Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Geoscience and Petroleum

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Optimized Design of Horizontal Gas-Oil-Water Gravity Separators

Master's thesis in Petroleum Geoscience and Engineering
Supervisor: Audun Faanes
Co-supervisor: Milan Stanko
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Trondheim, Date 11.06.2022
Elias Vølstad Bogen

Summary

The aim of this thesis is to present the implementation of a tool for optimizing design of horizontal gas-oil-water gravity separators. The work has been based on previous work done by Grødal & Realff (1999). Their work used a single case as input to find a design. This tool has been implemented in Excel by using the Visual Basic for Application (VBA). The tool can be used in the concept planning phase of the field development process.

The tool can optimize the cost or the footprint of the separator, meaning that the minimum of these variables can be found. The design is optimized by altering four design parameters: the inner diameter of the separator, the length of the gravity settling section of the separator, the normal liquid level and the normal oil-water interface level. A set of constraints ensure that the design is feasible and that all phases are separated. New variables and constraints have also been introduced after feedback with representatives from Equinor. The variables provide more design information and can be used to improve the design of separators in the early phase of a project. A proposed method to find a design for multiple cases has been implemented and tested.

Three case studies have been performed to test the tool. One case study has been done to compare the tool with results from the work of Grødal & Realff (1999). The tool gives the same results as Grødal and Realff report. The second case study has been conducted to test the tool with data from a field in real life. The data is from the Volve field in the North Sea. Five different cases have been run and a design that works for all five cases has been found. The final case study has compared the tool with a similar tool used by Equinor. One of the cases from the Volve field was used as input and the tools give very similar results.

Sammendrag

Denne oppgaven sikter på å presentere arbeidet for hvordan et verktøy for optimalisert design av horisontale gass-olje-vann gravitasjonsseparatorer har blitt implementert. Arbeidet har blitt basert på tidligere arbeid av Grødal & Realff (1999). Tidligere arbeid bruker en enkelt case som input for å finne et design. Verktøyet har blitt implementert i Excel ved hjelp av Visual Basic for Application (VBA). Verktøyet kan bli brukt i konseptplanleggings fasen av feltutvikingsprosessen.

Verktøyet kan optimere kostnaden eller avtrykket av separatoren, med andre ord er minimumet av disse variablene funnet. Designet er optimert ved å endre fire design parametere: den indre diameteren av separatoren, lengden av gravitasjonsseparasjon seksjonen av separatoren, normal væske-nivået og normal olje-vann grensesnitt-nivået. Ett sett med begrensninger passer på at designet er gjennomførbart og at alle faser er separert. Ny variabler og begrensninger har blitt introdusert etter tilbakemeldinger fra representer fra Equinor. Variablene gir mer informasjon om designet og kan bli brukt til å forbedre design for separatorer i en tidlig fase av prosjektet. En metode for å finne design for flere caser har blitt implementert og testet.

For å studere hvordan verktøyet fungerer har case studier blitt gjennomført. En har blitt gjort for å sammenligne verktøyet med resultatene fra arbeidet til Grødal & Realff (1999). Verktøyet gir samme resultater som Grødal og Realff rapporterer. Den andre case studien har blitt gjort for å teste verktøyet med data fra et felt i virkeligheten. Dataene er fra Volve feltet i Norskehavet og fem forskjellige caser har blitt kjørt. Et design som fungerer for alle fem casene har blitt funnet. Den siste case studien har sammenlignet verktøyet med et lignende verktøy brukt av Equinor. En av casene fra Volve feltet ble brukt som input og verktøyene gir veldig like resultater.

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1 Introduction

Separation is an important process when producing hydrocarbons. The hydrocarbons are stored in reservoirs deep below the surface. To get access to the hydrocarbons wells are drilled from the surface and down to the reservoir. The reservoirs often have high pressure and high temperature. But every reservoir is different and the properties change over time. As every reservoir is different, each one brings a new challenge. Some reservoirs have gas, oil and water while others only have two phases. During the lifetime of a field the reservoir pressure decreases, which limits further movement of the hydrocarbons. When producing the hydrocarbons from the reservoir all the fluids are transported through pipes up to the surface. When reaching the surface it is normally desired to separate the phases. The phases can be separated by using one or several tank separators. A tank separator will typically be installed on a platform when producing from an offshore field or on the ground when producing from an onshore field. The end products after the separation process are gas free from oil and stabilized oil.

The fluids enter the tank separator from one end through an inlet pipe. First the fluids are handled by an inlet device which starts to separate the phases. A cyclone is an example of such an inlet device. After leaving the inlet device the fluids start to flow though the separator from one end towards the other. Fluids segregate by the gravity force. The gas flows upwards, the oil stays in the middle while the water sinks to the bottom of the separator. In the outlet end of the separator there are two or three outlet pipes. Each phase leaves the separator through its own pipe separated from the other phases. 100 % separation is usually not possible to achieve, so there is some residual for example oil droplets in water, water droplets in oil and so on.

Several (two or three) separators can be chained together. Each separator has different operation condition and make up a stage. For each stage that the fluids pass through the pressure and temperature decrease. For a three stage system the separator in the first stage has high pressure, the second stage has medium pressure and the last stage has low pressure. In the first separator all phases can be present, while there may only be two phases present in the separators later in the chain.

Selection of a correct design for the separators is important. They have to be large enough to perform the separation efficiently. If the separator is designed inappropriate, the separator will not fulfill its purpose efficiently. For example, if too small, there won't be enough time for the phases to separate and there will be significant contamination in the outlet streams. A larger design gives more weight and larger footprint. This increases the requirements for the structures that will bear the separator and will increase the weight and footprint even more. It is therefore desired that the design is not too large.

The goal of this report is to implement a design tool for horizontal gravity based vessel separators. It is a continuation of the project report on "Optimized Design of Horizontal Gas-Oil Gravity Separators" (Bogen 2021) where a design tool for two phase gas-oil separators was implemented. In this report the tool is extended to three phase gas-oil-water horizontal separators. The tool is implemented based on previous work by Grødal & Realff (1999). Modifications and improvements are made after discussions and input from Equinor and supervisors. After implementing the tool, the report focuses on testing the tool. Cases studies are performed to compare the tool with previous work, another tool, and use input parameters from different periods of the production profile from an actual field. The report is written as part of the course "TPG 4920 - Petroleum Engineering, Master's Thesis".

- In the theory section the theory behind separators is presented. In addition, theory of the black oil model, optimizing and field development is presented.
- In the methodology section the methodology for using the theory to implement the tool is presented. The three case studies and the input parameters are also presented here.
- In the tool results section the tool is presented with screenshots of the Excel-sheet. Both the original tool based on earlier work and the improvements are presented and discussed.
- In the case studies results section the results from the three case studies are presented and discussed.
- The conclusions are presented in the conclusion section.
- Recommendations for further work are presented in the further work section.

1.1 List of abbreviations

Below the abbreviations are explained. First is the symbol, then the meaning of the symbol. After that comes the unit type and which units that are used. Last comes the SI-unit for the symbol. Take A as an example: A is the symbol, *cross-sectional area of separator between BV to level indicated by the subscript* is the explanation, $\mathscr{L}$ is the unit type and $\mathscr{m}$ is the SI-unit. The different unit types are listed in Table 1.1.

Table 1.1: Unit types

Unit type	Meaning
$\mathscr{L}$	Length
$\mathscr{M}$	Money
$\mathscr{m}$	Mass
$\mathscr{dimensionless}$	No dimension
$\mathscr{t}$	Time
$\mathscr{degrees}$	Angle degrees

First is the nomenclature listed in Section 1.1.1, then the Greek Letters in Section 1.1.2 and the subscripts in Section 1.1.3. The list of abbreviations is from Grødal & Realff (1999).

1.1.1 Nomenclature

A = cross-sectional area of separator between BV to level indicated by the subscript, $\mathscr{L}^2$, m^2

C = separator manufacturing cost, $\mathscr{M}$, \$

C_D = spherical drag coefficient, *dimensionless*

D = total separator diameter, $\mathscr{L}$, m

D_H = hydraulic diameter, $\mathscr{L}$, m

D_i = inner separator diameter, $\mathscr{L}$, m

D_m = mean separator diameter, $\mathscr{L}$, m

d = droplet/bubble diameter, $\mathscr{L}$, m

E = joint efficiency, *dimensionless*

F_a = factor for determining surface area of a vessel head from vessel diameter squared (≈ 1.09 for $2:1$ elliptical heads), *dimensionless*

F_c = cost factor per unit mass to manufacture a vessel shell, $\mathscr{M}/m$, \$/kg

F_h = ratio of cost per unit mass to manufacture a vessel head compared with that of vessel shell usually 1.5 to 3.0), *dimensionless*

g = gravitational acceleration, $\mathscr{L}/t^2$, m/sec^2

h = height from bottom of separator, $\mathscr{L}$, m

L = length, $\mathscr{L}$, m

L_b = interbaffle distance, $\mathscr{L}$, m

L_c = length of separator section with cyclone, $\mathscr{L}$, m

L_e = length of gravity separation section, $\mathscr{L}$, m

L_h = separator head section length, $\mathscr{L}$, m

L_n = length of separator end section, $\mathscr{L}$, m

L_{vx} = length of vane demister, $\mathscr{L}$, m

L_{vz} = width of vane demister, $\mathscr{L}$, m

N_{Re} = droplet or bubble Reynolds number, *dimensionless*

N_{Ref} = Reynolds film number, *dimensionless*

N_μ = interfacial viscosity number, *dimensionless*

P = wetted perimeter, $\mathscr{L}$, m

p = operating pressure, $m/\mathscr{L}t^2$, $\mathscr{P}a$

p_D = design pressure, $m/\mathscr{L}t^2$, $\mathscr{P}a$

q = volumetric rate, $\mathscr{L}^3/t$, m^3/sec

t = time, $\mathscr{t}$, $\mathscr{sec}$

t_c = corrosion allowance, $\mathscr{L}$, $\mathscr{m}$

t_{cs} = wall thickness of cylindrical section, $\mathscr{L}$, $\mathscr{m}$

t_r = retention time in L_e, $\mathscr{t}$, $\mathscr{sec}$

u = velocity, $\mathscr{L}/\mathscr{t}$, $\mathscr{m}/\mathscr{sec}$

u_{gmax} = maximum gas velocity ahead of vane demister, $\mathscr{L}/\mathscr{t}$, $\mathscr{m}/\mathscr{sec}$

$u_{r\,\text{max}}$ = maximum relative velocity between gas and oil $\mathscr{L}/\mathscr{t}$, $\mathscr{m}/\mathscr{sec}$

1.1.2 Greek Letters

α = pitch degree, $\mathscr{degrees}$

μ = dynamic viscosity, $\mathscr{m}/\mathscr{Lt}$, $\mathscr{kg/msec}$

ρ = density, $\mathscr{m}/\mathscr{L}^3$, $\mathscr{kg/m}^3$

σ = tensile strenght, $\mathscr{m}/\mathscr{Lt}^2$, $\mathscr{Pa}$

σ_{og} = surface tension between oil and gas, $\mathscr{m}/\mathscr{t}^2$, $\mathscr{kg}/\mathscr{sec}^2$

Δh_{NOR} = height interval NORSOK standard, $\mathscr{L}$, $\mathscr{m}$

Δh_s = safety margin height, $\mathscr{L}$, $\mathscr{m}$

Δt_{NOR} = time interval NORSOK standard, $\mathscr{t}$, $\mathscr{sec}$

1.1.3 Subscripts

$BV =$ bottom vessel
$g =$ gas
$go =$ gas bubble in oil phase
$HHIL =$ high-high interface level
$HHLL =$ high-high liquid level
$HIL =$ high interface level
$HLL =$ high liquid level
$i =$ the set $\{HHLL, HLL, NLL, LLL\}$
$j =$ the set $\{HLL, NLL, LLL, LLLL\}$
$LIL =$ low interface level
$LLIL =$ low-low interface level
$LLL =$ low liquid level
$LLLL =$ low-low liquid level
$NIL =$ normal interface level
$NLL =$ normal liquid level
$o =$ oil
$og =$ oil droplet in gas phase
$ow =$ oil droplet in water phase
$p =$ the set $\{HHIL, HIL, NIL, LIL\}$
$q =$ the set $\{HIL, NIL, LIL, LLIL\}$
$S =$ steel
$TV =$ top vessel
$u =$ the set $\{HLL, NLL, HIL, NIL\}$
$v =$ the set $\{NLL, LLL, NIL, LIL\}$
$vdi =$ vane demister inlet
$vdm =$ vane demister mounting point
$vdo =$ vane demister outlet
$WH =$ weir
$w =$ water
$wo =$ water droplet in oil phase

2 Theory

2.1 Theory Behind Separators

The formulas and the theory behind presented in this section are mainly from Grødal & Realff (1999). The theory presented can be used for both two and three phase separators. Most of the theory in this section was also presented in the project report by Bogen (2021), but was more focused on two-phase separators then.

2.1.1 Settling Theory

The settling theory considers the horizontal velocities for the different phases in the different layers (gas, oil and water) through the separator. They are compared to the settling velocities of the droplets and bubbles in the separator. If the horizontal velocities are greater than the settling velocities, this means there is not enough time to ensure separation. If the horizontal velocities are smaller than settling velocities, there is enough time to ensure separation. To find the settling velocity for one droplet or bubble one has to look at the forces that are acting on that droplet or bubble. All droplets and bubbles are assumed to be spherical. In Figure 2.1 the forces acting on a liquid droplet moving in the gas layer is viewed. It will be the same for a gas bubble in the liquid phase but the gas bubble will move upwards.

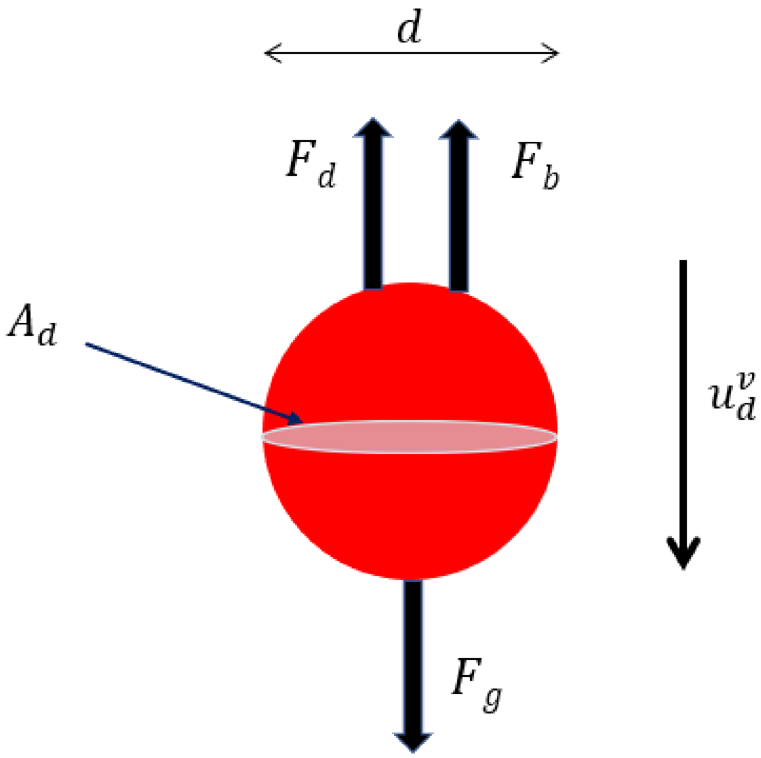

Figure 2.1: Forces acting on a droplet moving downwards in a continuous fluid.

A_d is the cross sectional area of the droplet, d is the diameter of the droplet, F_d is the drag force acting on the droplet, F_g is the gravity force acting on the droplet, F_b is the buoyancy force acting on the droplet and u_d^v is the settling velocity of the droplet.

