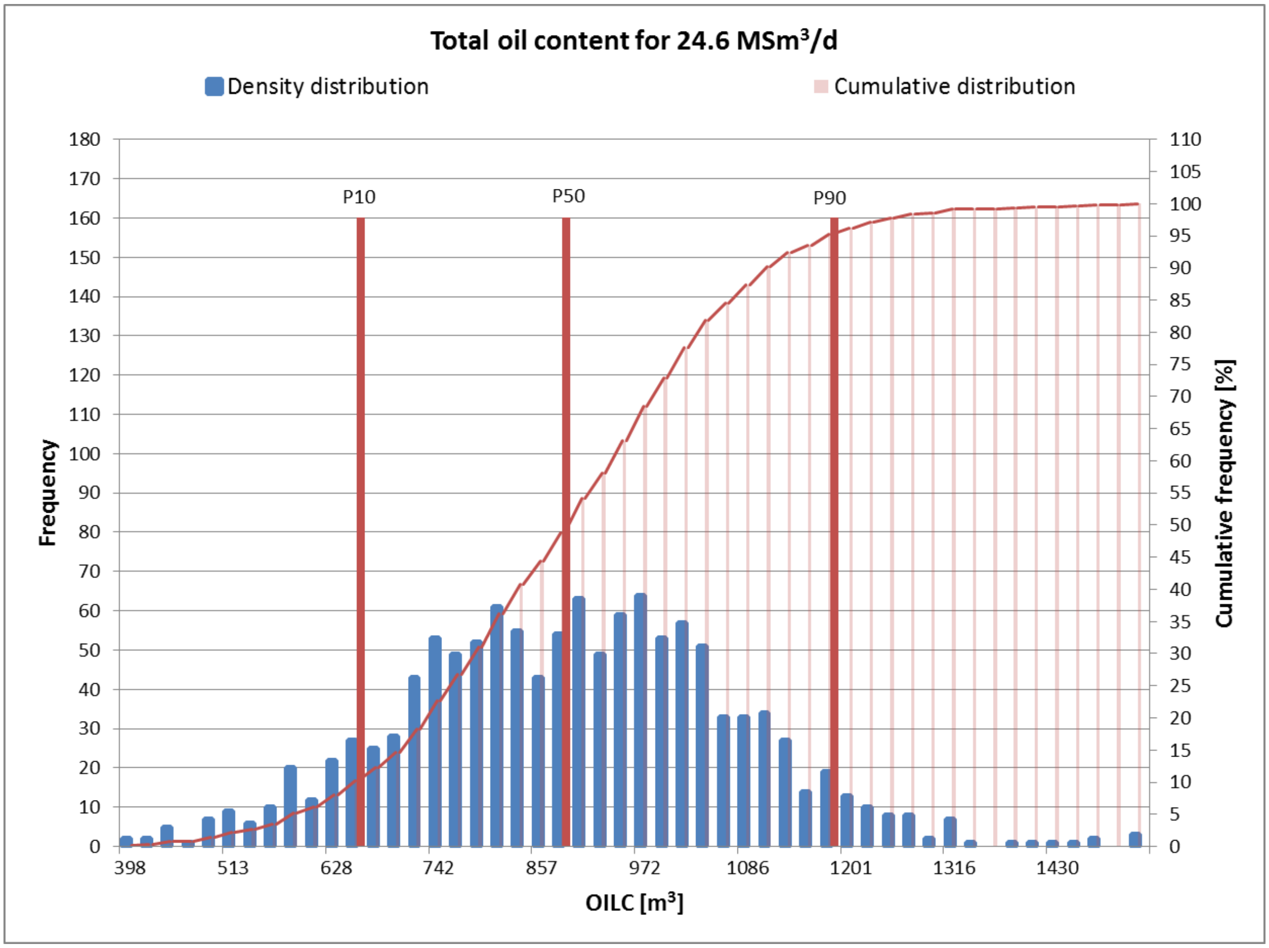


**Figure 6-19: Distribution plot for total oil content, P10 pipeline, 24.6 MSm$^3$/d**

***Total water content***

The distribution plot from the uncertainty analysis of the total water content can be found in Figure 6-20. The distribution is quite skewed, with a steep rise towards P50 and a very gradual decline after. Most of the higher values have very low probability frequencies, but there are many of them, so P90 is shifted to the right.

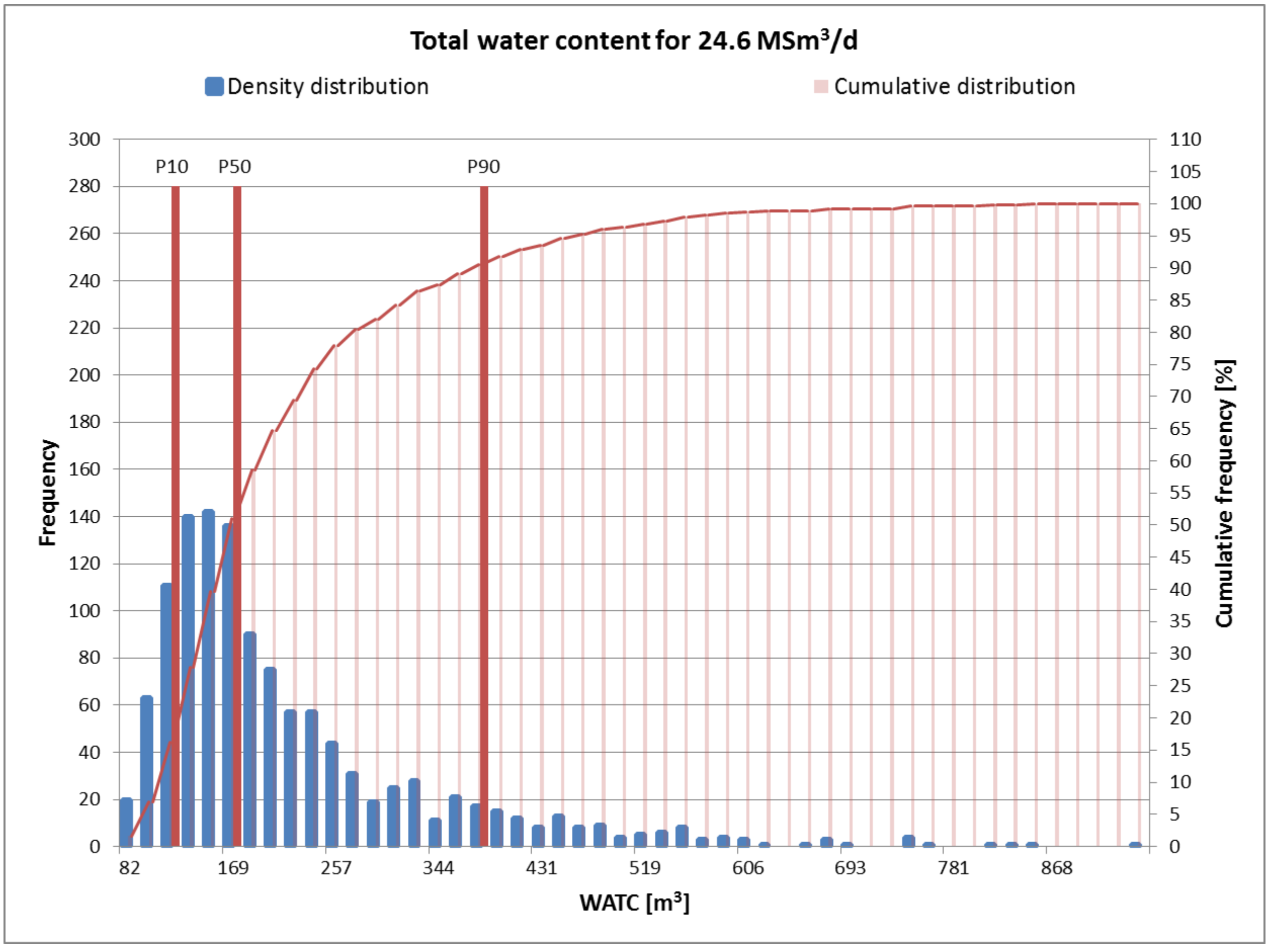


**Figure 6-20: Distribution plot for total water content, pipeline, 24.6 MSm$^3$/d**

***Summary***

In Table 6-9 is a summary of the key data in the distribution plots. The minimum and maximum values for the output parameters are the minimum and maximum values of the general band containing the output values, i.e. none of the extreme values. The default value is the one value OLGA calculates for the output parameter. Two different kinds of uncertainties are also stated; one showing the difference between P10 and P50 (-), and between P50 and P90 (+), and the other showing the difference between the minimum and default value (-), and the default and maximum value (+). A comparison of these results with the measurement data from the Troll P10 pipeline can be found in Table 6-10.

**Table 6-9: Summary of results from uncertainty analysis, 24.6 MSm$^3$/d**

| Output variable | P10 | P50 | P90 | Min. | Default | Max. | Uncertainty P10-P50-P90 | Uncertainty Min-Default-Max |
|---|---|---|---|---|---|---|---|---|
| PT [bar] | 100.9 | 102.3 | 104.0 | 99.7 | 102.8 | 111.0 | -1.3% / +1.7% | -3.0% / +8.0% |
| DPBR [bar] | 11.3 | 12.6 | 14.3 | 10.0 | 13.1 | 18.6 | -10.8% / +13.4% | -23.7% / +41.8% |
| LIQC [m$^3$] | 872 | 1110 | 1346 | 591 | 1217 | 1747 | -21.5% / +21.2% | -51.4% / +43.6% |
| OILC [m$^3$] | 661 | 896 | 1118 | 387 | 994 | 1534 | -26.3% / +24.8% | -61.1% / +54.2% |
| WATC [m$^3$] | 115 | 176 | 380 | 73.3 | 222 | 947 | -34.6% / +116% | -67.0% / +326% |

For the inlet pressure and the pressure drop the OLGA calculations are quite close to the P50 values, while for the liquid, oil and water content the calculations are higher. The uncertainties for liquid, oil and water content are generally very high. When comparing the two different uncertainties, the Min-Default-Max uncertainty is significantly larger than the P10-P50-P90 uncertainty, especially for the water content. This shows that some calculations can be quite high or low, even though they do not occur as frequent.

**Table 6-10: Comparison with Troll measurement data, 24.6 MSm$^3$/d**

| | **Troll measurement** | **OLGA calculation** | **Within P10-P90** | **Within Min-Max** | **P- value the measurement represents** |
|---|---|---|---|---|---|
| Inlet pressure [bara] | 101.7 | 102.8 | Yes | Yes | P30 |
| Pressure drop [bar] | 12.0 | 13.1 | Yes | Yes | P30 |
| Total liquid accumulation [m$^3$] | 1386 | 1217 | No | Yes | P100 |
| Condensate accumulation [m$^3$] | 856 | 994 | Yes | Yes | P42 |
| Water accumulation [m$^3$] | 530 | 222 | No | Yes | P97 |

From this it is seen that the inlet pressure, pressure drop and oil content measurements fall inside the P10-P90 uncertainty range and all measurements are within the Min-Max range. For this gravity dominated case the measured liquid accumulation is much higher than for the friction dominated case and OLGA under-predicts it. Thus, the measured liquid content represents a high percentile value. The water content is just within the maximum value. The measured inlet pressure, pressure drop and oil content are between the P10 and P50 value.