Since the liquid droplet has a higher density than the gas, the gravitational force will be larger than the buoyancy force. Therefore the gravity force will accelerate the droplet while the buoyancy force will work against this acceleration. The droplet will start to move and when the velocity is increasing the drag force will also start to increase. When the sum of forces, Equation (2.1), equals zero the velocity will become constant and the settling velocity is reached. For gas bubbles in liquid the buoyancy force will be larger than the gravitational force and the droplet will move upwards.

$$(\uparrow +) \sum F = F_b + F_d - F_g \tag{2.1}$$

The arrow indicates that the positive direction is set upwards. The forces are given with the Equations (2.2) - (2.4).

$$F_b = \rho_c g V_d \tag{2.2}$$

$$F_d = C_D A_d \frac{1}{2} \rho_c (u_v^d)^2 \tag{2.3}$$

$$F_g = \rho_d g V_d \tag{2.4}$$

V_d is the volume of a droplet or bubble, g is the gravitational acceleration (9.81 m/s^2), ρ_d is the density of the bubble or droplet and ρ_c is the density of the continuous phase. When the sum of forces equals 0, Equation (2.1) - (2.4) can be combined to give an expression for the settling velocity for a droplet or bubble in a continuous phase. This is given in Equation (2.5).

$$u_d^v = \left[\frac{4}{3} \frac{d}{C_D} g \frac{\rho_d - \rho_c}{\rho_c} \right]^{0.5} \tag{2.5}$$

d is the diameter of the droplet or bubble and C_D is the spherical drag coefficient. The spherical drag coefficient can be found with Equation (2.6).

$$C_D = \frac{24}{N_{Re}} + \frac{3}{\sqrt{N_{Re}}} + 0.34 \tag{2.6}$$

N_{Re} is the droplet Reynold's number and can be found with Equation (2.7).

$$N_{Re} = \frac{\rho_c u_d^v d}{\mu_c} \tag{2.7}$$

μ_c is the dynamic viscosity of the gas. In Equation (2.5) one can see that the settling velocity is one of the parameters to determine the droplet Reynold's number. The settling velocity depends on the spherical drag coefficient, which again depends on the droplet Reynold's number. So a iterative method has to be used to find the settling velocity.

In total there are 6 different settling velocities in a three phase separator that must be considered.

- Water droplet settling in continuous gas phase
- Oil droplet settling in continuous gas phase
- Water droplet settling in continuous oil phase

- Gas bubble settling in continuous oil phase
- Oil droplet settling in continuous water phase
- Gas bubble settling in continuous water phase

For a two phase oil-gas separator only two settling velocities has to be considered. The oil droplet settling in continuous gas phase and the gas bubble settling in continuous oil phase. For a three-phase gas-oil-water separator three phases have to be considered. Oil droplet settling in continuous gas phase, water droplet settling in continuous oil phase and oil droplet settling in continuous water phase.

2.1.2 Separator Levels

Figure 2.2 shows a typical 3 phase separator. D is the inner diameter of the separator. The liquid level is the intersection between the gas phase and oil phase. The interface section is the intersection between the oil phase and the water phase. In a 2 phase gas-oil separator, there is no interface level, only a liquid level.

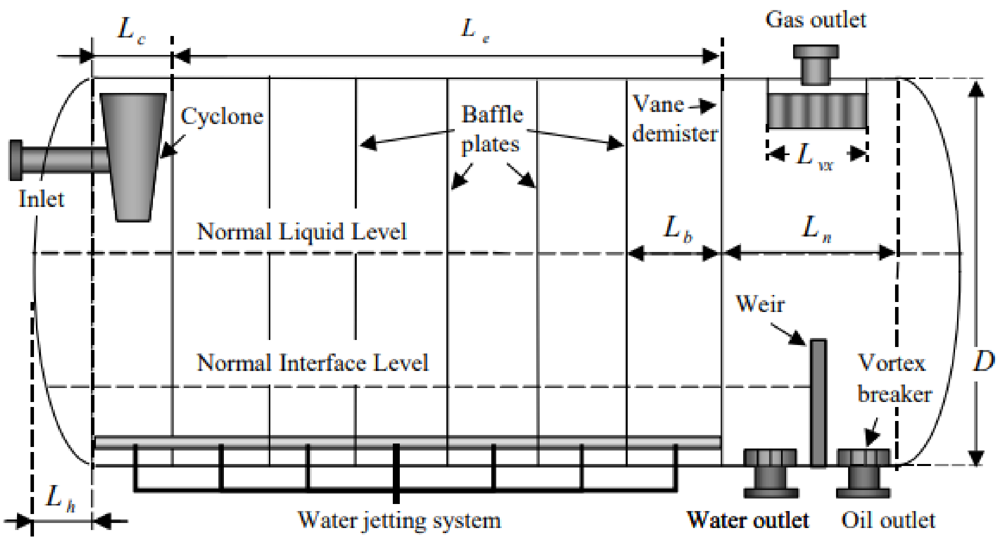

Figure 2.2: 3 phase separator (Grødal & Realff 1999)

The flow enters the separator through the inlet and goes to the cyclone. The cyclone absorbs the fluid momentum and directs the gas to go upwards and the liquid to go downwards. After leaving the cyclone and the inlet section with length L_c, the fluids enter the gravity settling section with length L_e. This is the main part of the separator and here the fluid will settle in accordance with the theory in Section 2.1.1. The interbaffle distance, L_b, is the distance between the baffle plates that are placed in the gravity settling section. The baffle plates are perforated and helps to direct the fluids on a offshore moving vessel. L_h is the separator head length and D is the diameter of the separator.

After leaving the gravity settling section the fluids enters the end section, L_n. In the end section the outlets, a vane demister and a weir are located. The weir stops the water from flowing to the end of the separator and enter the oil outlet. The water will therefore leave the separator through the water outlet. The oil phase will flow over the weir and leave through the oil outlet. The oil and water nozzles are equipped with vortex breakers to remove gas bubbles. Before the gas can reach the gas outlet it has to pass through a vane demister. The gas passes through, but the small liquid droplets that has been travelling with the gas will get separated from the gas. When enough liquid droplets is assembled it will fall down from the vane demister and be a part of the liquid phase. Then it will leave through one of the other outlets.

The liquid level is where the gas phase and the oil phase intersect and the interface level is where the oil phase and the water phase intersect. These will change with the flow into the separator and the composition of the flow. Nominal levels are selected and the flow out of the separator is regulated to keep the levels and pressure stable. If the liquid rates increase the liquid level will also increase. The regulator will work to bring the liquid level back by opening the valve of the liquid line or by increasing the frequency of the pump on the liquid line and after some time the initial liquid level is reached again. If the gas rate increases the separator pressure will increase and the regulator will increase the gas rate out of the separator by opening the control valve on the gas line. If the regulators are perfect the levels will be constant, and the rate variations will propagate through the system. In real life it is very difficult to obtain a perfect regulator. If the rates in to the separator change all the time, the levels will also go up and down. As long as the levels are inside the alarm levels the separator will handle this and the variations will be smaller downstream the separator.

When the fluids enter the separator it will flow from the inlet part of the separator to the outlet part. The different fluids will flow with different horizontal velocities. This is captured in Figure 2.3. In real life the velocity will vary within different positions for a liquid. The velocity will be lower close to the walls and close to another phase that has lower velocity. For phases that have lower velocity than the phase next to it the velocity will be higher closer to the other phase. So the transition from one velocity that one phase has is in real life will be gradual. For simplicity it is here assumed that the velocity is constant through the whole phase and only changes at the borders where two phases meet. The plug flow assumption means that settling bubbles and droplets will have a linear settling path.

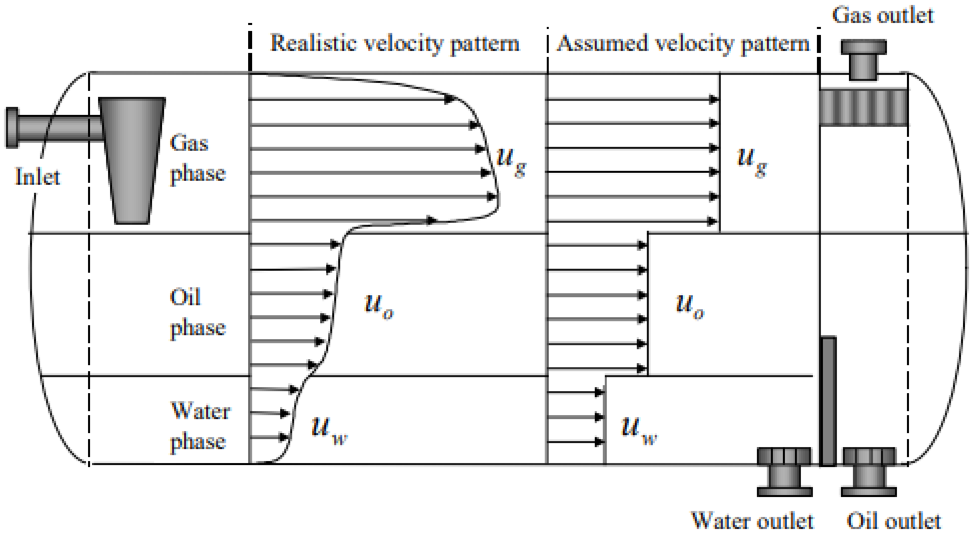

Figure 2.3: Horizontal velocity for the different phases (Grødal & Realff 1999).

u_g is the horizontal velocity for the gas phase, u_o is the horizontal velocity for the oil phase and u_w is the horizontal velocity for the water phase.

Both the liquid and the interface have four different alarm levels. When the height of the liquid increases it will reach the high liquid level and trigger an alarm. If it increases further and reach the high-high level, the separator will shut down. The same system of levels are for low and low low. If the liquid height decreases and reach the low level an alarm will go off. If the liquid height continues to decrease and reach low-low level the whole system will shut down. The same is applied to the interface level and can be seen in Figure 2.4. The abbreviations used in Figure 2.4 are listed in Table 2.1.

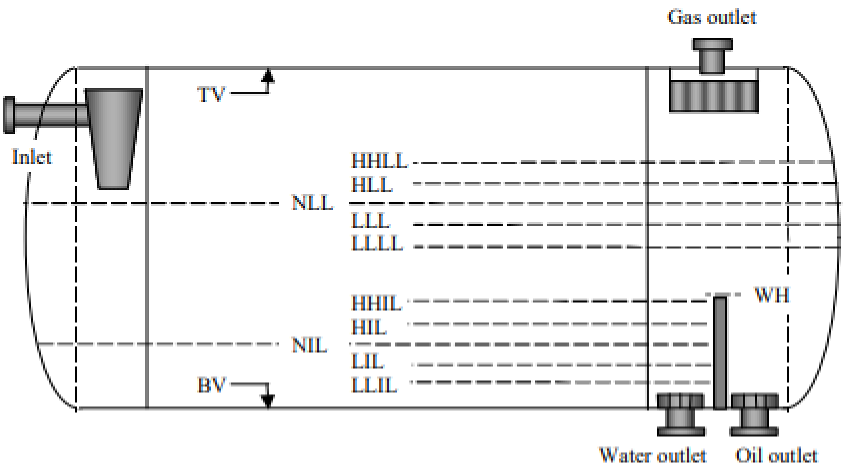

Figure 2.4: Liquid and Interface levels in separators (Grødal & Realff 1999).

Figure 2.5 shows a cross section of the separator the separator is seen from the end. The liquid levels and the areas can be seen in the six different sub figures. Each area is from the given height and down to the bottom of the separator. The sub figure up to the left

HHLL	high-high liquid level	HHIL	high-high interface level
HLL	high liquid level	HIL	high interface level
NLL	normal liquid level	NIL	normal interface level
LLL	low liquid level	LIL	low interface level
LLLL	low-low liquid level	LLIL	low-low interface level
TV	top of vessel	WH	weir
BV	bottom of vessel		

Table 2.1: Abbreviations for liquid and interface levels.

show the area of low-low liquid level, the one up to the right show the area of low liquid level and in the middle are the area of normal and high liquid level. The one down to the left show the the area of high-high liquid level and the one down to the right show the area of the whole pipe.

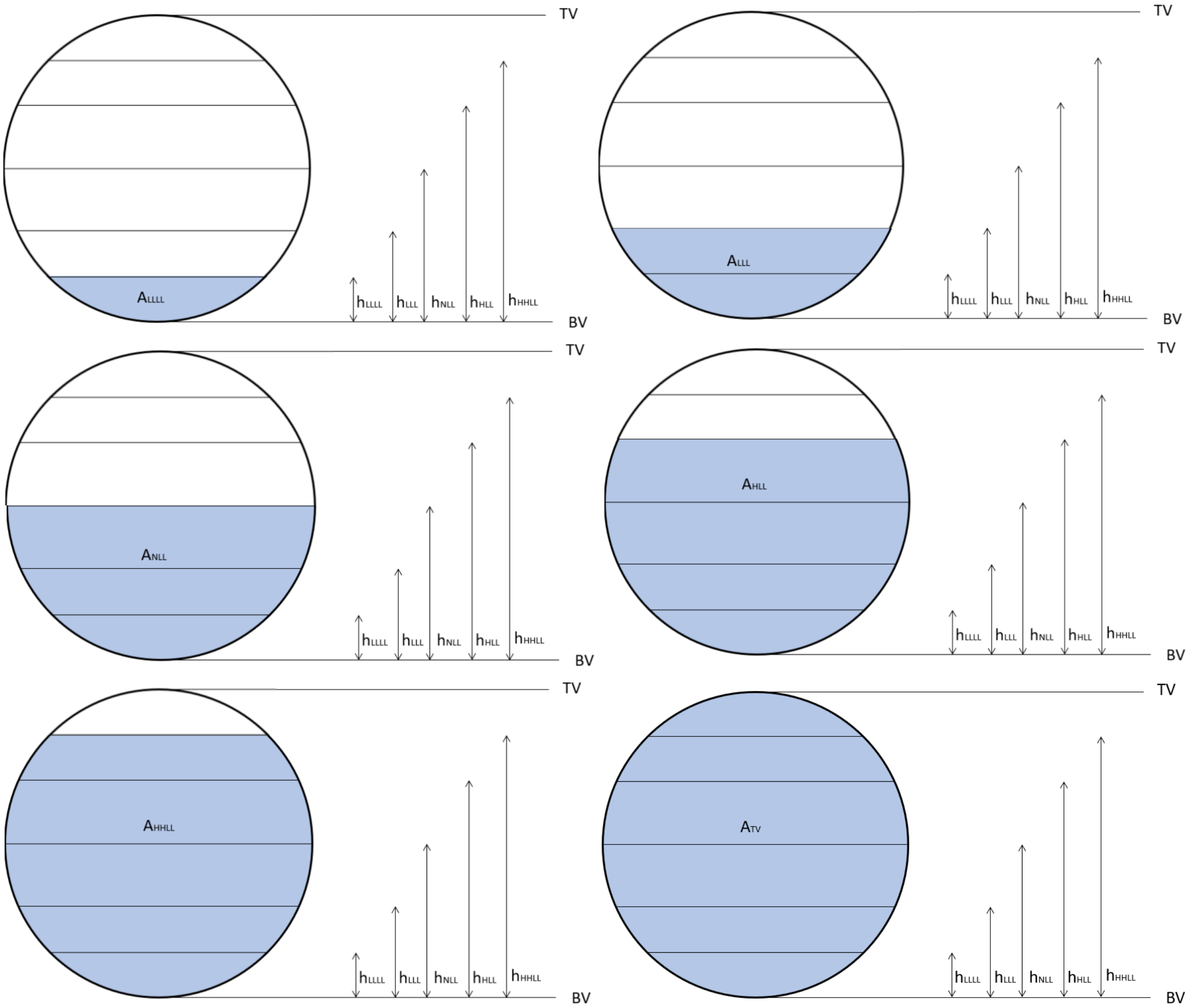

Figure 2.5: Areas and heights for the liquid levels and a full separator (Bogen 2021).

Figure 2.5 only shows the areas for a two phase separator. For a three phase separator the interface levels will be below the liquid levels and the areas for the interface levels are defined in the same way.

To know how much time the separation takes the critical settling path is needed. The critical settling path is the longest distance a bubble or droplet will have to travel in order to reach its phase. A water droplet will have the longest way from the top of the gas phase. It will have to travel through both the gas and the oil phase to reach the interface level. An oil droplet in the gas phase has to travel through the gas phase to the oil phase. An oil droplet in the water phase has to travel to the water phase to the oil phase. A gas bubble in the water phase will have to travel through the water phase and the oil phase to the gas phase. The different critical settling paths are visualized in Figure 2.1.2.

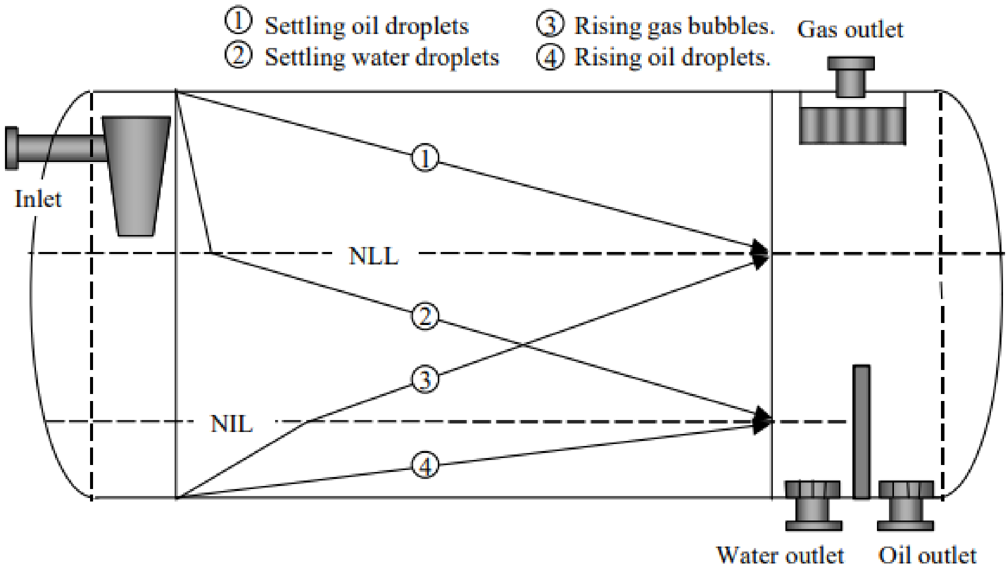

Figure 2.6: Critical settling paths in three-phase horizontal separator.
(Grødal & Realff 1999)

For a two phase gas-oil separator the two settling paths needed is oil droplet i gas phase (path 1) and gas bubble in oil phase (path 3, but starting in the oil phase).

2.1.3 Settling and Residence time

When the critical settling paths are known, the settling time for a droplet and a bubble can be calculated. This is done by using the correlations between distance, speed and velocity. The settling time for an oil droplet in gas is given by Equation (2.8). For a gas droplet in oil Equation (2.9) gives the settling time.

$$t_{og} = \frac{Di - h_{LLL}}{u_{og}} \tag{2.8}$$

$$t_{go} = \frac{0 - h_{HLL}}{u_{go}} \tag{2.9}$$

t_{og} and t_{go} is the settling time for oil in gas and gas in oil. Di is the diameter, while u_{og} and u_{go} is the settling velocity for oil in gas and gas in oil.

The residence time for gas and oil is given by Equation (2.10) and (2.11).

$$t_g = \frac{L_e}{u_g} \tag{2.10}$$

$$t_o = \frac{L_e}{u_o} \tag{2.11}$$

t_g and t_o is the residence time for oil and gas, L_e is the length of the gravity settling section, and u_g and u_o is the horizontal velocity for the different phases. To make sure that the separation has enough time for to occur at a satisfactory extent the residence time for each phase has to be larger than the settling time for a droplet or bubble in that phase. This gives the Equation (2.12) and (2.13).

$$t_g \geq t_{og} \tag{2.12}$$

$$t_o \geq t_{go} \tag{2.13}$$

By combining Equation (2.8), (2.10) and (2.12) one can get an expression for the length of the gravity settling section for gas separation. The length calculated is the minimum length required to make sure the separation is at a satisfactory extent in the gas phase and can be found in Equation (2.14.)

$$Le \geq Le_g = \frac{u_g(D_i - h_{LLL})}{u_{og}} = \frac{q_g(D_i - h_{LLL})}{u_{og}(A_{TV} - A_{NLL})} \tag{2.14}$$

q_g is the flow rate of gas and A_{TV} is the whole area from the bottom of the vessel and up to the top of the vessel. A_{NLL} is the area below the normal liquid level.

The same relation for length of separation section for the oil phase can be found by combining Equation (2.9), (2.11) and (2.13). Equation (2.15) gives the oil capacity constrain for a two phase separator with oil and gas.

$$Le \geq Le_o = \frac{u_o h_{HLL}}{u_{go}} = \frac{q_o h_{HLL}}{u_{go} A_{NLL}} \tag{2.15}$$

q_o is the flow rate of oil and u_{go} is the settling velocity for gas in oil. For a three phase separator the oil capacity constraint has to consider the water interface level and is given in Equation (2.16).

$$Le \geq Le_o = \frac{u_o(h_{HLL} - h_{LIL})}{u_{wo}} = \frac{q_o(h_{HLL} - h_{LIL})}{u_{wo}(A_{NLL} - A_{NIL})} \tag{2.16}$$

A_{NIL} is the area below the normal interface level. For a three phase separator a water capacity constraint is also needed. This is given in Equation (2.17).

$$Le \geq Le_w = \frac{u_w h_{HIL}}{u_{ow}} = \frac{q_w h_{HIL}}{u_{ow} A_{NIL}} \tag{2.17}$$

2.1.4 K-value

In Section 2.1.3 capacity constraints for all three phases were presented. For the gas phase another constraint is also often used. The K-value is defined as presented in Equation (2.18). The theory in this section is from a personal conversation with Inge Fosse (Leading Advisor Upstream Oil Production Equinor, 25.05.2022).

$$K = u_{gmax}\sqrt{\frac{\rho_g}{\rho_l - \rho_g}} \tag{2.18}$$

K is the K-value and ρ_l is the density of the liquid phase. If there is more than one liquid phase the lightest should be used. That will in most cases be the oil density. u_{gmax} is the maximal horizontal velocity of gas. The velocity is calculated with Equation (2.19). It is calculated for when the gas occupies the smallest area while still fulfilling all the constraints because that is when the velocity will be highest.

$$u_{gmax} = \frac{q_g}{A_{gas}} = \frac{q_g}{A_{TV} - A_{HLL}} \tag{2.19}$$

2.1.5 Slug and surge

The separator should be designed to handle some slug and surge without reaching the alarm levels. The Equations below give the constraints that will take care of surge and slug. V_{slug} is the slug volume and V_{surge} is the surge volume. Equation (2.20) gives the slug constraint for liquid level.

$$V_{slug} \leq (L_c + L_e + L_n)(A_{HLL} - A_{NLL}) \tag{2.20}$$

Equation (2.21) gives the surge constraint for liquid level.

$$V_{surge} \leq (L_c + L_e + L_n)(A_{NLL} - A_{LLL}) \tag{2.21}$$

Equation (2.22) gives the slug constraint for interface level.

$$V_{slug}\left(\frac{q_w}{q_o}\right) \leq (L_c + L_e + 2d_{n,w})(A_{HIL} - A_{NIL}) \tag{2.22}$$

Equation (2.23) gives the surge constraint for interface level.

$$V_{surge}\left(\frac{q_w}{q_o}\right) \leq (L_c + L_e + 2d_{n,w})(A_{NIL} - A_{LIL}) \tag{2.23}$$

2.1.6 Relative Velocity

The slenderness is defined as the ratio between internal length, without the head sections, and internal diameter of the separator as seen in Equation (2.24). The internal length is also called the tan-tan length and can be seen in Equation (2.25). Typical values used for slenderness ratio are between 3 and 5.

$$SL = \frac{L_{TT}}{D_i} \tag{2.24}$$

$$L_{TT} = L_c + L_e + L_n \tag{2.25}$$

The slenderness ratio should have a value such that it avoids having excessive gas velocities that can lead to re-entrainment of the liquid into the gas. To avoid this to occur, a constraint can be included to limit the velocity difference between gas and oil. It is also known as the maximum relative velocity ($u_{r\,\max}$) and the actual relative velocity ($u_{\text{r act}}$) has to be smaller than the constraint. This is shown in Equation (2.26).

$$u_{r\,\max} \geq u_{\text{r act}} \tag{2.26}$$

The actual relative velocity is calculated with Equation (2.27).

$$u_{\text{r act}} = u_g - u_o = \frac{q_g}{A_{TV} - A_{NLL}} - \frac{q_o}{A_{NLL} - A_{NIL}} \tag{2.27}$$

To calculate the upper bound of the relative velocity, the Reynolds film number and the interfacial viscosity number are used. They are calculated with Equation (2.28) and (2.29). The Reynolds film number (N_{Ref}) will tell if the flow is laminar or turbulent. The interfacial viscosity number (N_μ) characterize the two-phase flow.

$$N_{\text{Ref}} = \frac{\rho_o u_o D_H}{\mu_o} \tag{2.28}$$

$$N_\mu = \frac{\mu_o}{\left[\rho_o \sigma_{og} \left(\sigma_{og} / \left(g\left(\rho_o - \rho_g\right)\right)\right)^{0.5}\right]^{0.5}} \tag{2.29}$$

σ_{og} is the surface tension between oil and gas, μ_o is the viscosity of the oil and D_h is the general hydraulic diameter which is defined in Equation (2.30).

$$D_h = \frac{4A_{HLL}}{P_{HLL}} \tag{2.30}$$

P_{HLL} is the wetted perimeter and given by Equation (2.31).

$$P_{HLL} = D_i \cos^{-1}\left(1 - 2h_{HLL}/D_i\right) \tag{2.31}$$

When the Reynolds film number and the interfacial viscosity number are found the next step is to check which of the equations for the maximum relative velocity to use.

For low Reynolds film number regime ($N_{Ref} < 160$), laminar flow, Equation (2.32) gives the expression for the maximum relative velocity.

$$u_{r\,\max} = 0.4572 \left(\frac{\sigma_{og}}{\mu_o}\right)\left(\frac{\rho_o}{\rho_g}\right)^{0.5} N_{\text{Ref}}^{-0.5} \tag{2.32}$$

For medium Reynolds film number regime ($160 \leq N_{Ref} \leq 1635$), also known as the transition regime, and interfacial viscosity number below 1/15 ($N_\mu \leq 1/15$) Equation (2.33) gives the expression for the maximum relative velocity.

$$u_{r\,\max} = 3.5905 \left(\frac{\sigma_{og}}{\mu_o}\right)\left(\frac{\rho_o}{\rho_g}\right)^{0.5} N_\mu^{0.8} N_{\text{Ref}}^{-1/3} \tag{2.33}$$

For Reynolds film number in the transition regime ($160 \leq N_{Ref} \leq 1635$) and interfacial viscosity number over 1/15 ($N_\mu > 1/15$) Equation (2.34) gives the expression for the maximum relative velocity.

$$u_{r\max} = 0.4115 \left(\frac{\sigma_{og}}{\mu_o}\right) \left(\frac{\rho_o}{\rho_g}\right)^{0.5} N_{\text{Ref}}^{-1/3} \tag{2.34}$$

When the Reynolds film number is in the rough turbulent regime ($N_{Ref} > 1635$), and the interfacial viscosity number is low ($N_\mu \leq 1/15$) Equation (2.35) applies.

$$u_{r\max} = 0.3048 \left(\frac{\sigma_{og}}{\mu_o}\right) \left(\frac{\rho_o}{\rho_g}\right)^{0.5} N_\mu^{0.8} \tag{2.35}$$

When the Reynolds film number is in the rough turbulent regime ($N_{Ref} > 1635$), and the interfacial viscosity number is high ($N_\mu > 1/15$) Equation (2.36) is used.

$$u_{r\max} = 0.03493 \left(\frac{\sigma_{og}}{\mu_o}\right) \left(\frac{\rho_o}{\rho_g}\right)^{0.5} \tag{2.36}$$

2.1.7 Alarm and trip level

The NORSOK standards are used to define the operational constraints. The first constraint, Equation (2.37), states that the residence time between normal level and alarm level and between alarm level and shut down level should not be less than 30 seconds (Δt_{NOR}) for the liquid levels.

$$(q_o + q_w)\, \Delta t_{NOR} \leq (L_c + L_e + L_n)\, (A_i - A_j) \tag{2.37}$$

i and j are the sets {HHLL, HLL, NLL, LLL} and {HLL, NLL, LLL, LLLL}. The NORSOK standard also states that the height between normal level and alarm level, and alarm level and shut down level should not be less than 0.08 m (Δh_{NOR}) for the liquid levels. This is given in Equation (2.38).

$$\Delta h_{NOR} \leq (h_i - h_j) \tag{2.38}$$

Both constraints are valid for two and three phase separators. But for three phase separators there also has to be constraints associated to the interface level. Equation (2.39) states that the residence time between normal level and alarm level and between alarm level and shut down level should not be less than 30 seconds (Δt_{NOR}) for the interface levels.

$$q_w \Delta t_{NOR} \leq (L_c + L_e + 2d_{n,w})\, (A_p - A_q) \tag{2.39}$$

p and q are the sets {HHIL, HIL, NIL, LIL} and {HIL, NIL, LIL, LLIL}. Equation (2.40) gives that the height between normal level and alarm level, and alarm level and shut down level should not be less than 0.08 m (Δh_{NOR}) for the interface levels. That also according to the NORSOK standards.

$$\Delta h_{NOR} \leq (h_p - h_q) \tag{2.40}$$

To calculate the area that a liquid take up of a pipe when the height (h_1) is known Equation (2.41) is used.

$$A = \left(h_1 - \frac{D_i}{2}\right) \sqrt{D_i h_1 - h_1^2} + \frac{D_i^2}{4} \sin^{-1}\left(\frac{2h_1}{D_i} - 1\right) + \frac{\pi D_i^2}{8} \tag{2.41}$$

2.1.8 Moving Process Plant Constraint

Since the separator will be installed on a floating vessel, the motions of the vessel and the impact of these on the separator has to be considered. The motions will mainly be from wind, waves and current in the sea. The motions will affect the separator pitch and the separator will not be perpendicular to the gravitational force. This will make the cross-sectional area for flow of the different phases to alter. To control this perforated baffle plates will be installed as viewed in Figure 2.7. The length between each baffle plate can be calculated with Equation (2.42).

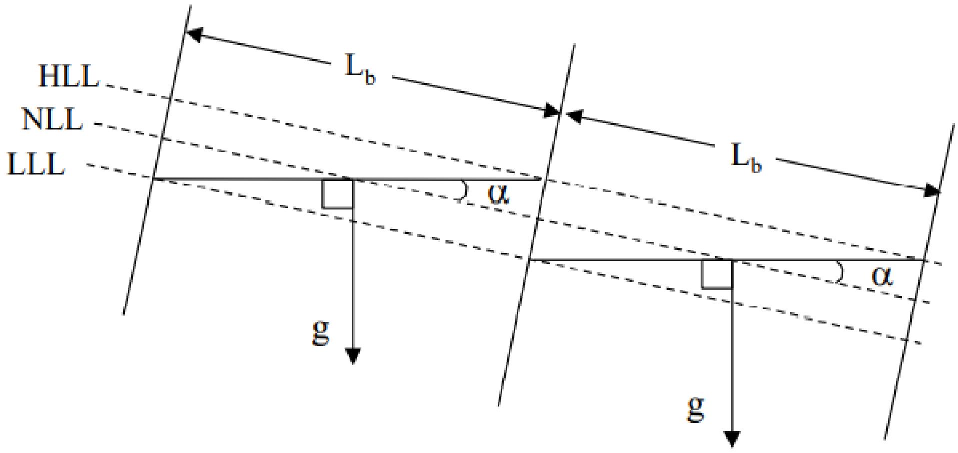

Figure 2.7: Model of interbaffle spaces at maximum pitch angle (Grødal & Realff 1999)

$$h_u - h_v \geq \frac{\tan(\alpha) L_b}{2} \qquad (2.42)$$

L_b is the length between the baffle plates, α is the pitch angle, while h is the height and u and v is the sets {HLL, NLL} and {NLL, LLL}. u and v can also be expanded to include the interface levels for a three phase separator.