### 6.2.3 Tuning

For this gravity dominated case, there was generally an over-prediction of the pressure drop compared to the field measurements. The liquid content and water content are, however, under-predicted which is different from the friction dominated case. In addition, the uncertainties for the gravity dominated case are much larger. This makes a general tuning difficult. By trying to achieve higher values for the calculations, the liquid content will be even more over-predicted. Due to OLGA 7.1.4's poor calculation of water content (Nygård, 2012) (Valle & Johansson, 2011), the water accumulation has not been taken into account. Therefore it was decided to perform the same tuning as for the friction dominated case, to get a background for comparison. A new uncertainty analysis with a shifted range for KTGGRAVFAC and KTGWAVYFAC was executed (Table 6-5), while all other parameter ranges were the same as before. The results are summarized in Table 6-11, and a comparison with Troll measurements is found in Table 6-12. Scatter plots and distribution plots can be found in Appendix B.

**Table 6-11: Summary of results from tuning, 24.6 MSm$^3$/d**

| Output variable | P10 | P50 | P90 | Min. | Default | Max. | Uncertainty P10-P50-P90 | Uncertainty Min-Default-Max |
|---|---|---|---|---|---|---|---|---|
| PT [bar] | 99.2 | 100.3 | 101.8 | 98.0 | 100.1 | 103.8 | -1.1% / +1.5% | -2.1% / +3.7% |
| DPBR [bar] | 9.5 | 10.6 | 12.1 | 8.3 | 10.5 | 14.1 | -10.4% / +14.0% | -21.0% / +34.7% |
| LIQC [m$^3$] | 631 | 834 | 1051 | 432 | 821 | 1388 | -24.4% / +26.0% | -47.4% / +69.1% |
| OILC [m$^3$] | 502 | 704 | 912 | 303 | 695 | 1222 | -28.7% / +29.7% | -56.3% / +75.9% |
| WATC [m$^3$] | 95.5 | 131 | 169 | 64.9 | 126 | 314 | -26.9% / +29.6% | -48.5% / +150% |

Compared to the uncertainty analysis, all the output results from the tuned simulations are a great deal lower in value, especially the maximum values. The P10-P50-P90 uncertainties are quite similar as before for the tuned inlet pressure and pressure drop, while the Min-Default-Max uncertainties are lower. For the liquid and oil content, the P10-P50-P90 uncertainties are higher after the tuning, the Min-Default (-) uncertainties are smaller, and the Default-Max (+) uncertainties are higher. For the water content, all uncertainties are lower for the tuned results.

**Table 6-12: Comparison of tuning with Troll measurement data, 24.6 MSm$^3$/d**

| | Troll measurement | OLGA calculation | Within P10-P90 | Within Min-Max | P- value the measurement represents |
|---|---|---|---|---|---|
| Inlet pressure [bara] | 101.7 | 100.1 | Yes | Yes | P89 |
| Pressure drop [bar] | 12.0 | 10.5 | Yes | Yes | P89 |
| Total liquid accumulation [m$^3$] | 1386 | 821 | No | Yes | P100 |
| Condensate accumulation [m$^3$] | 856 | 695 | Yes | Yes | P82 |
| Water accumulation [m$^3$] | 530 | 126 | No | No | Over P100 |

The OLGA calculations are not closer to the Troll measurements after the tuning; the tuned values are now lower than the measurements. This is also seen in the percentile values of the measurements, as they are now considerably higher than before. With the exception of the water content, all the measurements are still within the minimum and maximum values, and the inlet pressure, pressure drop and oil content are still within P10 and P90. The water content is now very under-predicted, and the measurement is far above the maximum value obtained in the tuning, i.e. over P100.

# 7 Discussion

## 7.1 On using the RMO module for uncertainty estimation

The module is easily accessed from OLGA, and it does not take long to set up analyses with ranges and distributions. The features for the sensitivity analysis and the uncertainty analysis are user friendly and not difficult to understand. The tuning/optimization cycle, however, was not found to be very intuitive and was not used in this project. After setting up an analysis, the simulations can be started and will then run by themselves automatically until completed, which is very practical. The automatic Tornado plots generated from the sensitivity analyses are good, although editing the design and appearance of the plot is quite time consuming and not very intuitive. The visualization tools for the uncertainty analyses are useful; there are several different plot options for the data and there is a user guide available for these in the RMO module. It is also very easy to export the different data sets to e.g. Microsoft Excel if that is preferred instead. The RMO module is a good alternative to using the full MEPO program if all that is needed are the uncertainty estimation features.

The negative experience with the RMO module is that it often behaves erratically, and the user does not have many options to fix the problems. The RMO analyses are opened automatically when entering the module from OLGA, and if for some reason it cannot find the files there is no way to open them manually. The backup files must then be accessed to see if a previous version can be opened instead, potentially causing loss of data. The module also crashed several times during the analyses for no apparent reason, and exited the module without warning. This also causes loss of data, as the analyses must finish and then be saved in the program to be stored on the computer. The uncertainty analysis may take hours or days to execute, and it is problematic if the RMO module suddenly turns off during the simulations. The idea for executing the analyses for this project was so set up simulations during the day, and let them run overnight and assess the results the next day. Unfortunately, due to these shut downs, this proved difficult. Small batches of simulations had to be performed under supervision instead, to ensure storage of the results along the way. Thus, this proved a lot more time consuming than anticipated, and became much more inconvenient.

More an annoyance than an actual problem is the fact that the program sometimes freezes, and can spend a lot of time opening and closing, switching between analyses, and post-processing the data. The RMO module also does not seem to handle alterations in the OLGA project, e.g. if the OLGA project is run after an analysis has been performed in the RMO module, it will not be able to run a new analysis because the OLGA project is changed. According to SPT Group, many of these issues with the RMO module are resolved in OLGA 7.2. Until the new version is available, further use of the RMO module is not recommended.

It would probably have been beneficial to have attended SPT Group's course, or at least learned the program from someone who knows it. This would have been especially useful for the tuning function. Better understanding of all the functions could lead to improved use, which again could lead to fewer errors. However, these courses are quite expensive, and there was no opportunity to take such a course during this project.

## 7.2 On the results

The sensitivity analyses showed the linear effect of the minimum and maximum values of the input- and model parameters on the output parameters. For the friction dominated case, input parameters that had significant impact were densities of oil and gas, mass flows of liquid and gas, inner wall roughness, heat transfer coefficient, surface tension liquid/gas and the ambient temperature. Model parameters with a large effect were turbulence parameters for gravity dominated flow and for wavy flow, droplet roughness, entrainment rate of droplets and the diameter exponent in the droplet entrainment scaling expression. For the gravity dominated case, significant input parameters were much the same as for the friction dominated case, with the exception of the heat transfer coefficient. The total water fraction also had a larger effect for the gravity dominated case. Important model parameters were turbulence parameters for gravity dominated flow and for wavy flow, tuning coefficient for void in slug flow, and the interfacial friction factors (liquid-gas and oil-water).

The mass flow rates, densities and surface tension were expected to be significant for both cases, as these input parameters influence the flow regimes and thus the general behavior of the flow. For the friction dominated case, the flow rates are higher, meaning that wall and droplet roughness will have a large impact on the pressure drop. Droplet entrainment from liquid to the gas is also important; a high entrainment rate will tear off droplets from the liquid layer, thus resulting in a decreased liquid content and a decrease in hydrostatic pressure drop. These parameters are also important for the gravity dominated case, although not to the same extent because the flow rates are lower. For both cases, a low ambient temperature gives an increase in liquid content, due to the fact that more liquid is condensed from the gas at low temperatures. This is approximately the same effect as having a high heat transfer coefficient; the fluids in the pipe will cool faster due to the colder sea temperature outside the pipe. The total water fraction is more significant for the gravity dominated case, because there in more liquid in the pipe and OLGA calculates more sections with high holdup solutions. A small addition of water can result in a high holdup solution, giving a relatively high sensitivity of this parameter.

The turbulence parameters had a large impact in both cases. The turbulence parameter for wavy flow was not surprising, as there is mostly wavy flow in the pipeline, but it was unexpected that the turbulence parameter for gravity dominated flow would have such significance in the friction dominated case. The expectation was that it would only impact the gravity dominated case. A possible explanation could have been that OLGA calculates high holdup solutions somewhere in the pipeline which causes it to have an effect, but after checking the output from OLGA it was found that the friction dominated case does not have any sections with high holdup. It is, however, possible that the KTGGRAVFAC parameter is important in the high inclination sections towards the landfall (see Figure 3-3) even though the holdup is not larger than about 0.1. The equations used in OLGA are confidential to SPT Group, thus making it difficult to determine why this parameter influences the output so much. For the gravity dominated case, there was also an effect from the tuning coefficient for void in slug, meaning there is transition to slug flow in the high inclined sections towards the landfall. Different flow regimes cause the flow to behave differently, so the parameter has a significant effect. The interfacial friction factors were also important in this case; a high interfacial friction factor makes it easier for the gas to drag the liquid along the pipeline, thus giving a decrease in required pressure drop. It was also expected that high interfacial friction would also give a decrease in liquid content, but the sensitivity analysis showed the opposite. An explanation was found when looking at the OLGA output. At the end of the P10 pipeline, where it rises to shore, there are areas where OLGA calculates transition to a slug flow regime. When increasing the friction factor, tendencies to slug flow are reduced, giving wavy flow instead. Wavy flow has a higher liquid content than slug flow, thus giving a larger value. Consequently, increased interfacial friction does not give a higher liquid content; this is caused by the resulting flow regime transition. This shows the complexity associated with parameter tuning and its effect on flow regime transitions.

For both cases, the changes in output values were higher for the liquid, oil and water content compared to the pressure drop and inlet pressure. This means that the total liquid content is more sensitive to changes in the input- and model parameters. When looking at the friction dominated case compared to the gravity dominated case, the changes in the pressure drop are much larger for the gravity dominated case. The changes in liquid and oil content are quite similar for the two cases, while the water content has a very high upper value for the gravity dominated case. Generally, the gravity dominated case was more sensitive to input- and model parameter variations than the friction dominated case.

From the uncertainty analyses it was found that the linear effects from the sensitivity analyses could amplify or cancel each other when varying the parameters simultaneously. For the friction dominated case, the density distribution of the pressure drop was quite steep, with high probability frequencies near the P50 value. The distributions for the liquid and oil contents were more widespread with gradual rise and decline in probability frequencies. The water content distribution was very narrow with many high frequencies, followed by a tail of higher values with very low frequencies. For the gravity dominated case, the density distributions of the output parameters were generally much more widespread than for the friction dominated case. The water content density distribution was quite skewed, with higher frequencies for values between P10 and P50, and then a very gradual decline towards and past P90.

When looking at the uncertainties of P10 and P90 with respect to P50, and the uncertainties of the minimum and maximum values with respect to the default value, the uncertainties in the friction dominated case are smaller for the inlet pressure, pressure drop and water content, and larger for the total liquid content and the oil content, compared to the gravity dominated case. However, the liquid content values for the gravity dominated case are generally much higher than for the friction dominated case, and the difference between minimum and maximum values are significantly larger. For both cases, the Min-Default-Max uncertainties are approximately the double of the P10-P50-P90 uncertainties, showing that there are many high and low values outside the P10-P90 span with small density frequencies. Especially for the water content, the maximum value is very large. For both cases, uncertainties in the inlet pressure and pressure drop are small compared to the liquid contents, indicating that the Troll pipeline pressure drop is not as sensitive to the changes in the input- and model parameters.

For the friction dominated case, the measured Troll values approximately represented a percentile P1, i.e. 99 % of the predicted values were higher than the measurements. The water content was an exception, with a measurement representing P94. As stated previously, OLGA 7.1.4 does not predict water content adequately; consequently the water content will not be discussed further. Thus, OLGA over-predicts the output parameters in the friction dominated case. The gravity dominated case was quite different. The measured inlet pressure, pressure drop and oil content were all inside the P10-P90 range, while the measured total liquid content and water content were under-predicted as the measurements represented approximately P100. As stated earlier, the under-prediction of water content is a known problem for OLGA 7.1.4, so this is one reason why the total liquid content is under-predicted. Another reason is the fact that OLGA predicts slug flow in the high inclined parts of the pipeline, giving a lower liquid inventory. Turning off the slug model in OLGA improves the prediction of liquid accumulation for the gravity dominated case. The uncertainty ranges in this case are quite large, and this may be a reason why the measurements fall inside the output distribution.

The tuning sessions were performed to attempt to shift the OLGA calculations closer to the Troll measurements. For the friction dominated case, this was straightforward to do, as all the measurements were over-predicted. By altering two of the most influential model parameters, the OLGA calculations were increased, but unfortunately not by much; the measurements were still among the lowest calculations. To get the measurements closer to P50, the model parameters would have to be changed considerably. For the gravity dominated case, tuning was not as intuitive because some output parameters were over-predicted and some were under-predicted. To compare with the friction dominated case, the same tuning of model parameters was performed. The influence of the model parameters was much greater in this case, and all the measurements represented values higher than P80 after the tuning. Looking at the pressure drop for instance, the change in model parameters barely increased the measurements from P0.3 to P1 with respect to the calculations for the friction dominated case; the measurements went from P30 to P89 for the gravity dominated case. Another observation for both cases when changing these parameters was that the general uncertainties became lower. This is most likely due to a narrower output distribution of the liquid content in the flowline since the overall liquid content is reduced.

The intention was to continue with further tuning with other model parameters and possibly also other ranges and/or distributions. However, because of the erratic behavior of the RMO module, this proved difficult.

# 8 Conclusion

As a methodology for uncertainty estimation of multiphase simulation results, the RMO module has potential to be a useful tool. If uncertainty estimation is the only function needed, it is more practical than having to utilize the whole MEPO program. Currently it is too unstable, at least for OLGA version 7.1.4. This being said, it is user friendly and practical to use, and if the erratic behavior is resolved in the new OLGA 7.2.0 soon to be released, it is a good alternative to MEPO. If the RMO module is continuously improved along with the OLGA versions, it could be an efficient way of estimating uncertainty.

The most influential input- and model parameters with respect to the pipeline pressure drop and liquid accumulation for the field cases were found from the sensitivity analyses (Table 6-2 and Table 6-8). The friction dominated case was mostly affected by roughness, mass flows and densities, and the gravity dominated case was mostly affected by turbulence parameters, densities and void in slug. The effects of the parameters seemed reasonable, and were mostly explainable. The only parameter effect that could not be explained was the strong influence of KTGGRAVFAC on the friction dominated case since none of the pipe sections showed high holdup solutions. It is not known how the parameter is implemented in the equations in OLGA, because these are confidential. It was therefore difficult to investigate this further.

From the uncertainty analysis, a P10-P90 uncertainty range was found for both cases, as well as a min-max uncertainty range (Table 6-3 and Table 6-9). For the friction dominated case, all the Troll measurements, except for the water content, was over-predicted. As mentioned earlier, the under-prediction of water content is a known problem for OLGA 7.1.4. For the gravity dominated case, the inlet pressure, pressure drop and oil content were still over-predicted, but much closer to P50. The total liquid content, however, was under-predicted. This can be partly explained by a premature transition to slug flow in the high inclined sections of the pipeline.

The flow in the Troll P10 pipeline was challenging to tune because of the low liquid loading and the high pipe inclination towards land. In addition, the friction dominated case and the gravity dominated case showed opposite trends with regard to liquid content. The tuning was done with respect to the friction dominated case, to try to lower the OLGA predictions by altering two of the most influential model parameters. However, the output was not improved much by this, and the Troll field test measurement was still among the lowest predicted output values (Table 6-7). Altering the model parameters had a much greater effect on the gravity dominated case, which under-predicted all the Troll measurements severely after the tuning (Table 6-12). It is therefore difficult to achieve better results for both cases with a general tuning, not only because there were different trends in the predictions for the two different cases, but also because the gravity dominated case is more sensitive to variations in the parameters.

Generally, this sort of uncertainty estimation methodology was very useful to visualize flow assurance risk in connection with a field development project, and represents a significant step forward in this regard.

# 9 Recommendations for further work

- When it is commercially released, the pipeline simulations should be run in the OLGA 7.2.0 version. This version is supposed to have better calculations for water content, so if a more correct solution is desired this should be investigated.
- The RMO module should be tested in OLGA 7.2.0 to see if some of the erratic behavior has disappeared. If it has been improved, more simulations can be performed in the uncertainty analysis without fear of crashing, thus giving a more extensive representation of parameters and a more accurate result.
- Other probability distribution functions than the triangular distribution should be evaluated, e.g. truncated normal, uniform, etc.; there are several options in the RMO module for the uncertainty analysis. The triangular distribution may be conservative towards the minimum and maximum values.
- Include potential other uncertainty parameters that are found to be relevant. More parameters may become available in OLGA in the future, in addition to the ones considered in this study.
- Evaluate whether the pipeline in OLGA should be modeled over time, and not as steady-state.
- Study the grid/pipeline profile dependence on the OLGA results.
- Recheck the Troll field test data in order to confirm estimated liquid flow rates.

# 10 References

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**General information:**

- User Manual OLGA 7, embedded in the OLGA program
- Flow Assurance with OLGA 7: Guided Tour and Exercises, a booklet from an OLGA course taken during spring 2012 with SPT Group
- www.sptgroup.com, last visited 22.04.13