2.1.9 Outlets

Figure 2.8 shows the end section of a separator. The three different outlets and the weir are all located in this section of the separator. Below the gas outlet is the vane demister, and on top of the oil and water outlet vortex breakers are mounted. The vane demister removes liquid from the gas, while the vortex breakers remove gas from the liquid.

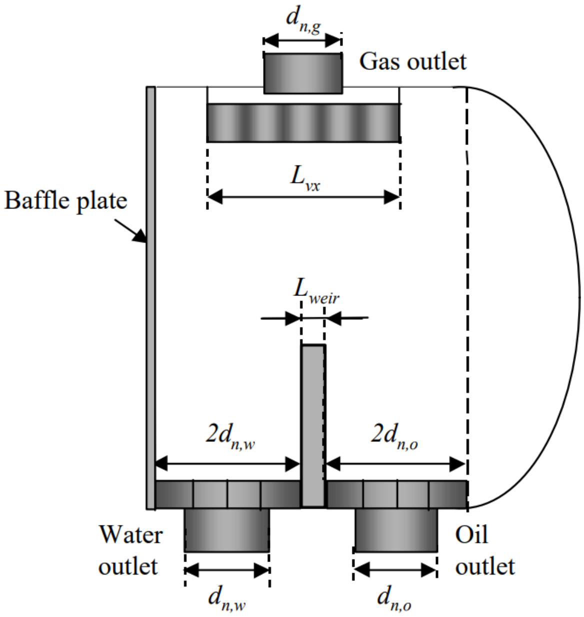

Figure 2.8: Three phase separator end section (Grødal & Realff 1999)

$d_{n,o}$ is the diameter of the oil outlet, $d_{n,g}$ is the diameter of the gas outlet and $d_{n,w}$ is the diameter of the water outlet. Lvx is the length of the vane demister and L_{weir} is the length of the weir plate.

The length on the end section depends on which components that require most space. The different components are the gas outlet, the vane demister, and the liquid outlets including the weir. The vortex breakers mounted on top of the liquid outlets are twice the size of the inner diameter of the nozzles. The length of the end section is defined by Equation (2.43). This is the minimum length that is possible with enough space for the different equipment.

$$L_n \geq \max\left[L_{vx}, d_{n,g}, 2d_{n,w} + 2d_{n,o} + L_{\text{weir}}\right] \tag{2.43}$$

To calculate the size of the outlets Equation (2.44) is used. For the oil outlet, oil density and oil flow are used. The same applies for gas and water.
$d_{n,g}$, $d_{n,w}$ and $d_{n,o}$ is the the nozzle size of the outlets for gas, water and oil. They are calculated with Equation (2.44) and have the unit $m^{0.25}s^{0.5}/kg^{0.25}$.

$$d_n \geq 0.161\sqrt{q\rho^{0.5}} \tag{2.44}$$

The vane demisters are a set of parallel vanes with a height of 20 centimeters. To make sure the vane demisters work properly the gas velocity has to be monitored. Too high gas velocity will make re-entrainment possible and flooding a concern. Equation (2.45) gives a gas velocity that will will avoid both re-entrainment and flooding.

$$u_{g\,\max} = \frac{q_g}{L_{vx}L_{vz}} \leq 2.38\left(\frac{\sigma_{og}g}{\rho_o}\right)^{0.25}\left(\frac{\rho_o - \rho_g}{\rho_g}\right)^{0.5} \tag{2.45}$$

Lvx is the length of the vane demister and Lvz is the width of the vane demister. For a horizontal separator Equation (2.46) gives Lvz.

$$L_{vz} = 2\sqrt{D_i h_{vdm} - h_{vdm}^2} \tag{2.46}$$

h_{vdm} is the height of the vane demister mounting point.

2.1.10 Safety and Geometrical Constraints

Safety constraints are used to prevent the separator to reach conditions that are unwanted. During these conditions fluids can exit the separator from the wrong outlet or the separator and the equipment in and around the separator can be damaged. One such condition is when the liquid reaches the vane demister. Equation (2.47) gives a constraint that specifies the minimum distance between the inlet of the vane demister and the high high liquid level.

$$h_{vdi} - h_{HHLL} \geq \Delta h_s \tag{2.47}$$

The gas should not enter the liquid outlet. Equation (2.48) gives a constraint that specifies the minimum distance between the low-low liquid level and the weir.

$$h_{LLLL} - h_{WH} \geq \Delta h_s \tag{2.48}$$

For a two phase separator these are the two constraints regarding the liquid level. For a three phase separator the interface level has to be taken into account. To avoid water flowing over the weir and in the oil outlet Equation (2.49) give a constraint for the distance between the weir and the high-high interface level.

$$h_{WH} - h_{HHIL} \geq \Delta h_s \tag{2.49}$$

Equation (2.50) give a constraint to avoid oil flowing in the water outlet.

$$h_{LLIL} \geq \Delta h_s \tag{2.50}$$

Figure 2.9 shows the safety levels for a three phase separator on the left and for a two phase separator on the right.
The normal liquid level should always be larger than the normal interface level. This can be expressed with Equation (2.51).

$$h_{NLL} - h_{NIL} = 4\Delta h_{NOR} + 2\Delta h_s \tag{2.51}$$

The total length of the separator is set to be a maximum of 20 meters while the maximum diameter is set to 4.5 meters. This is due to practical reasons, such as transportation. See Equation (2.52) and (2.53).

$$L = L_c + L_e + L_n + 2L_h + 2t_c \leq 20 \text{ m} \tag{2.52}$$

$$D = D_i + 2t_c \leq 4.5 \text{ m}, \tag{2.53}$$

t_c is the corrosion allowance and is the L_h is length of the head section. The length of the head section is calculated with Equation (2.54).

$$L_h = \frac{Di}{4} \tag{2.54}$$

Since the separator has to operate at high pressures this has to be taken into account when designing the vessel. The wall thickness is an important aspect of this. Too thin and

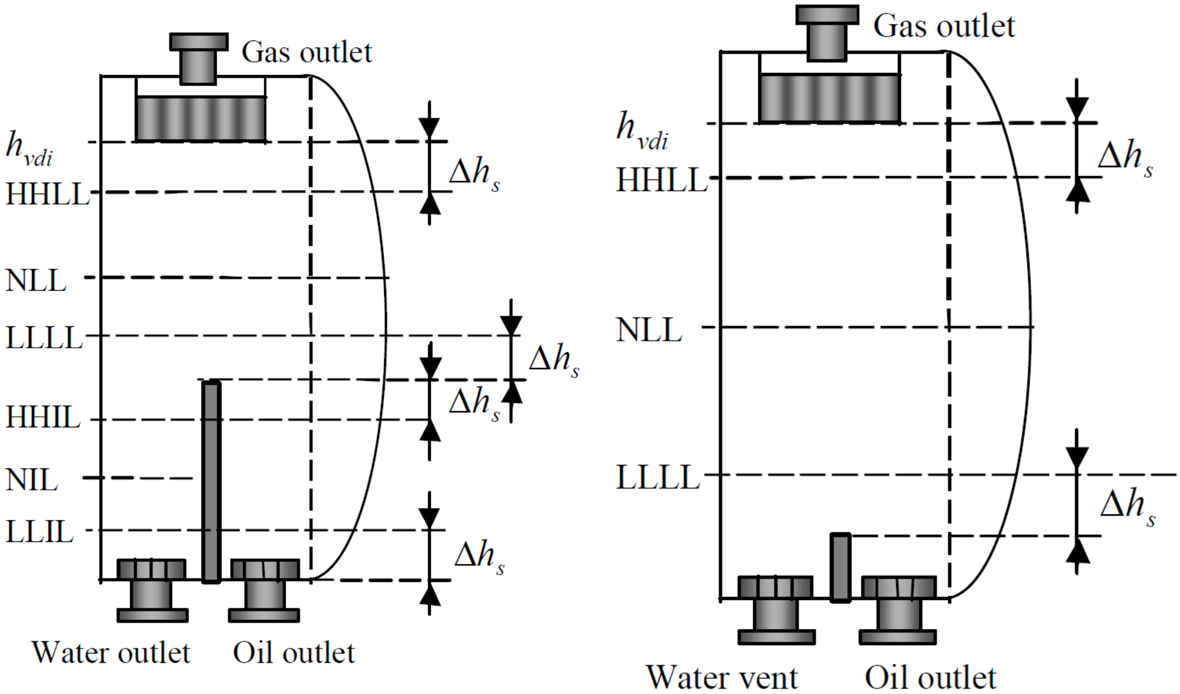

Figure 2.9: Safety levels for a three phase separator (left) and a two phase separator (right) (Grødal & Realff 1999).

the separator might not be able to handle the pressure. But if it is to thick it will become more expensive than necessary. The ASME Code for wall thickness in the cylindrical section is given by Equation (2.55).

$$t_{cs} \geq \frac{p_D D_i}{2\sigma E - 1.2p_D} + t_c \tag{2.55}$$

t_{cs} is the wall thickness in the cylindrical section, E is the joint efficiency and p_D is the design pressure, which the separator will operate on. The design pressure is given in Equation (2.56).

$$p_D \geq \max[p + p_{min}, 1.1p] \tag{2.56}$$

p is the operating pressure for the separator and p_{min} is the minimum pressure difference between the operating pressure and the design pressure. That minimum pressure difference is 2 bar.

2.1.11 Dimensionless area

Equation (2.41) gives a way to calculate the area of a pipe section for a given height. By dividing it on the total area of the pipe a dimensionless equation for area of a pipe section is obtained (Ahmed et al. 2020). This gives Equation (2.57) and the derivation of it can be found in Appendix A.1.

$$A_D = \frac{A}{A_T} = \frac{4}{\pi}\left(c - \frac{1}{2}\right)\sqrt{c - (c)^2} + \frac{\sin^{-1}(2c-1)}{\pi} + \frac{1}{2} \tag{2.57}$$

The constant c is the relation between the height and the diameter. c is a fraction between 0 and 1 and given in Equation (2.58).

$$0 \leq c = \frac{h_1}{D_i} \leq 1 \tag{2.58}$$

2.1.12 Weight and cost of separator

In this section the Equations (2.60) - (2.65) and the theory behind is from a personal conversation with Fosse (25.06.2021). The rest of the equations and theory is from Grødal & Realff (1999).

The weight of the shell and the two head sections of the separator can be calculated with Equation (2.59). The shell section is the main part of the separator while the head sections are on both sides of the shell.

$$W_{sh} = t_{cs}\rho_s \left[\pi D_m \left(L_c + L_e + L_n\right) + 2F_a {D_m}^2\right] \tag{2.59}$$

W_{sh} is the weight of shell and head sections of the separator, ρ_s is the density of steel, D_m is the mean separator diameter, and F_a is the factor for determining surface area of a vessel head from vessel diameter squared. To calculate the weight of the internals, nozzles and saddles Equation (2.60) and (2.61) are used.

$$W_{ns} = W_{sh} * 25\% \tag{2.60}$$

$$W_{int} = W_{sh} * 10\% \tag{2.61}$$

W_{ns} is the weight of nozzles and saddles while W_{int} is the weight of the internals. The total dry weight, the weight of the separator when empty, is given by Equation (2.62).

$$W_{dry} = W_{sh} + W_{ns} + W_{int} \tag{2.62}$$

W_{dry} is the total dry weight of the separator. During testing the separator is filled with water and when in use the separator is filled with varying amount of water, oil and gas. Since water has the highest density, the separator will be heaviest when it is filled with water. The weight of the water in the separator is calculated with Equation (2.63).

$$W_{water} = V_{sep}\rho_w \tag{2.63}$$

W_{water} is the weight of the water inside the separator, and V_{sep} is the volume of the separator. The volume is calculated from Equation (2.64).

$$V_{sep} = V_{shell} + 2V_{head} = \left(\frac{\pi D_i^2}{4} L_{TT}\right) + 2\left(D_i^3 \frac{\pi}{24}(3\frac{h}{D_i}^2 - 2\frac{h}{D_i}^3)\right) \tag{2.64}$$

V_{shell} is the volume of the shell and V_{head} is the volume of the head. The total weight of the separator full of water is then calculated with Equation (2.65).

$$W_{fullofwater} = W_{dry} + W_{water} \tag{2.65}$$

$W_{fullofwater}$ is the weight of the separator full of water.

The cost of the separator is calculated based on the steel made for constructing the vessel. The internals, nozzles and saddles are ignored for this. That means that the cost is calculated based on the weight of the head and shell sections of the separator. This is given in Equation (2.66).

$$C = t_{cs} F_c \rho_s \left[\pi D_m \left(L_c + L_e + L_n \right) + 2 F_a F_h {D_m}^2 \right] \approx F_c * W_{sh} \tag{2.66}$$

C is the manufacturing cost of the separator, F_c is the cost factor per unit mass to manufacture a vessel shell, and F_h is the ratio of cost per unit mass to manufacture a vessel head compared with that of vessel shell. The mean separator diameter is calculated with Equation (2.67).

$$D_m = \sqrt{\frac{D_i^2 + \left(D_i + 2 t_{cs} \right)^2}{2}} \tag{2.67}$$

2.1.13 Footprint

The footprint is how much space the separator takes up (Personal conversation with Inge Fosse, Leading Advisor Upstream Oil Production Systems Equinor, 25.05.2022). It is a function of the tan-tan length and the inner diameter and can be calculated with Equation (2.68).

$$F_p = (Di + 2 t_{cs}) * L_{TT} \tag{2.68}$$

2.2 Black Oil Model

The black oil model is used to characterize and quantify fluid behaviour. It consider that the fluid are divided into three phases: gas (gaseous phase), oil (liquid phase) and water (liquid phase). A set of variables are used to relate the volumetric amounts at standard conditions to the volumetric amounts at any other pressure and temperature conditions. The theory in this section is from Stanko (2021).

The oil volume factor, also called oil formation volume factor, is defined in Equation (2.69).

$$B_o(p,T) = \frac{V_o(p,T)}{V_{\bar{o}o}} \tag{2.69}$$

B_o is the oil volume factor, V_o is the local oil volume at pressure p and temperature T and $V_{\bar{o}o}$ is the volume oil from oil phase at standard conditions. The gas volume factor is defined similar in Equation (2.70)

$$B_g(p,T) = \frac{V_g(p,T)}{V_{\bar{g}g}} \tag{2.70}$$

B_g is the gas volume factor, V_g is the local gas volume at pressure p and temperature T and $V_{\bar{g}g}$ is the volume gas from gas phase at standard conditions. The solution gas-oil ratio is defined in Equation (2.71). It expresses how much gas that comes out of the oil phase when pressure and temperature changes.

$$R_s(p,T) = \frac{V_{\bar{g}o}}{V_{\bar{o}o}} \tag{2.71}$$

R_s is the solution gas-oil ratio and $V_{\bar{g}o}$ is the volume gas at standard condition from the oil phase. These three relations are known as the traditional black oil formulation. Other properties that often are used in the black oil model includes viscosity, density and interface tension between gas and oil.

2.2.1 Correlations

Correlations can be used to calculate the different black oil properties. Standing found some correlations to the black oil properties. The bubble pressure correlation is given in Equation (2.72).

$$p_b = 1.995 \cdot \left(\frac{R_s}{\gamma_g}\right)^{0.83} \cdot 10^{0.001643 \cdot T - 0.0125 \cdot \gamma_{API}} - 1.7566 \tag{2.72}$$

p_b is the bubble pressure, γ_g is the gas gravity and γ_{API} is the API gravity. For gas-in-oil ratio Standing found the correlation in Equation (2.73).

$$R_s = 0.571 \cdot \gamma_g \cdot 10^{0.0151 \cdot \gamma_{API} - 0.00198 \cdot T} \cdot (0.797 \cdot p + 1.4)^{1.205} \tag{2.73}$$

For oil formation factor Standing found the correlation in Equation (2.74).

$$B_o = 0.9759 + 0.000952 \cdot \left[\left(\frac{\gamma_g}{\gamma_o}\right)^{0.5} \cdot R_s + 0.401 \cdot T - 103\right]^{1.2} \tag{2.74}$$

γ_o is the oil gravity. For gas formation factor the definition give the correlation in Equation (2.75).

$$B_g = 0.00351 \cdot \frac{T \cdot Z}{p} \tag{2.75}$$

Z is the generalized compressibility factor.