# 11 Appendices

## 11.1 Appendix A – Scatter plots from the uncertainty analyses

**List of figures**

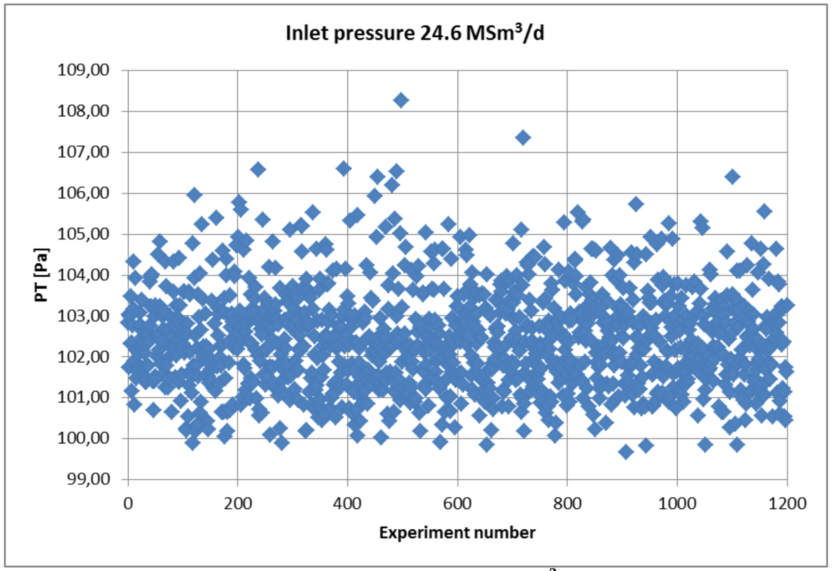


Figure A 1: Scatter plot for inlet pressure, 24.6 MSm$^3$/d

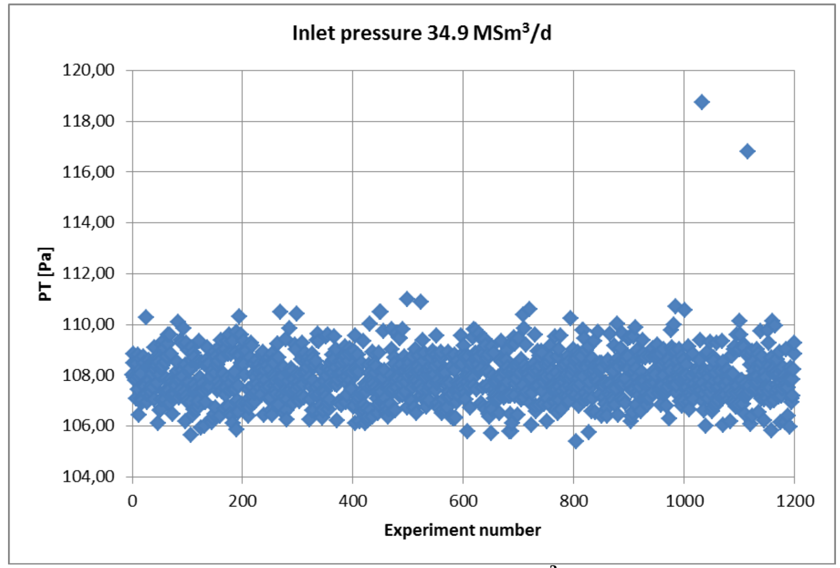


Figure A 2: Scatter plot for inlet pressure, 34.9 MSm$^3$/d

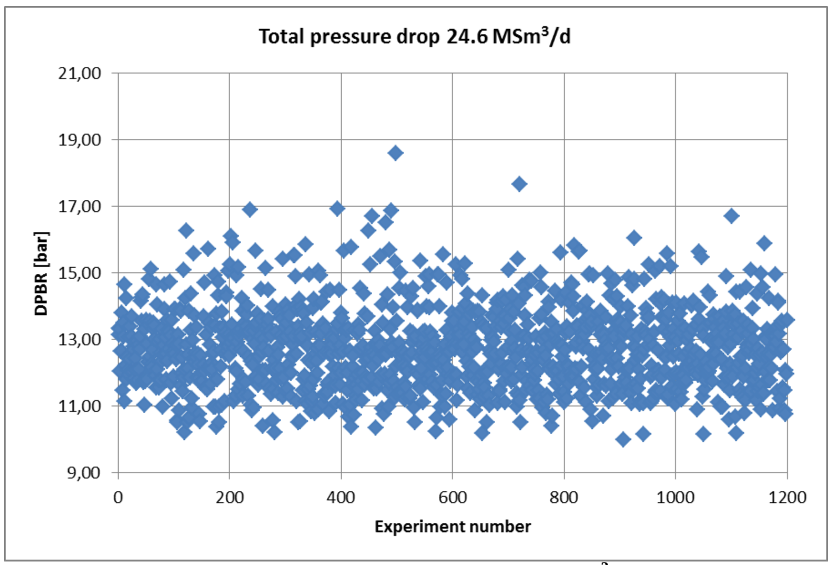


Figure A 3: Scatter plot for total pressure drop, 24.6 MSm$^3$/d

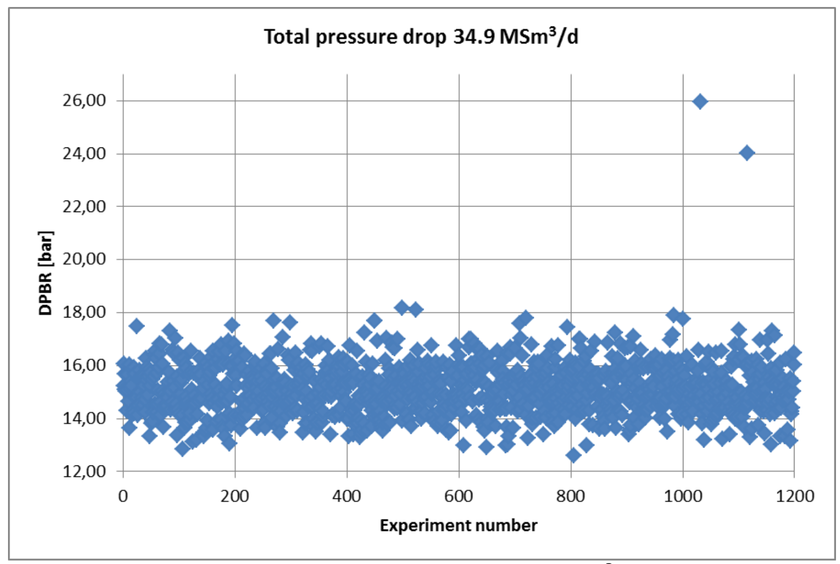


Figure A 4: Scatter plot for total pressure drop, 34.9 MSm$^3$/d

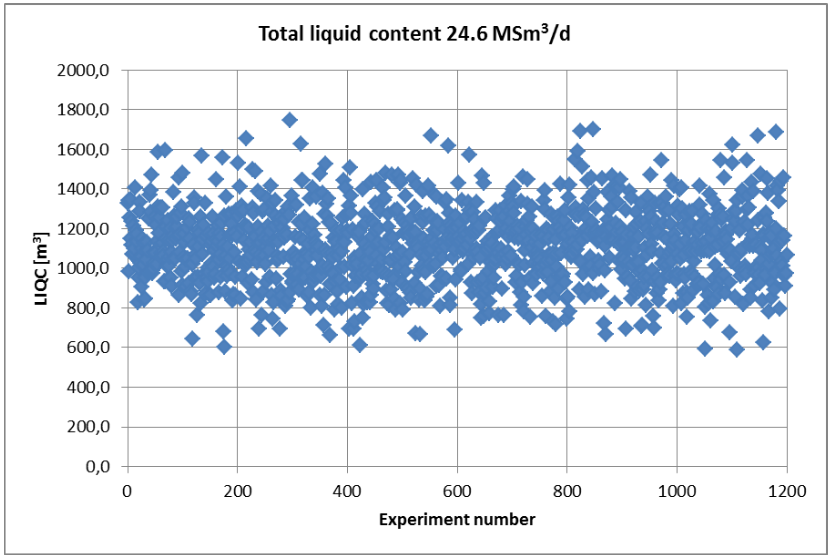


Figure A 5: Scatter plot for total liquid content, 24.6 $MSm^3/d$

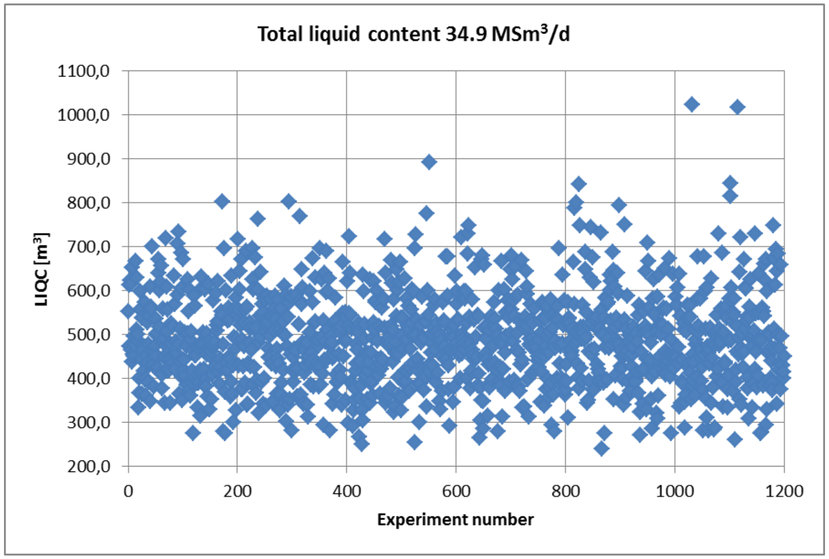


Figure A 6: Scatter plot for total liquid content, 34.9 $MSm^3/d$

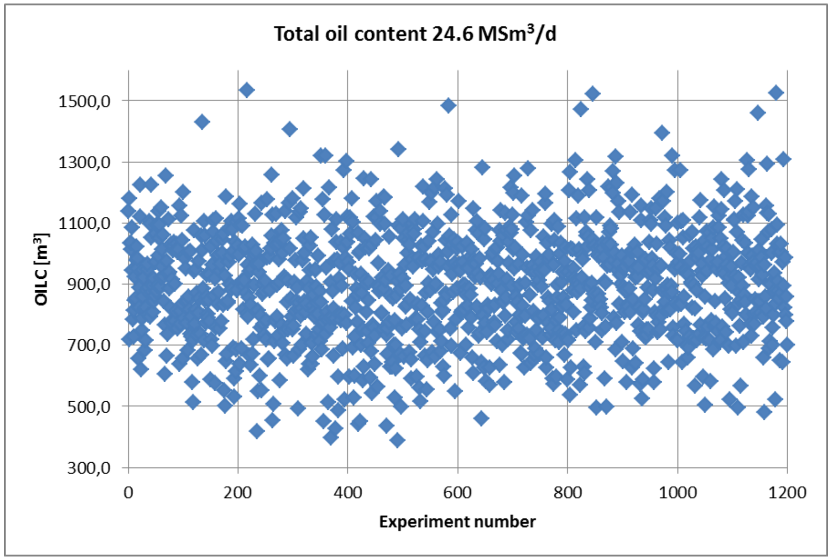


Figure A 7: Scatter plot for total oil content, 24.6 $MSm^3/d$

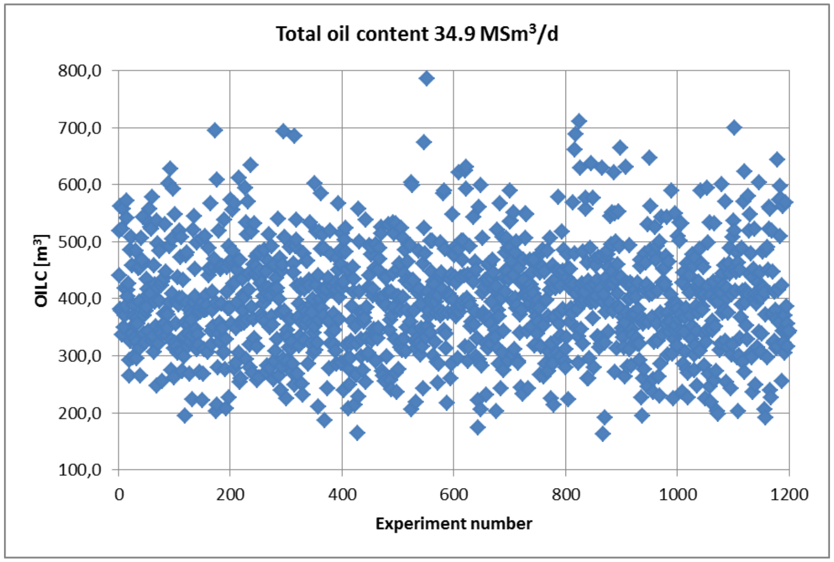


Figure A 8: Scatter plot for total oil content, 34.9 $MSm^3/d$

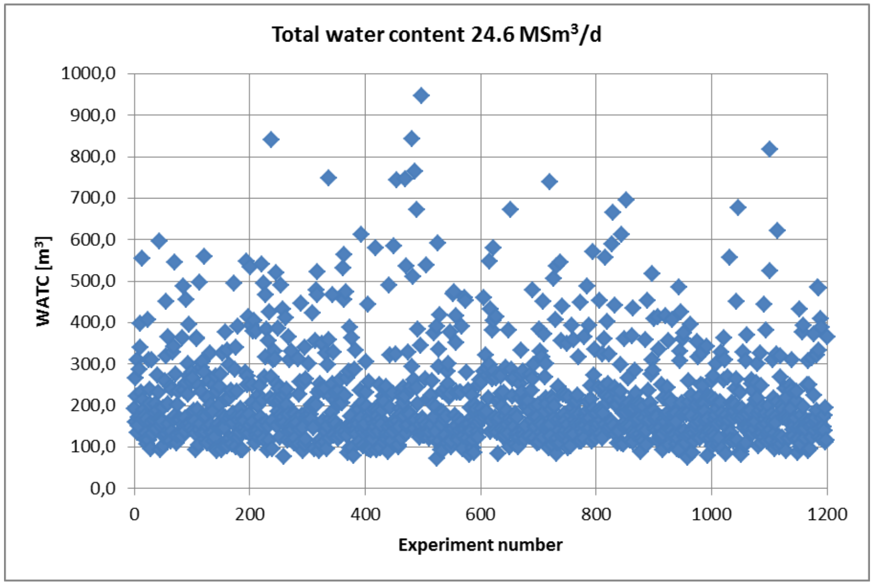


**Figure A 9: Scatter plot for total water content, 24.6 MSm$^3$/d**

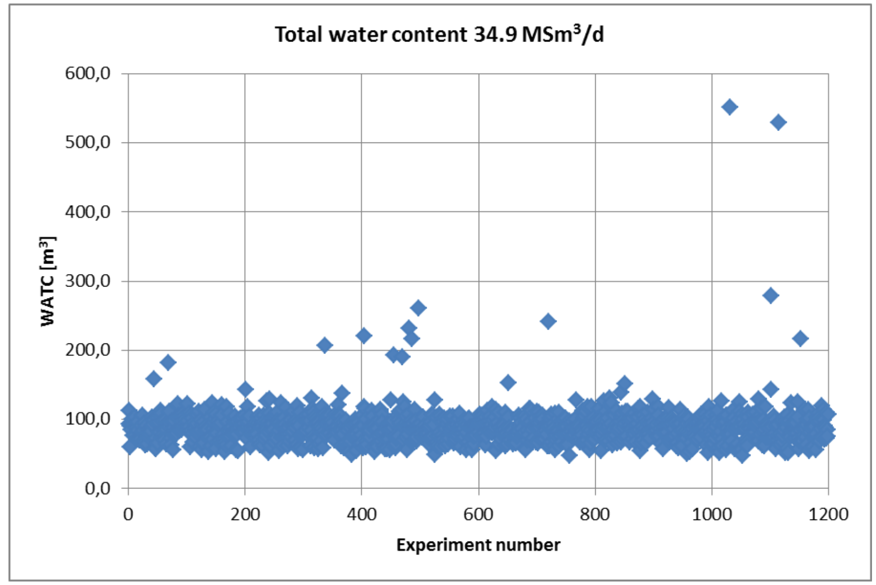


**Figure A 10: Scatter plot for total water content, 34.9 MSm$^3$/d**

## 11.2 Appendix B – Plots from the tuning sessions

**List of figures**

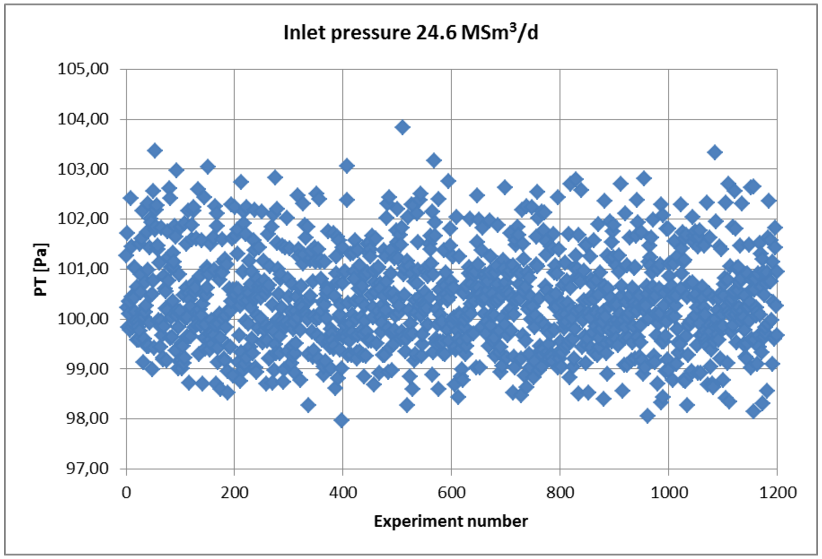


**Figure B 1: Scatter plot for inlet pressure, 24.6 $MSm^3/d$**

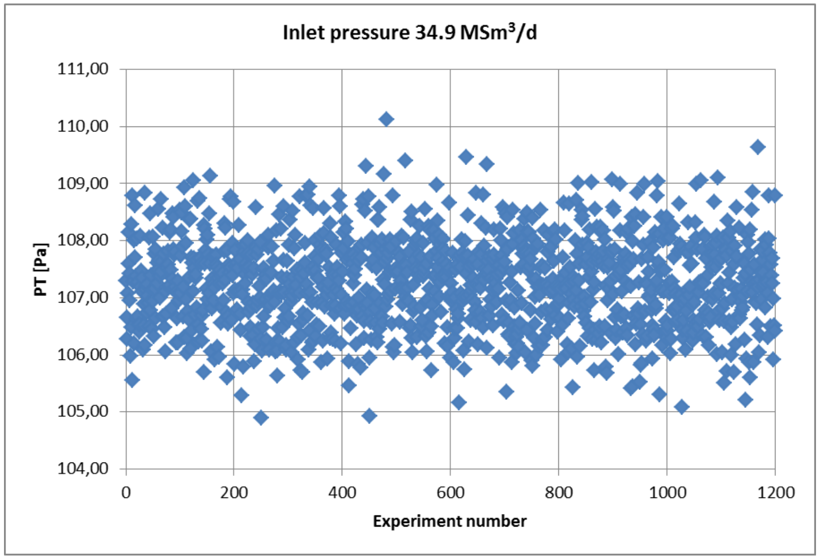