To match the black oil correlations to field data tuning can be performed. Tuning can be done as viewed in Equation (2.76) by introducing the two constants A and B.

$$value^c * A + B = value^m \tag{2.76}$$

A is the tuning multiplier, B is the tuning shifting, $value^c$ is the calculated property and $value^m$ is the measured property. The calculated property can be calculated with the correlations above. The idea behind tuning is to change the constants to get the difference between the measured and calculated properties to be as small as possible.

2.3 Optimizing

"Optimization is the process of maximizing or minimizing a desired objective function while satisfying the prevailing constraints." (Belegundu & Chandrupatla 2011, p. 1) The objective function is a function of one or more design variables. The value of these design variables are then changed to maximize or minimize the objective function. In another words, they are "optimized". The solution has to fulfill the constraints to make sure that different physical laws and objectives are respected.

There exist many different optimizing methods. Some are easy to apply and can quickly be performed, while others are more advanced and time consuming. The precision vary and for some problems one method is the well suited, while for other problems a completely different method is better suited.

2.3.1 Generalized Reduced Gradient (GRG) Method

The Generalized Reduced Gradient (GRG) Method, which is a method available in Excel Solver, is the method used in this thesis. It is used to solve problems of nonlinear optimization. It only requires that the objective function is differentiable. The method uses active inequalities to solve the nonlinear problem. The variables used are sorted into a set of dependent and independent variables. The reduced gradient is computed to find the minimum in the search direction. This process is repeated until convergence is obtained. (Maia et al. 2017)

To get the separator design into a mathematical program it can be formulated in the following form (Grødal & Realff 1999):

$$\max\ (or \min\ ) \quad z = f\left(x_1, x_2, \ldots . x_n\right), \text{ subject to}$$

$$\begin{aligned} & g_1\left(x_1, x_2, \ldots x_n\right)(\leq, =, \text{ or } \geq) b_1 \\ & g_2\left(x_1, x_2, \ldots . x_n\right)(\leq, =, \text{ or } \geq) b_2 \\ & \vdots \\ & g_m\left(x_1, x_2, \ldots . x_n\right)(\leq, =, \text{ or } \geq) b_m \end{aligned}$$

z is the objective function which is a function of the design variables, x_i. The objective function is to be minimized or maximized subject to a set of constraints, g_i. The constraints are also functions of the design variables and are expressed as inequalities or equities.

2.4 Field Development

The field development process consist of several phases and steps. They have to be performed to get a field up and running, and to shut it down. The aim for the whole process is to develop a design of the whole field and the production that maximize the economic values in the resources in a safe and environmental responsible manner. Figure 2.10 show a typical field development process. Both the figure and the theory in this Chapter are from Stanko (2021).

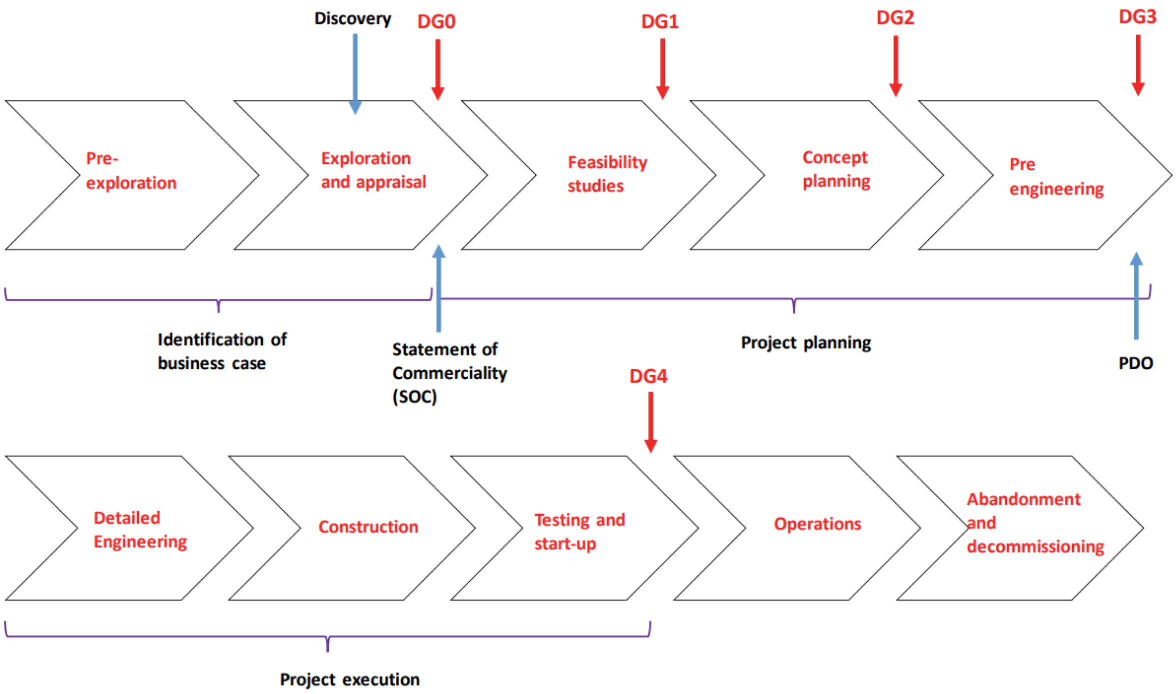

Figure 2.10: The field development process (Stanko 2021).

There are five decision gates: DG0, DG1, DG2, DG3 and DG4. These come at different stages in the process and are used to make decisions on which projects to continue with and which that are discarded.

2.4.1 Business case identification

The business case identification is the first phase in the field development process. The main goal is to prove economical potential of the discovery, and quantify and reduce uncertainty in the estimation of reserves. The business case identification involves the pre-exploration and the exploration steps. The pre-exploration step mainly focus on gathering information in areas of interest. This information can be technical like the expected size of reserves, or political like how the political regime is and how the government stability is. Other information can be taxation regime, personnel security, and environmental sensitivity.

During the exploration step geological studies, geophysical surveys, seismic surveys, and exploration drilling are performed. If these activities lead to a discovery the next step is to assess the discovery. Then appraisals are drilled, a probabilistic reserve estimation is done, and the uncertainties are reduced. After the business case identification step is the first decision gate, DG0. The outcome of DG0 can be to issue a Statement of Commerciality (SOC) and proceed with the development. The project will then continue to the next phase. Other outcomes of DG0 are to continue drilling more appraisals, sell the discovery, do nothing, or relinquish to the government.

2.4.2 Project planning

If the project pass DG0 it reaches the project planning phase. The main goal of the planning phase is to perform a systematic screening of concepts, to define a preferred development concept and to evaluate its profitability, technical feasibility and HSE within acceptable levels of uncertainty. This is done in three steps: feasibility studies, concept planning and pre-engineering.

During the feasibility studies further development has to be justified. The goal is to find one or more concepts that are technically, commercially, and organizationally feasible. Some of the tasks during this step is to establish feasible development scenarios, create a project timeline and a work-plan, identify possible technology gaps and blockers, identify needs for new technology, identify added value opportunities and make a cost evaluation for all options. The project then reach the second decision gate, DG1.

If the project pass DG1 the next step is the concept planning. The objective here is to identify development concepts, rank them, and select and document a viable concept. The tasks to achieve this includes to evaluate and compare alternatives for development and screen out non-viable options, elaborate a project execution plan and define the commercial aspects, legislation, agreements, licensing, financing, marketing and supply. This comes in addition to creating models of the reservoir, defining the depletion and production strategy and make a flow assurance evaluation. Drill and well planning, pre-design of facilities, planning of operations, start-up and maintenance, and cost and manpower estimates are other task that have to be done during this step. The concept planning leads to DG2. When designing separators the tool implemented in this thesis will be used during the concept planning step. That will give an idea about how the separator should be designed and different solutions.

After DG2 the project reaches the final step of the project planning phase, the pre-engineering. Here the development solution is further matured, defined and documented based on the selected concept. Some of the tasks are selection of the final technical solution, execute the Front-End Engineering Design (FEED), plan and prepare the execution phase, prepare for submission of the application to the authorities, perform environmental impact assessments and establish the basis for awarding contracts. This leads to DG3 which is to send a plan for Development and Operations (PDO) to the government. The government then has to approve the PDO for the project to continue to the next phase. In this step the separator design is selected..

2.4.3 Project execution

The project execution phase consist of three steps: detailed engineering, construction, and testing and start-up. The objective is to perform detailed design, procurement of the construction materials, construction, installation and commissioning of the agreed facilities. To do this either individual contracts are awarded or one main contractor are awarded an engineering, procurement, construction, and management contract (EPCM). Then preparing for start-up is done and the final decision gate, DG4, is reached. The separator is in this phase constructed and then tested.

2.4.4 Operations

After passing DG4 the project reaches the operations phase, when the field is producing. It is often in this phase the projects spend most time in. Some fields produce only a couple of years while other produce for decades. During the first stage in the operations phase is the production start-up which is followed by the build-up stage. When the production reaches the maximum it enters the plateau phase. It then produces at the plateau rate as long as possible before it enters the decline stage when the rate begin to decrease. Different measures can be activated to prolong and improve the production during the different stages. When the project is no longer economic valuable it is shut down and this is done in the shut-down stage. During this phase the separator is operational.

2.4.5 Decommissioning and abandonment

When the field is shut down only the last phase is left, the decommissioning and abandonment. This phase is concentrating on leaving the field in a responsible, safe, environmental way. All equipment, structures and pipelines should be removed or buried. The wells have to be plugged to avoid reservoir fluids to escape to the sea. The equipment has to be cleaned and transported to be re-used, scrapped or recycled.

3 Methodology

Section 3.1 is similar to Section 3.1 in the project report (Bogen 2021). As mentioned earlier the project report focused on a design for two phase separators. This thesis is focusing on the design of a three phase separator and therefore there will be similarities. But there are more variables and the procedures are repeated more frequently when designing a three phase separator.

3.1 Description of Separator Design

To find the optimal design of the separator, the method described by Grødal and Realff Grødal & Realff (1999) is used as a base. Microsoft Excel is the program used and several of the equations presented in Chapter 2 (separation constraints and equations) are implemented using functions in the programming language VBA (visual basic for applications). This to make the worksheet more user friendly and to reduce the chance for errors. After discussion with representatives from Equinor some changes have been done to the tool. Therefore two versions of the tool exist. Version 1 is the original tool with formulas from Grødal and Realff while Version 2 is the improved version with input from Equinor.

To make it easier to have an overview of the excel sheet the cells have a colour code, see Figure 3.1. Red is inserted input numbers that can be changed, blue is calculated from the different formulas, green is from another cell in the excel file, while purple is changed to find the optimal solution.

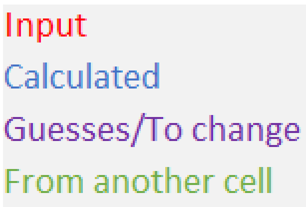

Figure 3.1: Color code for excel sheet (Bogen 2021).

To make the model for a three phase separator the algorithm in Figure 3.2 was used. It is based on an algorithm from Grødal & Realff (1999) and was first used in the project report (Bogen 2021).

First the input values were set up. The input values include the design parameters, the physical constants, the fixed variables, and initial guess for the optimization variables. Some of the inputs are the rates, the fluid properties, the design pressure, constants for cost and mass nozzle sizes, heights in end section and lengths of different separator sections.

After the inputs the next step is to calculate the design variables. The design variables are the unknown liquid and interface levels (high-high, high, low and low-low), the normal liquid and interface level are known. The distance between the baffle plates, the wall thickness and the length of the end section of the separator are also design variables.

When the design variables are calculated, the cost of the separator and the constraint variables are calculated. Then a check of all the constraints and if they have been fulfilled is done. If all the constraints are fulfilled and there is no value that gives a lower cost then the optimal separator design is found. If at least one of the constraints, but it could be more, are not fulfilled or there is a value for cost which is lower, the optimization variables values are altered. With these new values the design values are calculated over again and the procedure is repeated until all constraints are fulfilled and the lowest cost is found.

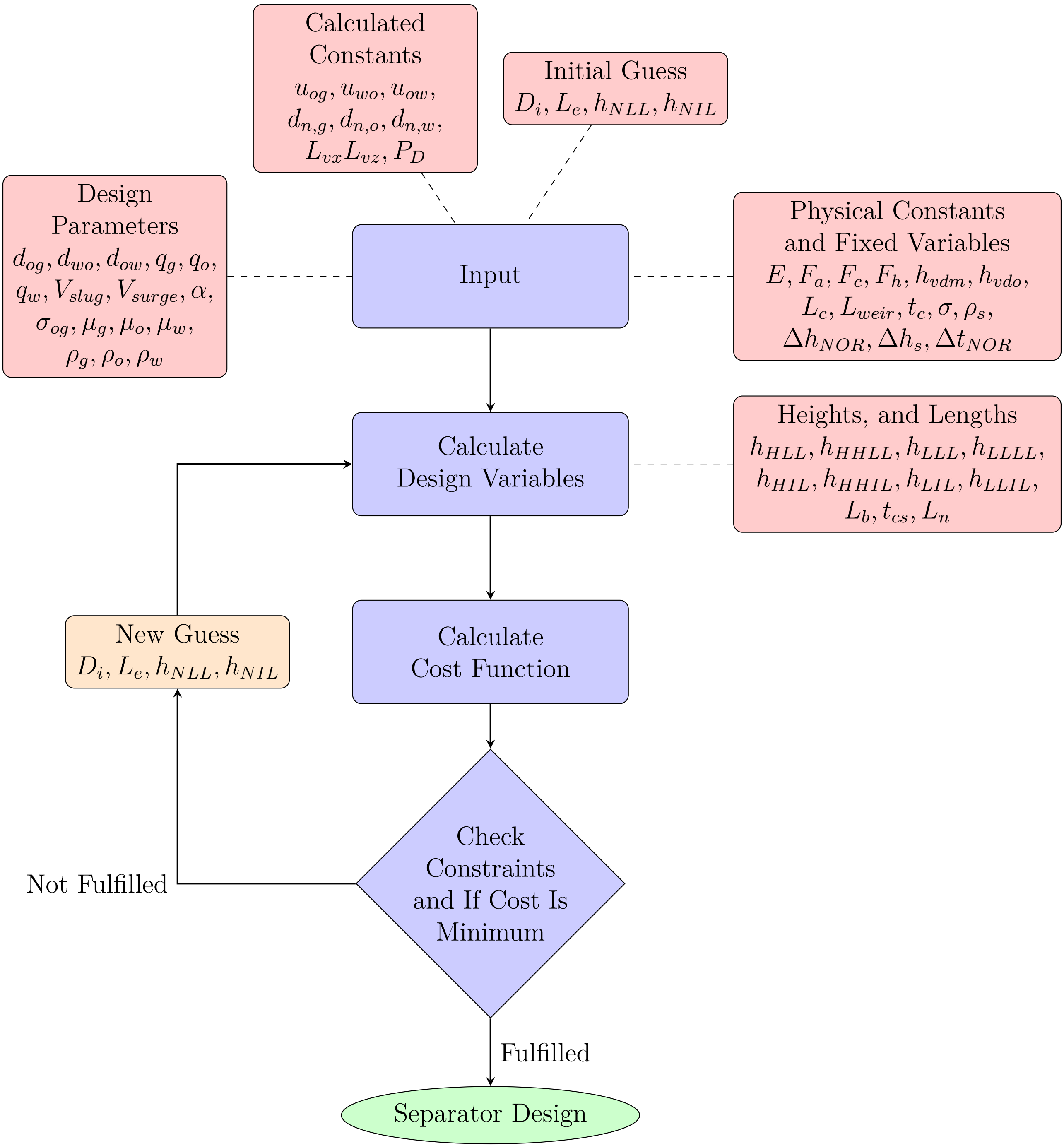

Figure 3.2: Algorithm for optimizing cost of separator based on previous work by Grødal & Realff (1999) and Bogen (2021).

In Figure 3.2 the arrows show how the algorithm works. It moves from *Input* to *Calculate Design Variables* to *Calculate Cost Function* to *Check Constrains and If Cost Is Minimum.* From there it either go to *Separator Design* or to *New Guesses* before it enters the loop in the box with *Calculate Design Variables.* The dashed lines show which variables that the blue boxes actually calculate. When calculating the design variables, the heights and lengths listed in the red box to the right are calculated.

3.1.1 Design Parameters

The design parameters are input values that are used to calculate other constants and variables. They include the flow rates for the separator, size of droplets and bubbles to be removed, surface tension, viscosity, density and pitch angle. The values used in this study are from Grødal & Realff (1999) and can be viewed in Table 3.1.

Table 3.1: Values of the design parameters used in the tool.

Parameter	Symbol	Value	Unit
Droplet diameter oil in gas	d_{og}	100	μm
Droplet diameter water in oil	d_{wo}	250	μm
Droplet diameter oil in water	d_{ow}	250	μm
Rate gas	q_g	1.501	m^3/s
Rate oil	q_o	0.226	m^3/s
Rate water	q_w	0.041	m^3/s
Pitch degree	α	10	$\circ$
Surface tension between oil and gas	σ_{og}	$1.78 * 10^-2$	kg/m^2
Viscosity gas	μ_g	$1.07 * 10^-5$	Pas
Viscosity oil	μ_o	$7.30 * 10^-4$	Pas
Viscosity water	μ_w	$3.70 * 10^-4$	Pas
Density gas	ρ_g	17.46	$kg/m3$
Density oil	ρ_o	767.7	$kg/m3$
Density water	ρ_w	974.6	$kg/m3$

The values for these variables are also used in the Grødal and Realff case study.

3.1.2 Physical Constants and Fixed Variables

The physical constants and fixed variables include joint efficiency, cost factors, heights connected to the vane demister, height of the weir, length of inlet section and weir, corrosion allowance, tensile strength, steel density, size of water outlet, safety constant and NORSOK constants.

Parameter	Symbol	Value	Unit
Joint efficiency	E	1	-
Surface area of vessel head factor	F_a	1.09	-
Cost Factor	F_c	5	$\$/kg$
Height vane demister mounting point	h_{vdm}	$Di - 0.1$	m
Height vane demister outlet	h_{vdo}	$Di - 0.2$	m
Height vane demister inlet	h_{vdi}	$h_{vdo} - 0.2$	m
Length inlet section	L_c	1	m
Length weir	L_{WH}	0.01	m
Corrosion allowance	t_c	0.0032	m
Tensile strength	σ	95	MPa
Density steel	ρ_s	7850	$kg/m3$
Height interval NORSOK	h_{NOR}	0.08	m
Safety margin height	h_s	0.05	m
Time interval NORSOK	t_{NOR}	30	sec

Table 3.2: Values of the Physical Constants and Fixed Variables used in the model.

The height interval (h_{NOR}) is the minimum distance between the liquid levels and between the interface levels. For example between the normal liquid level and the high liquid level. The safety margin height (h_s) however is the distance between the different levels. For example between the low-low liquid level and the weir. This can be seen in Figure 2.9 in Section 2.1.10.

3.1.3 Calculated Constants

The calculated constants are calculated based on the input parameters, and are also treated as input values. The calculated constants include the settling velocities, the size of the gas, oil and water outlets, the product of the length and width of the vane demister and the design pressure.

Settling velocities (u_{og}, u_{wo}, u_{ow})
The settling velocities that are calculated are for oil droplets in the gas phase, water droplets in oil phase and oil droplets in water phase. This is done by using the settling theory presented in Section 2.1.1. The spherical drag coefficient, C_d, initial value is 0.34 and is used to calculate the settling velocity, u_{og}, u_{wo} and u_{ow}, by Equation (2.5). The settling velocity is then used to calculate the Reynolds number, N_{Re} with Equation (2.7). Then a new spherical drag coefficient is calculated with Equation (2.6). This procedure is repeated over and over again and calculate new values for the three properties. To find the difference between each step Equation (3.1) is used. All these calculations are done with using a while-loop. The while-loop is included in Appendix B.1.

$$\text{Convergence check} = \frac{C_{d,i}}{C_{d,i-1}} - 1 < \epsilon \tag{3.1}$$

$C_{d,i}$ is the spherical drag coefficient from the current step and $C_{d,i-1}$ is the spherical drag coefficient from the last step. The difference between these two should be less than a set constraint, ϵ. The constraint is in this model set to 10^{-5}.

Size Outlet Nozzles $(d_{n,g}, d_{n,o}, d_{n,w})$
The size of the outlet nozzles are calculated with Equation (2.44) as described in Section 2.1.9.

Size vane demisters $(LvxLvz)$
The size of the vane demisters that the gas have to pass through before entering the gas outlet can be calculated with Equation (2.45). Both the width (Lvz) and the length (Lvx) of the vane demisters are unknown, so at this stage only a product of the width and length is found. It is found by rearranging Equation (2.45) into Equation (3.2).

$$L_{vx}L_{vz} = \frac{q_g}{2.38}\left(\frac{\rho_o}{\sigma_{og}g}\right)^{0.25}\left(\frac{\rho_g}{\rho_o - \rho_g}\right)^{0.5} \tag{3.2}$$

Design pressure (p_D)
The operating pressure of the separator is calculated as described in Section 2.1.10 with Equation (2.56).

3.1.4 Optimized Variables

The variables that are to be optimized are the variables that the optimizing software will determine based on initial guesses given by the user. The four variables are the inner diameter (D_i), the length of the gravity separation section (L_e), the normal liquid level (NLL) and the normal interface level (NIL). The initial guess of the inner diameter was 4 m. For the length of the gravity separation section the initial guess was 15 m, for the normal liquid level it was 2 m and for the normal interface level it was 1 m.

3.1.5 Design Variables

Liquid Level and Interface Level

To find the optimal size of the separator, finding the height of the gas-oil interface and the oil-water interface is essential. The heights are calculated with Equations (2.37) - (2.40). The normal liquid level and the normal interface are two of the optimization variables and are therefore taken as a base for the other levels. The normal liquid level is used to calculate the other liquid levels and the normal interface level is used to calculate the other interface levels. Equation (2.37) is transformed to Equation (3.3) and (3.4). Equation (3.3) is used for calculating the area for high liquid level and the high-high liquid level. Equation (3.4) is used for calculating the area for low liquid level and the low-low liquid level.

$$A_i \geq A_j + \frac{(q_o + q_w)\,\Delta t_{NOR}}{(L_c + L_e + L_n)} \tag{3.3}$$

$$A_j \geq A_i - \frac{(q_o + q_w)\,\Delta t_{NOR}}{(L_c + L_e + L_n)} \tag{3.4}$$

Likewise Equation (2.39) is rearranged to Equation (3.5) and (3.6). Equation (3.5) is used for calculating the area for high interface level and the high-high interface level. Equation (3.6) is used for calculating the area for low interface level and the low-low interface level.

$$A_p \geq A_q + \frac{q_w \Delta t_{NOR}}{(L_c + L_e + 2d_{n,w})} \tag{3.5}$$

$$A_q \geq A_p - \frac{q_w \Delta t_{NOR}}{(L_c + L_e + 2d_{n,w})} \tag{3.6}$$

The Equations (2.20) - (2.23) are rearranged to calculate the area of the alarm levels required to take care of the surge and slug. Equation (3.7) gives the area of the high liquid level.

$$A_{HLL} \geq A_{NLL} + \frac{V_{slug}}{(L_c + L_e + L_n)} \tag{3.7}$$

Equation (3.8) gives the area of the low liquid level.

$$A_{LLL} \geq A_{NLL} - \frac{V_{surge}}{(L_c + L_e + L_n)} \tag{3.8}$$

Equation (3.9) gives the area of the high interface level.

$$A_{HIL} \geq A_{NIL} + \frac{V_{slug}}{(L_c + L_e + 2d_{n,w})} \left(\frac{q_w}{q_o} \right) \tag{3.9}$$

Equation (3.10) gives the area of the low interface level.

$$A_{LIL} \geq A_{NIL} - \frac{V_{surge}}{(L_c + L_e + 2d_{n,w})} \left(\frac{q_w}{q_o} \right) \tag{3.10}$$

The Equations (3.3) - (3.10) give the area of the cylindrical vessel section. But what is needed is the height of pipe section. So a way to go from area to height is needed. To use Equation (2.41) would be the best way, but it is not possible to solve the equation explicitly for height.

Therefore an alternative method were used. Dimensionless height, c, between 0 and 1 with steps of 0.001 were applied. The definition of dimensionless height are given by Equation (2.58). Inserting the dimensionless heights into Equation (2.57) give the corresponding dimensionless areas. A table with the results was made. From the table a polynomial of five degrees were made to get a way to calculate the height when the area is known. The polynomial was obtained using the excel-function "Linest". See Equation (3.11).

$$y = ax^5 + bx^4 + cx^3 + dx^2 + ex + f \tag{3.11}$$

The input for the polynomial is dimensionless area, x, and the output is dimensionless height, y. a, b, c, d, e and f are constants calculated from the table with dimensionless heights and areas.

To find the dimensionless area to put into Equation (3.11), the areas with dimensions calculated from the Equations (3.3) - (3.10) are divided on the total area of the pipe. When the dimensionless heights are found, they are multiplied with the diameter to find the height with dimension.

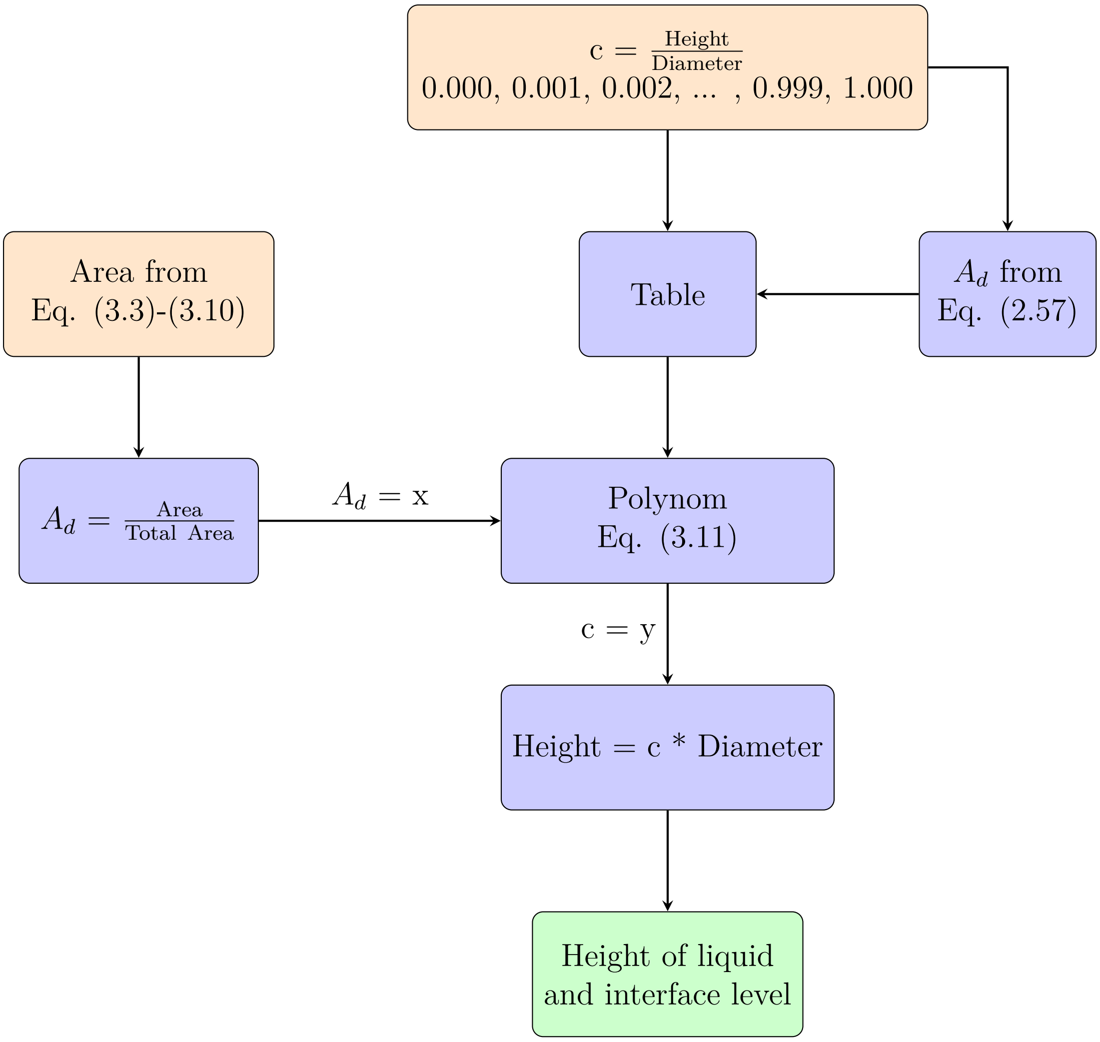

Figure 3.3: Algorithm for calculating height of liquid and interface levels (Bogen 2021). Equation (3.3) - (3.10) gives area and this algorithm describe how to get the corresponding height using a table. The areas with dimension have to be transformed to dimensionless areas (A_d). The height fractions (c) have to be multiplied with the diameter to find the height of the liquid and interface levels.

The Equations (3.3) - (3.6) in combination with the algorithm in Figure 3.3 give one expression for each of the liquid and interface levels. The Equations (3.7) - (3.10) in combination with the algorithm give another expression for the four alarm levels (high and low liquid and interface). In addition, Equation (2.38) and Equation (2.40) give another expression for all the liquid levels and all the interface levels. So there are three expressions for each of the alarm levels and two expressions for each of the shut down levels.

All the constraints have to be fulfilled and the right levels has to be selected. This is done by using the maximum high liquid and interface level. The same applies for the high-high level for the liquid and interface level. The maximum level is selected. For low and low-low the minimum level is selected. That will make sure that both the time, height, slug and surge constraints are fulfilled. The process described above is summarized in Fig. 3.3.

Length between baffle plates (L_b)
The length between the baffle plates can be found by rearranging Equation (2.42) to Equation (3.12). u and v is as mentioned in Section 2.1.8 the sets {HLL, NLL, HIL, NIL} and {NLL, LLL, NIL, LIL}. So four different values for length are calculated and the minimum of these are chosen as the length between the baffle plates.

$$L_b = 2\frac{h_u - h_v}{\tan(\alpha)} \tag{3.12}$$

The number of baffle plates is then given with Equation (3.13).

$$\mathrm{Nr}_{\mathrm{baffle}} = \frac{L_b}{L_e} \tag{3.13}$$

Thickness of cylindrical section (t_{cs})
The thickness of the cylindrical section is calculated with Equation (2.55) as described in Section 2.1.10.

Length of end section (L_n)
The end section needs to have enough space for all the equipment that will be present. The equipment include the outlets, weir, vane demisters and the vortex breakers. It is calculated how much space each of them will take up with Equation (2.43) as described in Section 2.1.9. The maximum length is the length used for the end section.

Length and width of vane demisters (Lvz, Lvx)
In Equation (3.2) the product of the length and width of the vane demisters were calculated. With Equation (2.46) the width is calculated. The length is then found by dividing the product on the width as seen in Equation (3.14).

$$Lvx = \frac{LvxLvz}{Lvz} \tag{3.14}$$

3.1.6 Constraints

There are 14 constraints in the model presented by Grødal & Realff (1999). They are explained below and an overview of all the constraints can be seen in Table 3.3.