**Figure B 2: Scatter plot for inlet pressure, 34.9 $MSm^3/d$**

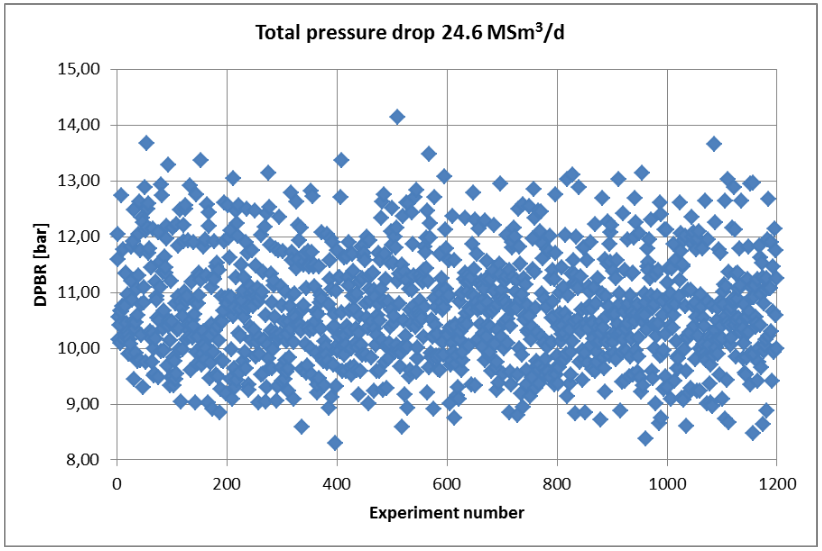


**Figure B 3: Scatter plot for total pressure drop, 24.6 $MSm^3/d$**

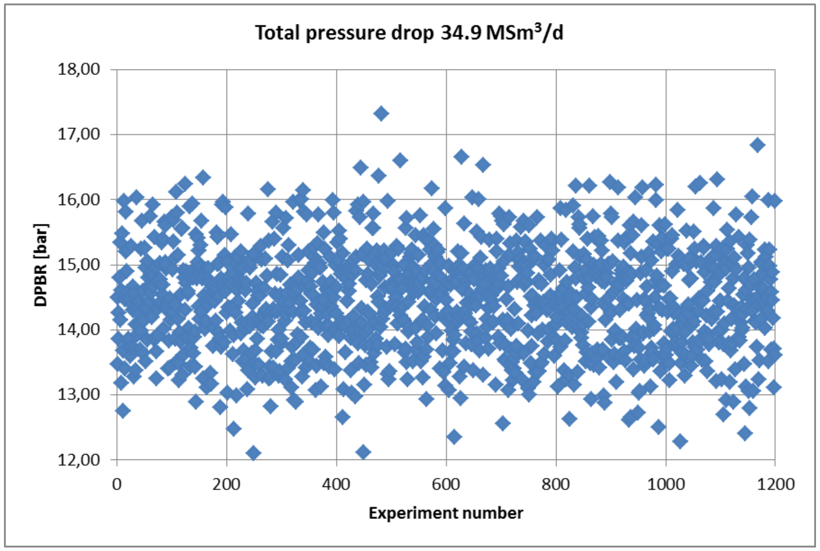


**Figure B 4: Scatter plot for total pressure drop, 34.9 $MSm^3/d$**

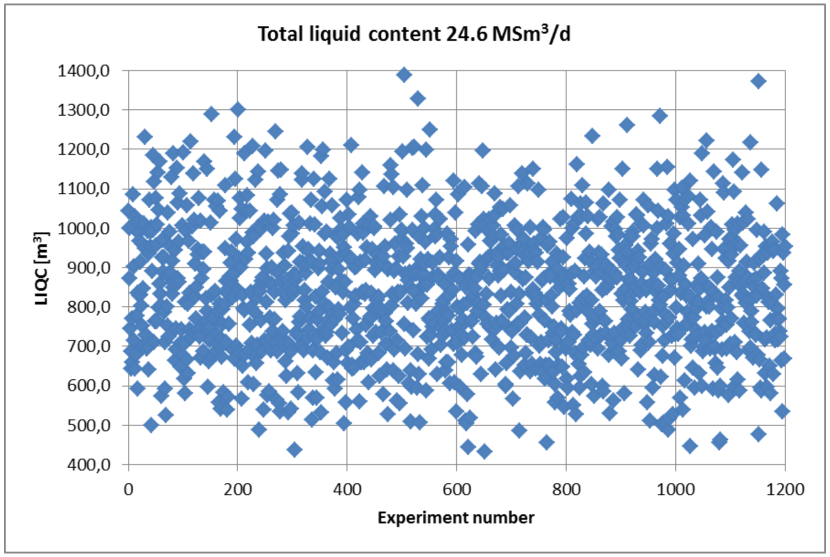


**Figure B 5: Scatter plot for total liquid content, 24.6 MSm$^3$/d**

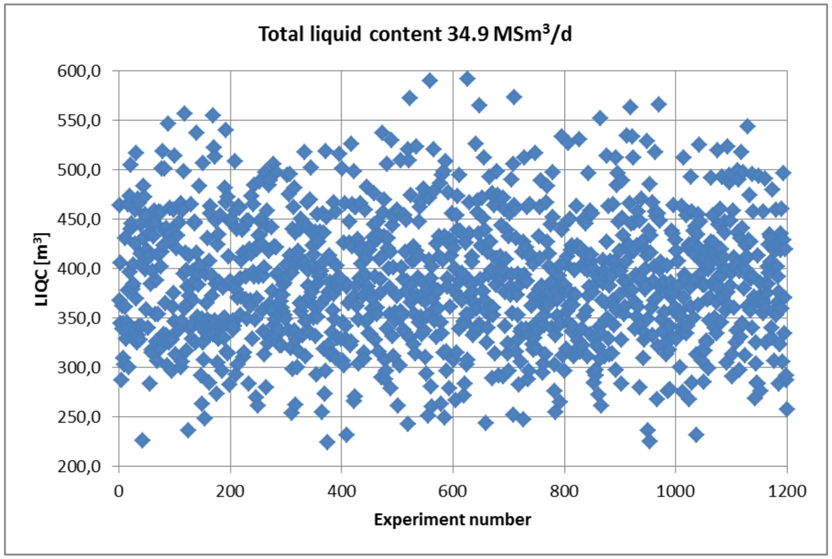


**Figure B 6: Scatter plot for total liquid content, 34.9 MSm$^3$/d**

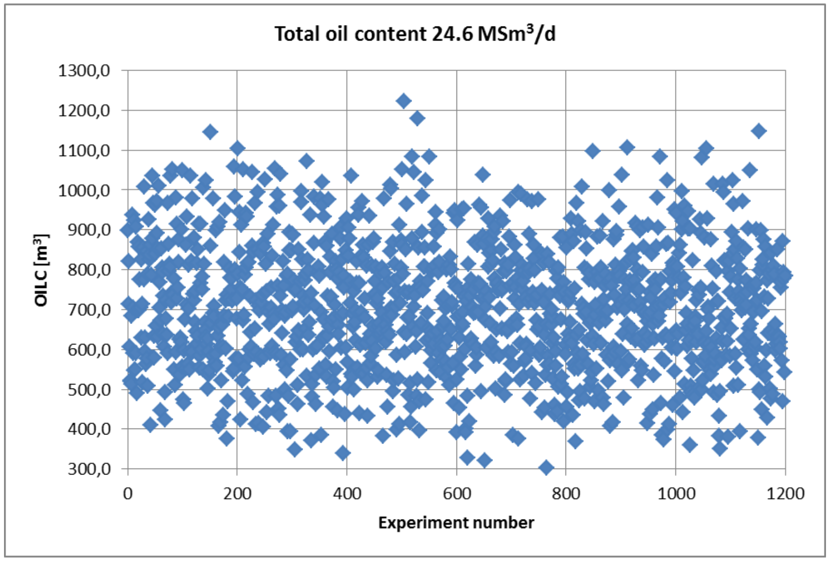


**Figure B 7: Scatter plot for total oil content, 24.6 MSm$^3$/d**

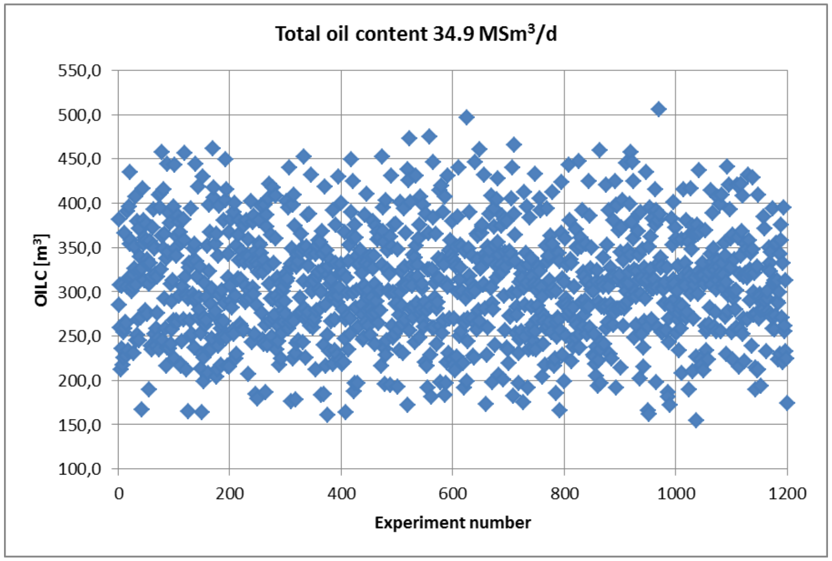