Gas Capacity (Le_g)
The first constraint is linked to the gas capacity of the separator and is calculated with Equation (2.14) as described in Section 2.1.3. The length of the gravity separation section must be larger than the constraint calculated here.

Oil Capacity (Le_o)
The second constraint is very similar to the first one, but for the oil capacity of separator. The constraint is calculated with Equation (2.16) as described in Section 2.1.3. The length of the gravity separation section must be larger than the constraint calculated here.

Water Capacity (Le_w)
The third constraint is for the water capacity of separator. The constraint is calculated with Equation (2.17) as described in Section 2.1.3. The length of the gravity separation section must be larger than the constraint calculated here.

Re-Entrainment ($u_{\mathrm{r\ act}}$)
The fourth constraint is for re-entrainment and the slenderness ratio. With Equation (2.27) the actual relative velocity is calculated and this has to be smaller than the maximum relative velocity. To calculate the maximum relative velocity the Reynolds Film number (N_{Re}) and the interfacial viscosity number (N_μ) must be calculated. These values are needed to know which of the Equations (2.32) - (2.36) to use for calculating the maximum relative velocity. The procedure is described in Section 2.1.6.

Oil In Gas Outlet ($h_{vdi} - h_{HHLL}$)
The fifth constraint is for oil in the gas outlet. The distance between the inlet of the vane demister and the high-high liquid level should be larger than the safety margin height which is set to 5 centimeters. See Equation (2.47) in Section 2.1.10.

Gas In Oil Outlet ($h_{LLLL} - h_{WH}$)
Constraint number six consider gas in oil outlet. The distance between the low-low liquid level and the top of the weir should be larger than the safety margin height which is set to 5 centimeters. See Equation (2.48) in Section 2.1.10.

Oil In Water Outlet (h_{LLIL})
This is the last constraint that consider fluid in the wrong outlet. The distance between the low-low interface level and the bottom of the vessel should be larger than the safety margin height which is set to 5 centimeters. See Equation (2.50) in Section 2.1.10.

Maximum Separator Length ($L_{\max}$)
Constraint number six is about the total length of the separator and is calculated with Equation (2.52). It has to be smaller than a set maximum length which is set to be 20 meters. See Section 2.1.10.

Maximum Separator Diameter ($D_{\max}$)
Constraint number seven is about the total diameter of the separator and is calculated with Equation (2.53). It has to be smaller than a set maximum diameter which is set to be 4.5 meters. See Section 2.1.10.

Optimization Variables (Di, L_e, h_{NLL}, h_{NIL})
The last constraints is the optimization variables. The optimization variables are the inner diameter, the length of gravity separation section, the normal liquid level and the normal interface level, and should all have positive values.

Table 3.3: Constraints for three phase separator.

	Constraint	Equation	Equation number
1)	Gas capacity	$Le < Le_g$	2.14
2)	Oil capacity	$Le < Le_o$	2.16
3)	Water capacity	$Le < Le_w$	2.17
4)	Re-entrainment	$u_{\text{r act}} < u_{\text{r max}}$	2.26-2.36
5)	Oil in gas	$h_{vdi} - h_{HHLL} > \Delta h_s$	2.47
6)	Gas in oil	$h_{LLLL} - h_{WH} > \Delta h_s$	2.48
7)	Oil in water	$h_{LLIL} > \Delta h_s$	2.50
8)	Normal levels distance	$h_{NLL} - h_{NIL} = 4\Delta h_{NOR} + 2\Delta h_s$	2.51
9)	Total length	$L_{sep} < 20$ m	2.52
10)	Total diameter	$D_{sep} < 4.5$ m	2.53
11)	Positive values	$Di > 0$	-
12)	Positive values	$Le > 0$	-
13)	Positive values	$h_{NLL} > 0$	-
14)	Positive values	$h_{NIL} > 0$	-

3.1.7 Solver

The constraints are set up in the solver. The solver is an add-in that can be used to find an optimal value for a formula (*Define and solve a problem by using Solver* 2021). The solver is used with the setting "GRG Nonlinear". That means that it uses the Generalized Reduced Gradient method that was presented in Section 2.3. The solver is set up with the constraints as viewed in Table 3.3 and run. To make the tool more user friendly the solver is set up in Excel VBA. That means that the user do not have to set up the constraints manually each time the solver is to be used. The code used can be viewed in Listing 3.1.

Listing 3.1: Set up of the solver in Excel VBA

```
Sub Macro8wi()
'
' Macro8wi Solve for cost
'
    Worksheets("3-phase calc").Activate

    'Reset solver
    SolverReset

    'Goal: Get cost as low as possible by changing Le, Di, h_NLL and h_NIL
    SolverOk SetCell:="$C$111", MaxMinVal:=2, ValueOf:=0, ByChange:="$V$15:$V$18", _
        Engine:=1, EngineDesc:="GRG Nonlinear"


        'Constraints

        'Gas capacity constraint: Le_g < Le
        SolverAdd CellRef:="$C$71", Relation:=1, FormulaText:="$J$72"

        'Oil capacity constraint: Le_o < Le
        SolverAdd CellRef:="$C$74", Relation:=1, FormulaText:="$J$72"

        'Water capacity constraint: Le_w < Le
        SolverAdd CellRef:="$C$77", Relation:=1, FormulaText:="$J$72"

        'Re-entrainment constraint: u_r_act < u_r_max
        SolverAdd CellRef:="$C$80", Relation:=1, FormulaText:="$J$75"

        'Oil out gas outlet constraint: hvdi - h_HHLL >= delta_h_s
        SolverAdd CellRef:="$C$83", Relation:=3, FormulaText:="$J$78"

        'Gas out oil outlet constraint: h_LLLL - h_WH >= delta_h_s
        SolverAdd CellRef:="$C$86", Relation:=3, FormulaText:="$J$78"

        'Water out oil outlet constraint: h_WH-HHIL >= delta_h_s
        SolverAdd CellRef:="$C$89", Relation:=3, FormulaText:="$J$78"

        'Oil out water outlet constraint: h_LILL >= delta_h_s
        SolverAdd CellRef:="$C$92", Relation:=3, FormulaText:="$J$78"

        'Normal levels apart constraint: h_NLL-h_NIL>= 4*delta_h_NOR+2*delta_h_s
        SolverAdd CellRef:="$C$95", Relation:=3, FormulaText:="$J$81"

        'Separator length constraint: Lsep < 20 m
        SolverAdd CellRef:="$C$98", Relation:=1, FormulaText:="$J$84"

        'Separator diameter constraint: Dsep < 4.5 m
        SolverAdd CellRef:="$C$101", Relation:=1, FormulaText:="$J$87"

        'K-value constraint: K_value < 0.15 m/s
        SolverAdd CellRef:="$C$104", Relation:=1, FormulaText:="$J$90"

        'Slenderness Ratio constraint: 3 < SL < 5
        SolverAdd CellRef:="$C$107", Relation:=1, FormulaText:="$J$94"
        SolverAdd CellRef:="$C$107", Relation:=3, FormulaText:="$J$93"

        'Variables always positive: Di,Le,h_NLL >= 0
        SolverAdd CellRef:="$V$15:$V$18", Relation:=3, FormulaText:="0"

    'Solve
    SolverSolve '(True)
End Sub
```

First the function is defined. Then the main sheet is activated to make sure that the correct sheet is used. If the wrong sheet is active the optimization will not work. Then the solver is reset with the function *SolverReset*. This avoid constraints from previous runs being stored. Then the goal of the solver is set with the *SolverOk* function. *SetCell* give the objective cell, which is the cost, and *MaxMinVal* give the relation to use. *MaxMinVal:=2* give that the objective cell is to find the minimum value. *ByChange* give the optimize variables. *SolverAdd* adds a new constraint, *CellRef* state the variable cell, *FormulaText* state the constraint cell or value and *Relation* give the relation between the variable cell and contraint cell/value. *Relation:=1* gives <=, *Relation:=2* gives =, and *Relation:=3* >=. *SolverSolve(True)* start the solver run and close the dialogue box that appears when finishing the optimization. (*SolverOk Function* 2021)

The code above describe how to optimize the cost by changing the four variables inner diameter, effective separation length, normal liquid level and normal interface level. This can easily be changed by changing the code. One can for example change the objective variable that are to be optimized, or the optimized variables that are being altered.

3.2 Improvements

After the tool has been implemented some improvements were made. These modifications were added to Version 2 of the sheet.

K-value (K)
Instead of calculating the gas capacity with Eqution (2.14) it is also possible to calculate the K value and set a limit for it. The theory behind the K-value is described in Section 2.1.4. The K-value is calculated by Equation (2.18) and can maximum have a value of 0.15 m/s.

Slenderness Ratio (SL)
The model presented by Grødal & Realff (1999) uses the slenderness ratio to derive the relative velocity constraint. However, the slenderness ratio is not calculated. So the slenderness ratio is introduced as a variable.

Constraints for the variables K-value and the slenderness ratio are used (Personal conversation with Inge Fosse, Leading Advisor Upstream Oil Production Systems Equinor, 2022). The slenderness ratio shall be kept between 3 and 5 and the K-value below 0.15 m/s. Thus, three new constraints are implemented into the tool. The three new constraints are all presented in Table 3.4.

Table 3.4: Additional constraints.

	Constraint	Equation	Equation number
15)	K-value	$K < 0.15m/s$	2.18
16) & 17)	Slenderness Ratio	3 < SL < 5	2.24

Weights and volume (W_{sh}, W_{ns}, W_{int}, W_{dry}, W_{water}, V_{sep}, $W_{fullofwater}$)
The cost is calculated as a function of the dry weight as given in Equation (2.66). But the weight of the separator when filled with fluids is also an important parameter when designing the separator. If the separator is to be placed on a floating structure the weight of the separator has to be considered. The weight of the dry separator and the water can be calculated with the Equations (2.59) - (2.64). The maximum weight is given from Equation (2.65).

Footprint (F_p)
The footprint is calculated with Equation (2.68). Since the footprint says how much space the vessel take up it can also be a useful parameter to optimize for. Space is limited at structures offshore and having a separator with smaller footprint is desirable.

To make the tool more adaptable, Version 2 of the tool also can optimize for footprint. This is done by switching the objective variable in Listing 3.1. Instead of the cost (cell C111), the footprint (cell C118) is set as the objective cell.

3.2.1 Design from varying conditions and application to field lifetime design

One significant problem has not been considered so far when optimizing the design of separators. During the lifetime of a field the properties and operating conditions (incoming rates of oil, gas, water) will change. They will not remain the same for the whole lifetime. It is not feasible to have several separators available and switch when needed. A workaround is to have two trains and switch between using 1 or 2 simultaneously, but the flexibility this provides is limited. Therefore a method to optimize the design for different properties should be considered.

Figure (3.4) show the process process proposed to determine an optimized design for varying operating conditions. The method is exemplified on having 5 possible operational conditions (Cases 1 to 5). For each single case an optimized design is found. Then, the optimized designs are verified for all other cases (for example, the optimized design found for case 1 is "verified" for cases 2 to 5).

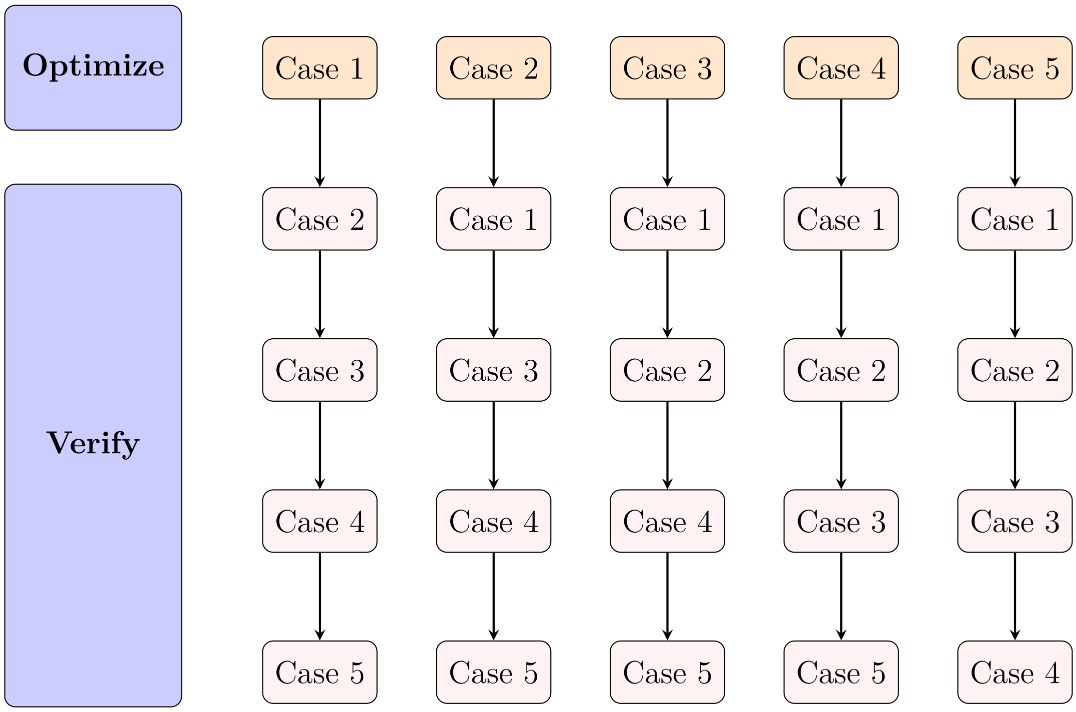

Figure 3.4: Overview for verifying design of the volve cases.

As seen in Figure 3.4 Case 1 is first optimized and given an optimized design. Then Case 2 is verified against the design from Case 1. Case 3 is so verified against the design from Case 1 before Case 4 and Case 5 is also verified. Then Case 2 is optimized and the procedure is repeated. This is done until all cases have been optimized and the other cases have been verified against the design from the optimizations.

The verification process works very similar to optimizing, but with one main difference. When checking the design the inner diameter and the effective length is constant. That means that the normal liquid and interface levels are the optimized variables. When optimizing, the inner diameter and effective length are also optimized variables. Note that it is important that first a case is optimized and then other cases can be verified against the design from the first case. A single case or multiple cases can be verified against a design at once. Figure (A.2) in Appendix A.3 shows the algorithm for verifying.

After this process has been performed the designs can be evaluated. A design is only suitable if all cases are fulfilling all the constraints. If not the design should be disregarded. If more than one design is fulfilling all constraints for all cases the design with the lowest value for the variable that is optimized should be selected. If no designs fulfill all constraints for all cases then no design has been found.

3.3 Case studies

After implementing the model the next step is to compare it with other works and tools. The results are first compared to the results that Grødal and Realff report. Then a Case study with data from the Volve field in the North Sea is done. Finally one of the Volve cases is run in a similar tool from Equinor and the results are compared to the results from the tool implemented in this thesis.

3.3.1 Comparing with case from Grødal and Realff

Grødal and Realff report the results of some of the variables. To compare the tool with the results they report the same inputs were used. Then the tool is run and the results are reported. The input values that were used are listed in Table (3.5) and Table (3.6) below. Note that for this case study Version 1 of the tool was used.

Table 3.5: Input data for case study to compare with the results Grødal and Realff report.

Fluid Properties					
Fluid		Gas	Oil	Water	
Flow Rate	q	1.501	0.226	0.041	m3/s
Density	ρ	18.00	767.7	974.6	kg/m3
Viscosity	μ	1.07E-05	7.30E-04	3.70E-04	Pa s
Surface tension oil and gas	σ_og		1.78E-02		kg/m2

Table 3.6: Input data for case study to compare with the results Grødal and Realff report.

		Oil in gas	Water in oil	Oil in water	
Droplet/Bubble size	dog/dwo/dow	1.00E-04	2.50E-04	2.50E-04	m

A larger overview of the values of the variables used can be viewed in Section 3.1.2.