**Figure B 8: Scatter plot for total oil content, 34.9 MSm$^3$/d**

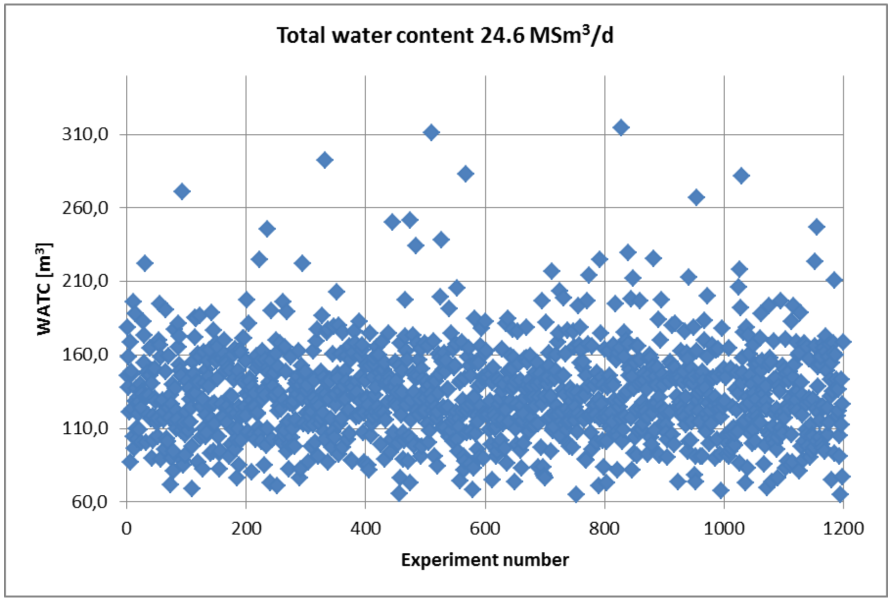


**Figure B 9: Scatter plot for total water content, 24.6 MSm$^3$/d**

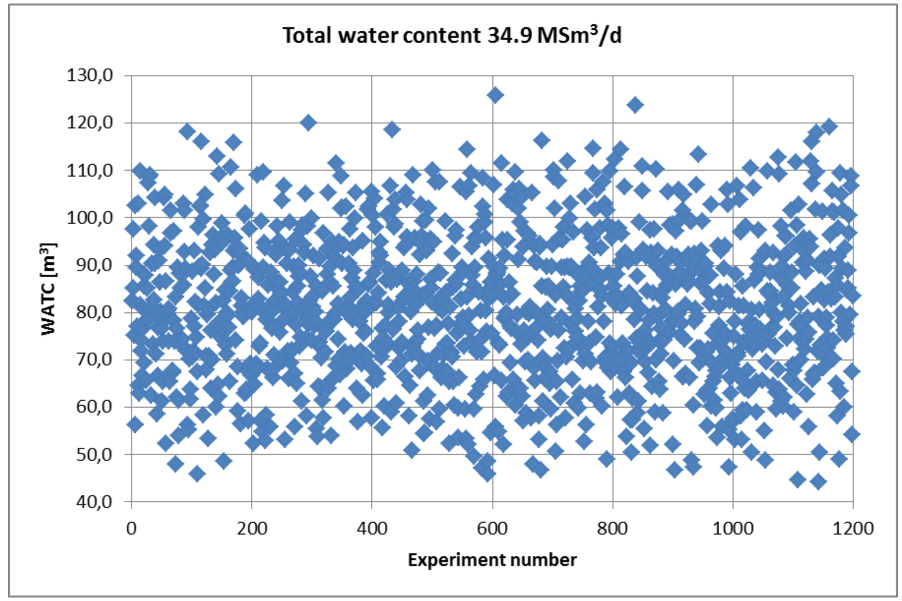


**Figure B 10: Scatter plot for total water content, 34.9 MSm$^3$/d**

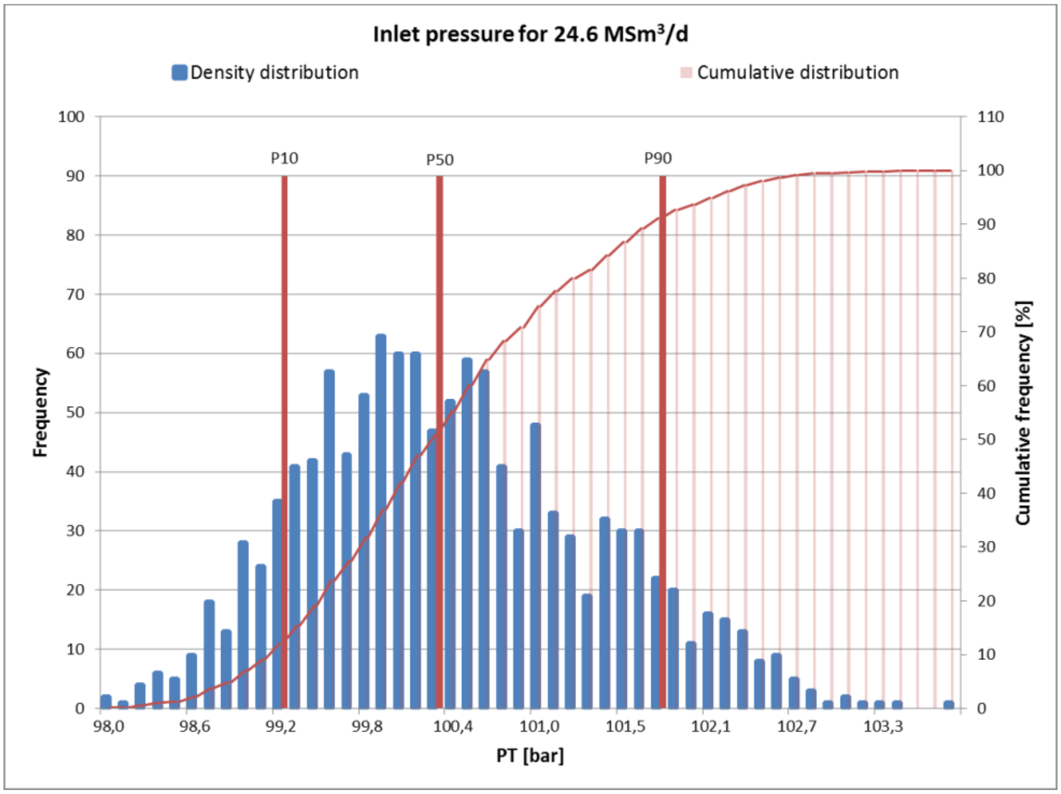


**Figure B 11: Distribution plot for inlet pressure, 24.6 MSm$^3$/d**

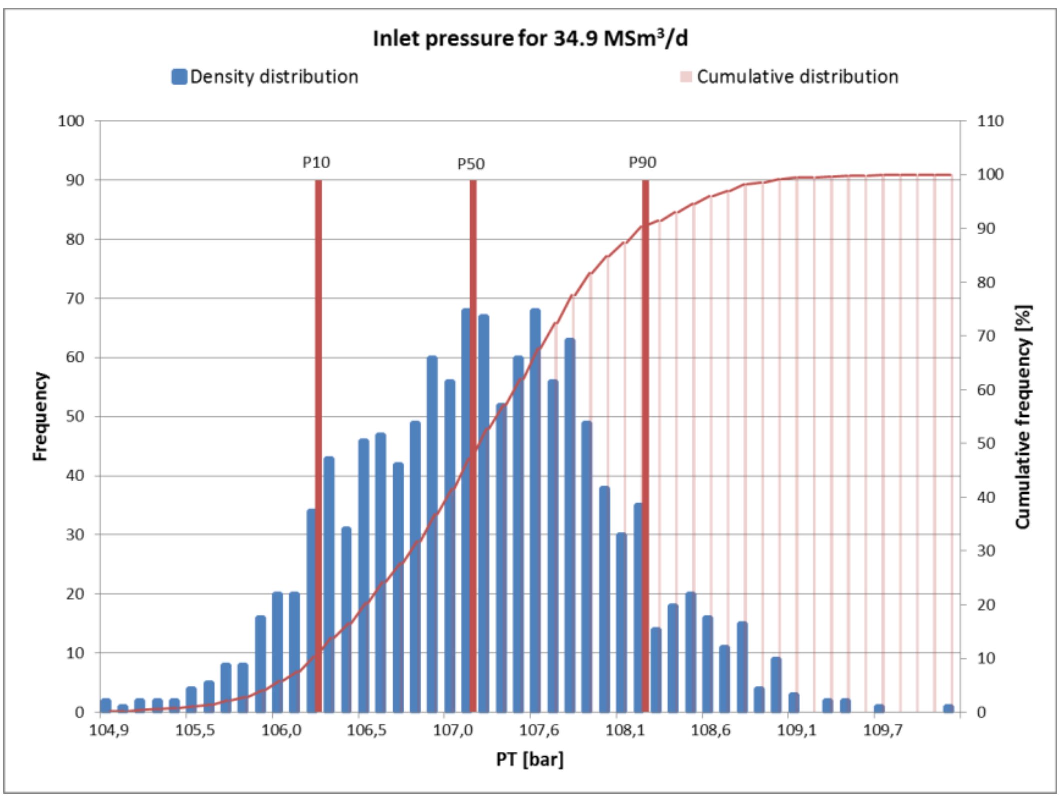


**Figure B 12: Distribution plot for inlet pressure, 34.9 MSm$^3$/d**

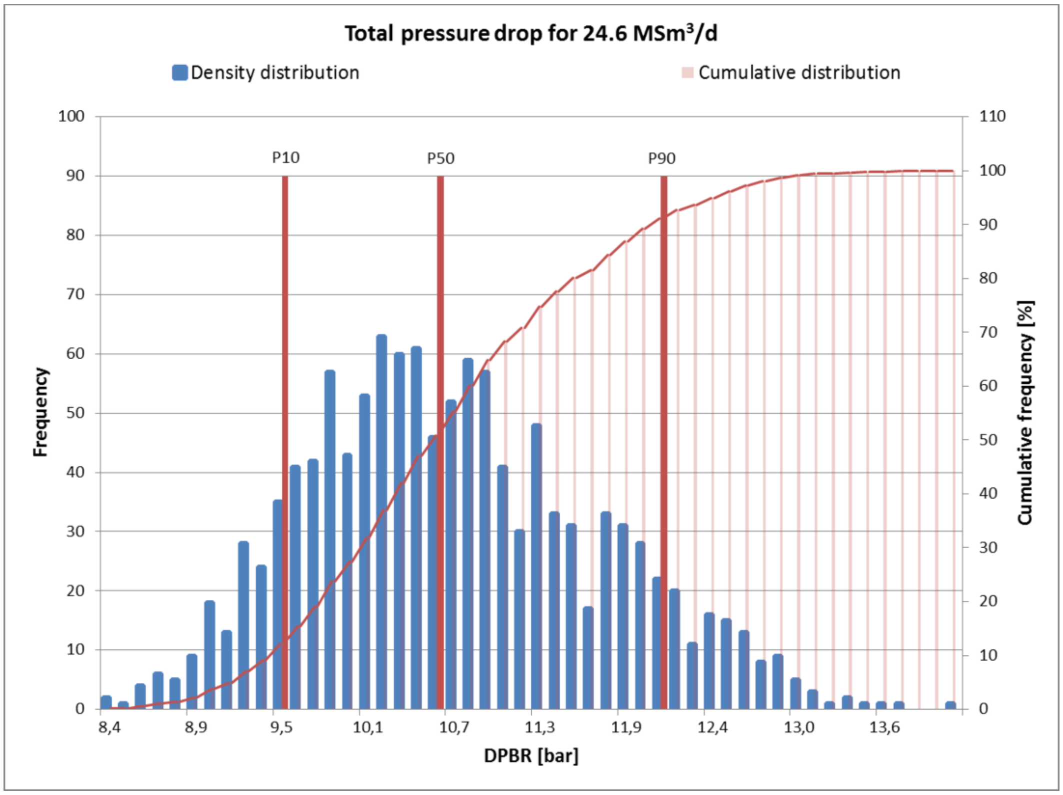


**Figure B 13: Distribution plot for total pressure drop, 24.6 MSm$^3$/d**

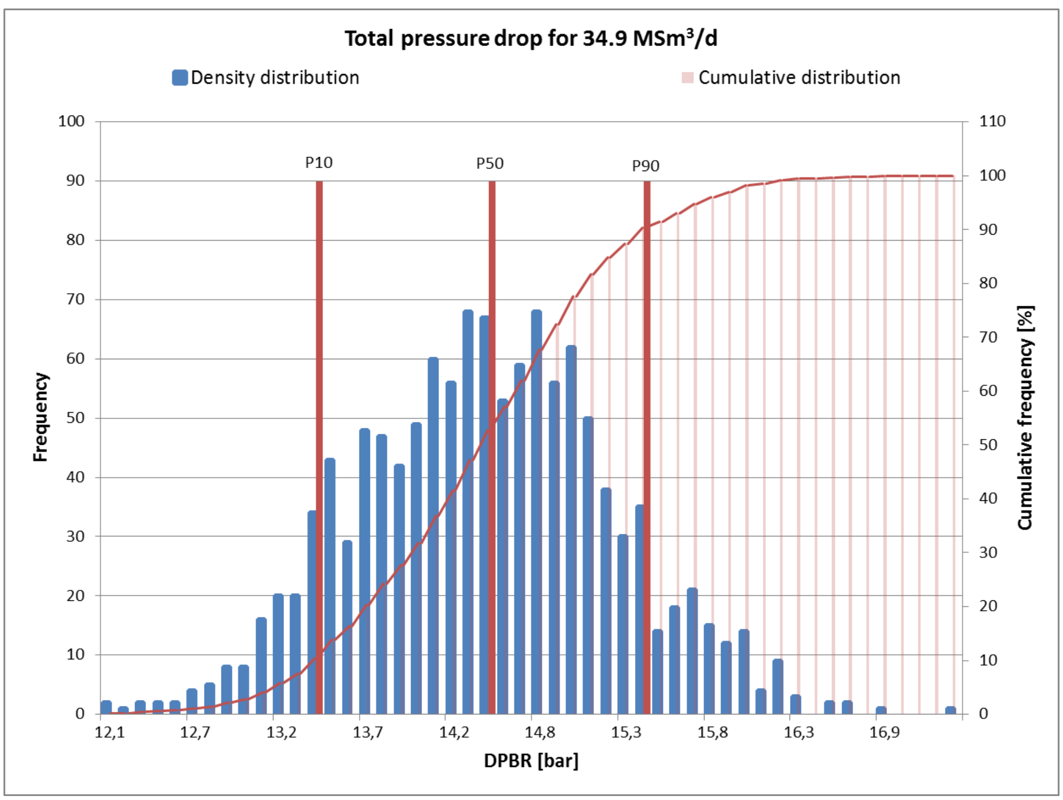


**Figure B 14: Distribution plot for total pressure drop, 34.9 MSm$^3$/d**

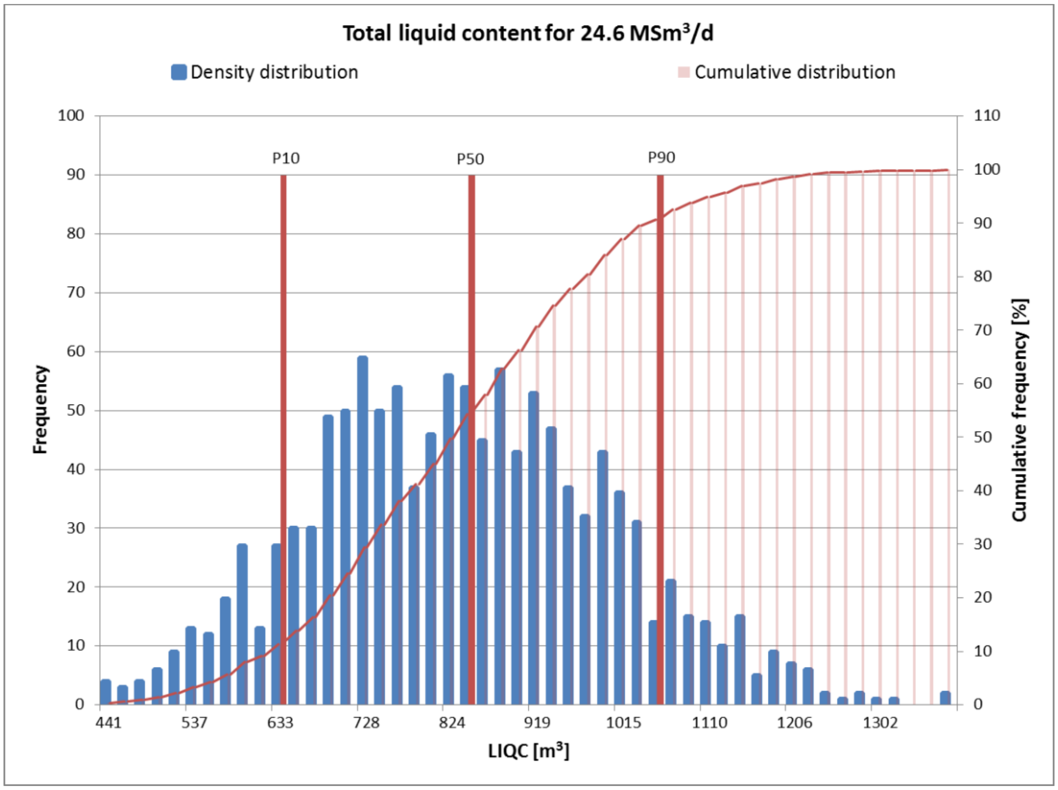


**Figure B 15: Distribution plot for total liquid content, 24.6 MSm$^3$/d**

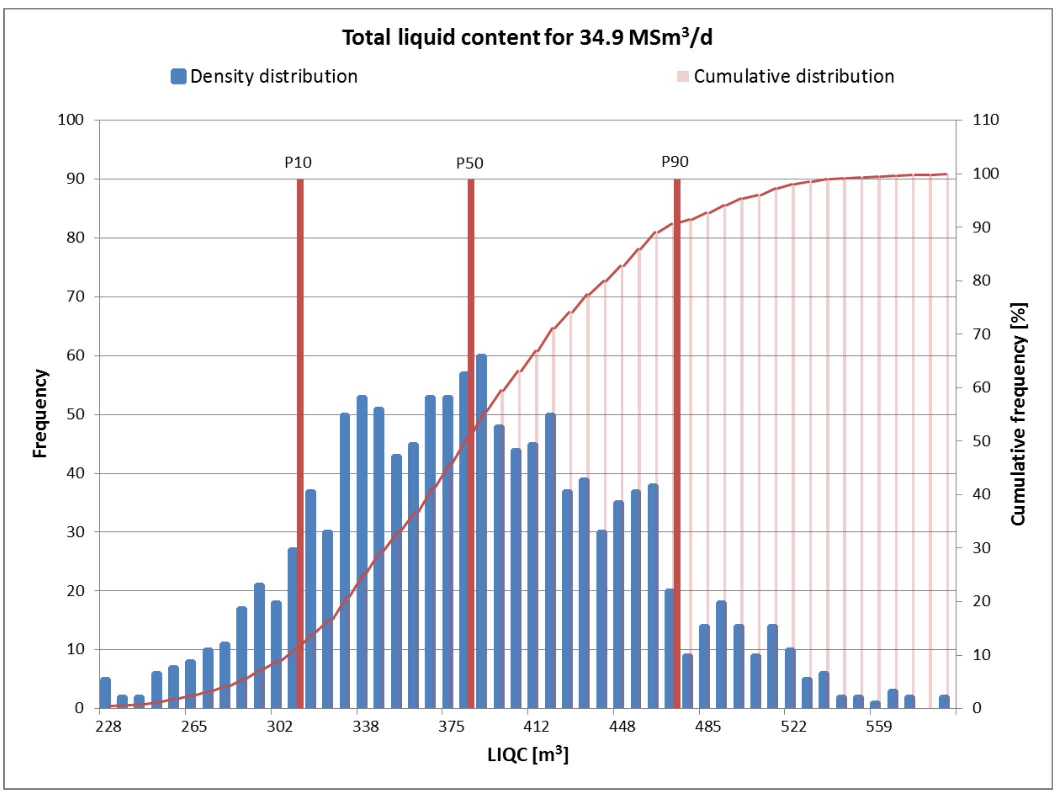


**Figure B 16: Distribution plot for total liquid content, 34.9 MSm$^3$/d**

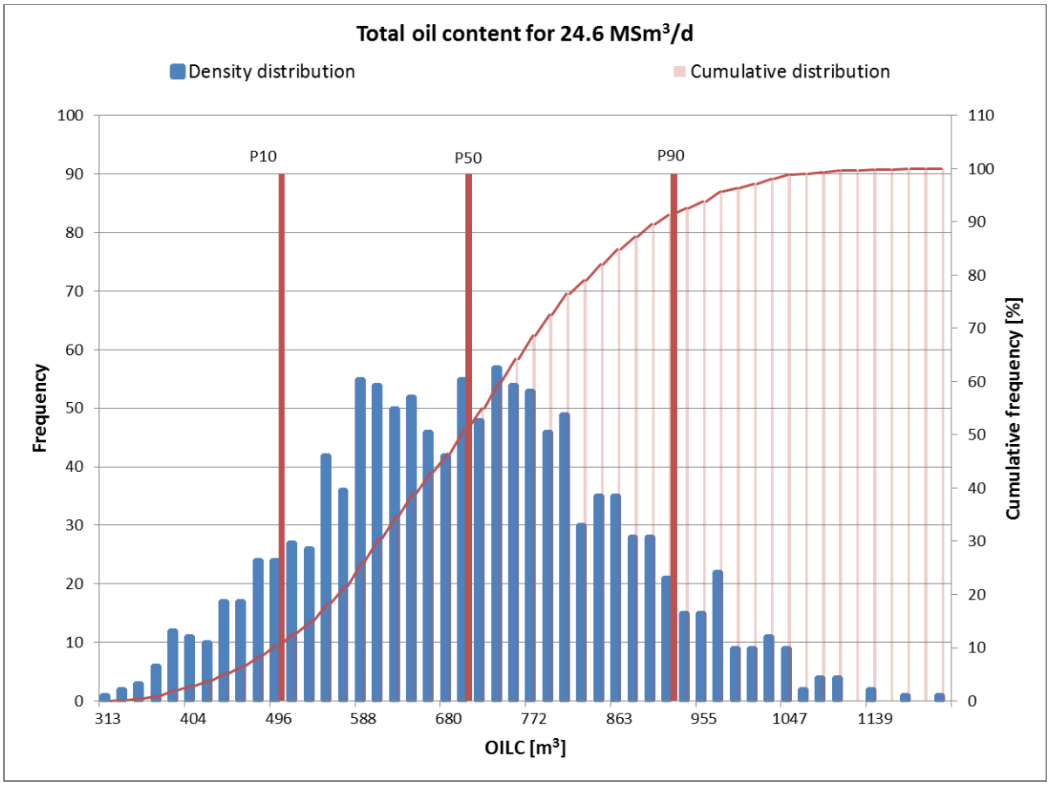


Figure B 17: Distribution plot for total oil content, 24.6 MSm$^3$/d

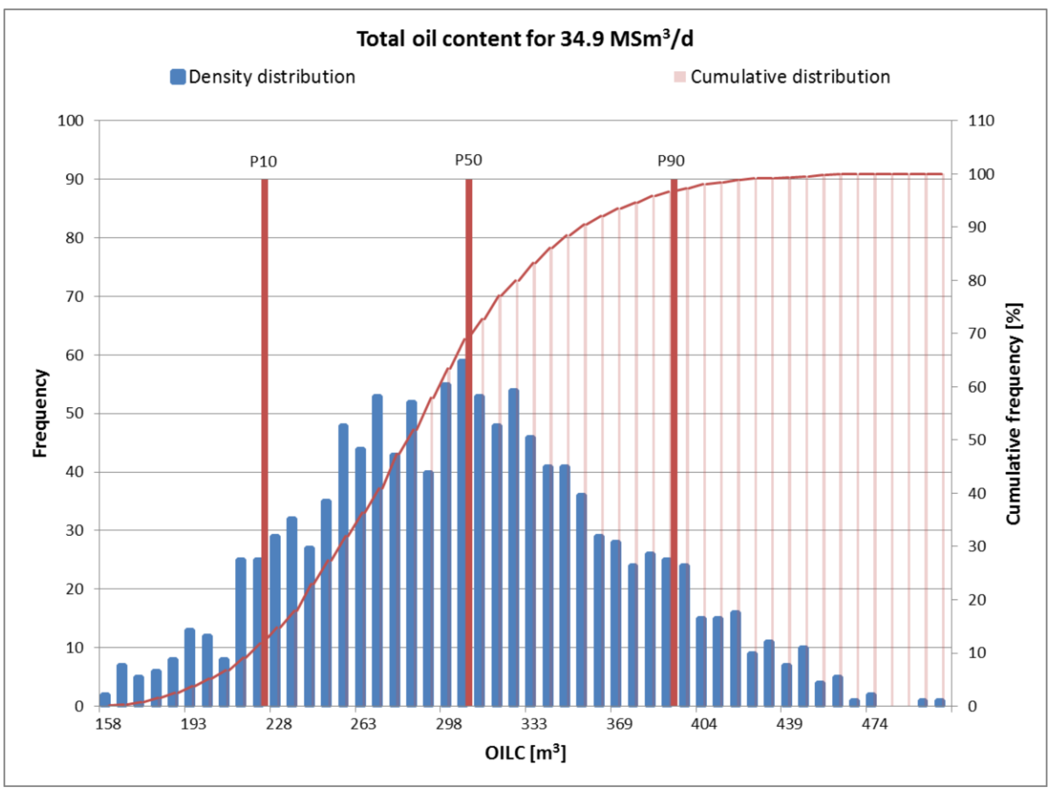


Figure B 18: Distribution plot for total oil content, 34.9 MSm$^3$/d

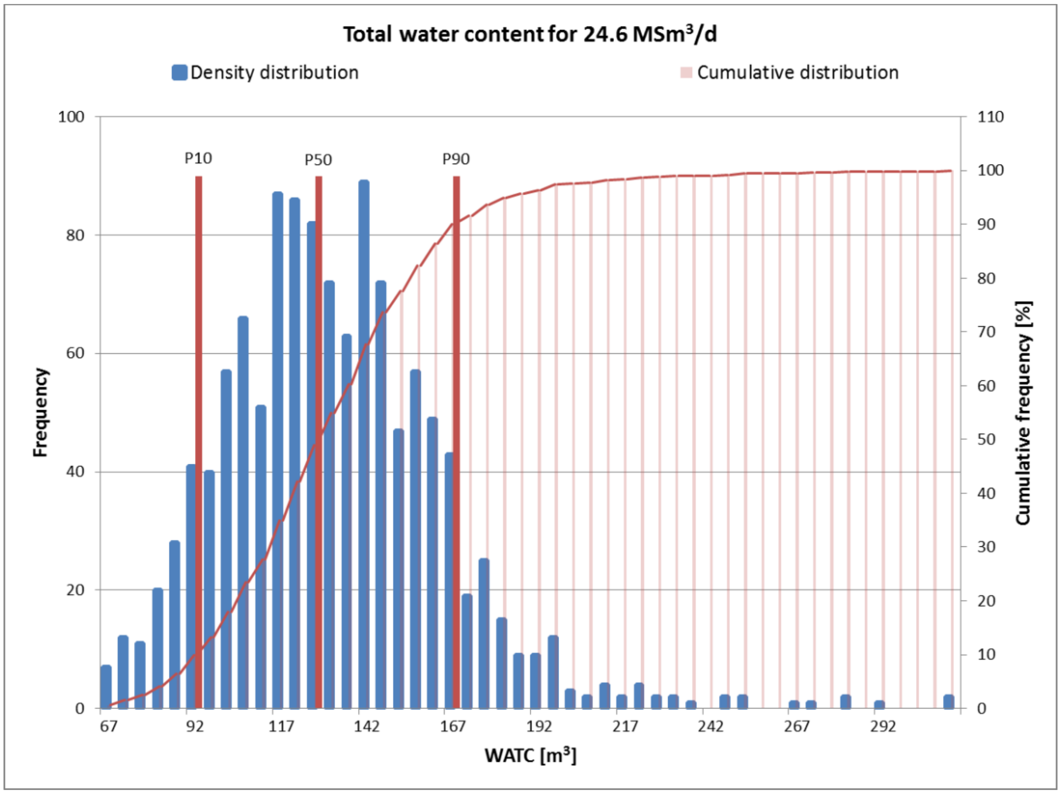


**Figure B 19: Distribution plot for total water content, 24.6 $MSm^3/d$**

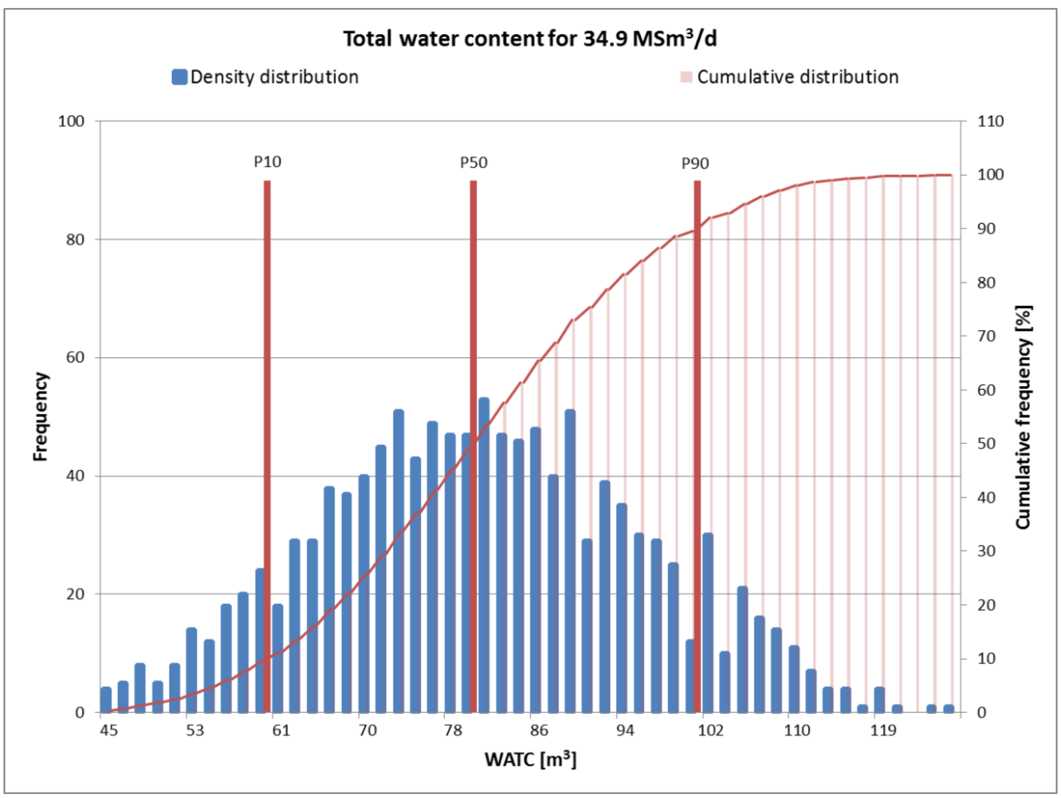


**Figure B 20: Distribution plot for total water content, 34.9 $MSm^3/d$**