3.3.2 Volve field

To test the design tool data from real life were used. Equinor has published the data from the Volve field in the North Sea (Equinor 2018, *Factpages Norwegian Petroleum Dictorate - Volve* 2022). From this data the production profile was plotted. The rates from five different periods of the production the volumetric rates were taken and used as input to the design tool. Figure 3.5 show the production profile.

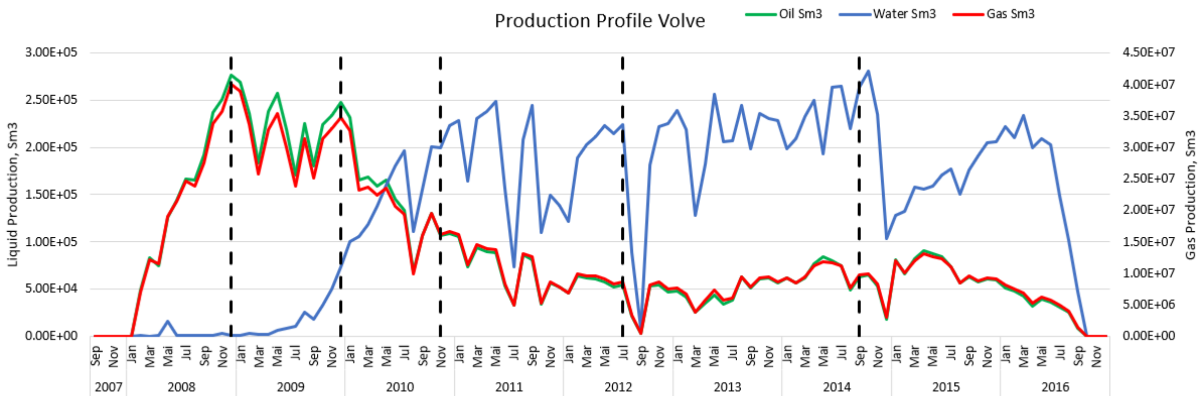

Figure 3.5: The production profile of the Volve field. Shows the production history from production start in February 2008 until shut down in September 2016. The data used for optimization are indicated by the vertical black lines.

The data used for optimization are indicated by the vertical black lines. The data was selected to properly capture the variability of operational conditions during the lifetime of the field. The field rates are given in standard cubic meters per day (Sm^3/d). But the separator needs the actual rates (m^3/s) as input. To calculate the actual rates that corresponds to the standard rates, the black oil model were used.

These data was put into Version 2 of the tool and optimized and verified as shown in Figure 3.4 to find the best design for all five cases overall. The input data is listed in Table 3.7 and Table 3.8. The rates change between the five different cases but the other parameters are constant. In real life all parameters would change, but this is done to save time. In real life one should calculate how the properties change over time.

Table 3.7: Input data for the Volve field case study. Note that the flow rates changes between the different cases.

Fluid Properties					
Fluid		Gas	Oil	Water	
Flow Rate	q	0.137	0.028	0.102	m3/s
Density	ρ	1.10	885.2	1101.3	kg/m3
Viscosity	μ	1.43E-05	1.10E-03	3.85E-04	Pa s
Surface tension oil and gas	σ_og		1.78E-02		N/m

Table 3.8: Input data for the Volve field case study.

	Oil in gas	Water in oil	Oil in water	
Droplet/Bubble size dog/dwo/dow	1.00E-04	2.50E-04	2.50E-04	m

3.3.3 Comparing with Equinor tool

To know how the tool performs compared with other tools a case study with a similar too from Equinor has been performed. Version 2 of the tool implemented has been used in this case study. A short summary of how the Equinor tool works is following below. The summary is short and not very detailed because that was part of the agreement for the use of the tool.

The tool from Equinor has similar inputs as Version 2. Density, viscosity and rates are all among these input variables. The ratio of the height of the normal liquid level and inner diameter is one of the design parameters that are used to optimize. Another of these parameters is the slenderness ratio. The tool calculate the normal liquid level and then the rest of the liquid levels. The same method is used for the interface levels. The inner diameter is calculated from a range of other variables, including the two ratios mentioned. The inner diameter is so used to calculate other variables. This is done in an iterative process. The tool can optimize either for minimum dry weight or for minimum footprint. To compare the two tools one of the cases from Volve is used as input data. The optimization is run in both tools and the results of some important variables are compared. The Equinor tool is optimized for dry weight while Version 2 is optimized for cost. Since the cost in Version 2 depend on the dry weight both tools will try to find the minimum dry weight.

4 Results and discussion - Tool

In this chapter the tool will be presented and discussed. First the Excel spreadsheet is presented and the different sheets are explained. First Version 1, which is the version that only is based on Grødal & Realff (1999), is presented. All the different sheets are viewed. Then the improvements from Version 1 is presented. These improvements are implemented into Version 2 of the tool.

4.1 Presenting Tool

The tool is made in Microsoft Excel. Version 1 consist of three sheets. The main sheet is called "3-phase calc". All the inputs are here and most of the calculations including the calculation of the cost are done here. Sheet number two is called "Height" and here the calculations of the different liquid and interface levels are performed. The third sheet is called "Velo" and is where the settling velocities are calculated.

4.1.1 Main sheet

The main sheet ("3-phase calc") consist of three parts. Input and initial calculations, design variables, and constraints and solution. For the color codes, see Figure 3.1 in Section 3.1.

Input and initial calculations

Table 4.1 shows the cells that contain the pressure, temperature and fluid properties. The fluid properties are the flow rates, densities and viscosities of gas, oil and water and the surface tension between the oil and the gas. Furthermore, the capacity of slug and surge are in the cells below. Then the gas-oil ratio and the water cut follows. In the three bottom rows are the droplet and bubble sizes and the settling velocities.

Table 4.1: Input values containing pressure, temperature, flow rates, densities, viscosities, surface tension, slug and surge volume, gas-oil ratio, water cut, droplet/bubble sizes and settling velocities.

Pressure and Temperature					
Operating temperature	T	362.15	K	89	C
Operating pressure	p	32.5	bar	3250000	Pa
Design Pressure	p_D	35.75	bar	3575000	Pa

Fluid Properties					
Fluid		Gas	Oil	Water	
Flow Rate	q	0.561	0.122	0.000	m3/s
Density	ρ	17.46	767.7	974.6	kg/m3
Viscosity	μ	1.07E-05	7.30E-04	3.70E-04	Pa s
Surface tension oil and gas	σ_og		1.78E-02		kg/m2
Slug volume	V_slug		10		m3
Surge volume	V_surge		10		m3
Gas-oil ratio, separator condit	GOR		4.599		-
Water cut, separator conditio	WC		0.004		-

		Oil in gas	Water in oil	Oil in water	
Droplet/Bubble size	dog/dwo/dow	1.00E-04	2.50E-04	2.50E-04	m
Settling velocity	uog/uwo/uow	0.182	0.008	0.013	m/s

The setup here is used in most of the Excel file. In the cell to the left is the name of the variable or constant, in the next cell is the symbol. After the symbol is the value and then the unit of the variable or constant. Where the values have the colour red they can be changed in that specific cell. When the cells are blue it means they are calculated from values from other cells. The green, which can be observed for the values for the settling velocities means that the values are from another cell in the Excel file. The settling velocities are retrieved from the sheet called "Velo".

Table 4.2 shows the physical constants and fixed variables, the pitch degree and the height and time variables.

Table 4.2: Input values containing physical constants and fixed variables.

Physical Constants and Fixed Variables			
Joint efficiency	E	1	-
Surface area of vessel head factor	Fa	1.09	-
Cost factor	Fc	5	$/kg
Cost per unit mass ratio	Fh	3	-
Gravitational acceleration	g	9.81	m/s2
Corrosion allowance	tc	0.0032	m
Tensile strength	σ	9.50E+07	Pa
Density steel	ρs	7850	kg/m3
Pitch degree	α	10	degrees

Height and time variables			
Height interval NORSOK standard	Δh_NOR	0.08	m
Safety margin height	Δhs	0.05	m
Time interval NORSOK standard	Δt_NOR	30	sec

Table 4.3 shows the heights of some of the components in the end section, the length of some separator sections and the nozzle sizes. The length of the weir and the inlet section are input values while the rest are calculated.

Table 4.3: End section heights, separator components lengths and the nozzle sizes.

End Section Height			
Vane demister inlet	h_vdi	2.008	m
Vane demister outlet	h_vdo	2.208	m
Vane demister mounting point	h_vdm	2.308	m

Separator Components Length			
Vane demister length*width	LvxLvz	0.796	m2
Cyclone section	Lc	1.000	m
Head section	Lh	0.602	m
Weir	L_WH	0.010	m

		Gas	Oil	Water	
Nozzle Diameter	d_n	0.406	0.403	0.182	m

Table 4.4 contains the optimized variables: the inner diameter, the length of the gravity separation section, the normal liquid level and the normal interface level. They are the variables that are changed during the optimization and affect the design variables. As shown in Table 4.4 the numbers are violet, which means that they are optimized.

Table 4.4: Optimized variables.

Optimized Variables			
Inner separator diameter	**Di**	**2.950**	**m**
Length gravity separation section	**Le**	**16.653**	**m**
Height normal liquid level	**h_NLL**	**2.201**	**m**
Height normal interface level	**h_NIL**	**1.038**	**m**

Design Variables

After the input the cells with the design variables are calculated. Table 4.5 shows the 5 different liquid levels and the 5 different interface levels. Below them is the interbaffle distance, the wall thickness, the length of the end section and the size of the vane demister. In the cells below is the number of baffle plates and the height of the weir.

Table 4.5: Liquid and interface levels, lengths of different sections and components in the separator, number of baffle plates and weir height.

Liquid Level Height				
High high	h_HHLL	1.826	m	46 %
High	h_HLL	1.746	m	44 %
Normal	h_NLL	1.600	m	40 %
Low	h_LLL	1.439	m	36 %
Low Low	h_LLLL	1.359	m	34 %

Interface Level Height				
High high	h_HHIL	0.960	m	24 %
High	h_HIL	0.880	m	22 %
Normal	h_NIL	0.800	m	20 %
Low	h_LIL	0.720	m	18 %
Low Low	h_LLIL	0.640	m	16 %

Length			
Interbaffle distance	Lb	0.91	m
Wall thickness cylindrical section	tcs	0.080	m
End section	Ln	0.639	m
Width of vane demister	Lvz	1.249	m
Length of vane demister	Lvx	0.235	m

Baffle plates	Nr_baffle	17	-

Weir Height			
Weir, from water	h_WH1	1.010	m
Weir, from oil	h_WH2	1.309	m
Weir	h_WH	1.160	m

Table 4.6 shows the different liquid and interface levels that are calculated from different constraints. The length required for different components in the end section is below. For high and high-high levels, the maximum level are chosen. For low and low-low levels, the minimum level are chosen. The maximum end section length are selected. This makes sure that all constraints are fulfilled. Table 4.5 shows the selected levels and length.

Table 4.6: Liquid and interface levels for different constraints. Below is the length required to have enough space in the end section.

Liquid Alarm and Area Level		
High high time	h_HHLL_time	1.705 m
High high alarm	h_HHLL_height	1.826 m
High time	h_HLL_time	1.649 m
High alarm	h_HLL_height	1.680 m
High slug	h_HLL_slug	1.746 m
Low time	h_LLL_time	1.536 m
Low alarm	h_LLL_height	1.520 m
Low surge	h_LLL_surge	1.439 m
Low low time	h_LLLL_time	1.480 m
Low low alarm	h_LLLL_height	1.359 m

Interface Alarm and Area Level		
High high time	h_HHIL_time	0.810 m
High high alarm	h_HHIL_height	0.960 m
High time	h_HIL_time	0.809 m
High alarm	h_HIL_height	0.880 m
High slug	h_HIL_slug	0.810 m
Low time	h_LIL_time	0.809 m
Low alarm	h_LIL_height	0.720 m
Low surge	h_LIL_surge	0.808 m
Low low time	h_LLIL_time	0.809 m
Low low alarm	h_LLIL_height	0.640 m

Length end section components		
Gas nozzle	Ln1	0.247 m
Vane demister	Ln2	0.235 m
Liquid outlets	Ln3	0.639 m

In Table 4.7 are the area of the liquid and interface levels that are calculated. Below them are the different interbaffle distances calculated. The minimum of them are selected and put into Table 4.5.

Table 4.7: Area of the liquid and interface levels. In the bottom are the interbaffle distances.

Area (residence time)						
Top of Separator		A_TV	4.555	m2	100	%
Liquid	High high	A_HHLL_time	3.538	m2	78	%
	High	A_HLL_time	3.111	m2	68	%
	Normal	A_NLL	2.685	m2	59	%
	Low	A_LLL_time	2.259	m2	50	%
	Low Low	A_LLLL_time	1.832	m2	40	%
Interface	High high	A_HHIL_time	0.595	m2	13	%
	High	A_HIL_time	0.526	m2	12	%
	Normal	A_NIL	0.458	m2	10	%
	Low	A_LIL_time	0.389	m2	9	%
	Low Low	A_LLIL_time	0.321	m2	7	%

Area (slug/surge)						
Liquid	High	A_HLL_slug	3.217	m2	71	%
	Low	A_LLL_surge	2.153	m2	47	%
Interface	High	A_HIL_slug	0.559	m2	12	%
	Low	A_LIL_surge	0.357	m2	8	%

Interbaffle distance				
Liquid	High - Normal	Lb1	2.60	m
	Normal - Low	Lb2	2.53	m
Interface	High - Normal	Lb3	0.91	m
	Normal - Low	Lb4	0.91	m

Constraints and solution

Table 4.8 shows the different constraints. The value in the middle are the calculated and to the right under "Unused capacity" are the unused capacity. With unused capacity it is meant how far from the constraint maximum capacity the different variables are.

Table 4.8: The constraints for designing the separator. In the middle are the value of the constraints calculated. To the right are the unused capacity listed.

Gas Capacity				Unused capacity	
Length required for gas capacity	Le_g	1.00	m	14.00	m
Oil Capacity				Unused capacity	
Length required for oil capacity	Le_o	5.40	m	9.596	m
Water Capacity				Unused capacity	
Length required for water capacity	Le_w	0.02	m	14.98	m
Re-Entrainment				Unused capacity	
Actual relative velocity gas and oil phase	u_r_act	0.029	m/s	0.683	m/s
Oil Out Gas Outlet				Unused capacity	
Height difference limit to avoid oil out gas outlet	hvdi-h_HHLL	1.774	m	1.724	m
Gas Out Oil Outlet				Unused capacity	
Height difference limit to avoid gas out oil outlet	h_LLLL-h_WH	0.20	m	0.150	m
Oil Out Water Outlet				Unused capacity	
Height difference limit to avoid oil out water outlet	h_LLIL	0.640	m	0.590	m
Normal Levels Apart				Unused capacity	
Height difference actual	Δh_N_act	0.800	m	0.380	m
Total Separator Length				Unused capacity	
Length separator	L_sep	18.65	m	1.35	m
Total Separator Diameter				Unused capacity	
Separator diameter	D_sep	4.16	m	0.34	m

Table 4.9 contain the cells with the different constraint limits that the values in Table 4.8 have to fulfill. The maximum length and diameter are input while the other values are calculated.

Table 4.9: The constraint limits used in the optimization.

Capacity			
Length of gravity separation section	Le	15.00	m
Re-entrainment			
Maximum relative velocity gas and oil phase	u_r_max	0.712	m/s
Safety margin			
Safety margin height	Δhs	0.05	m
Normal levels			
Normal levels minimum difference	Δh_N_min	0.42	m
Max Separator Length			
Maximum length separator	L_max	20.00	m
Max Separator Diameter			
Maximum diameter separator	D_max	4.50	m

Table 4.10 contain cells with the horizontal velocities. Below them are the some variables used to calculate the relative velocity between gas and oil. Below that are the residence and settling times and in the bottom are the mean separator diameter.

Table 4.10: Horizontal velocities, relative velocity calculation, residence and settling time and the mean separator diameter.

Horizontal velocities			
Gas velocity horizontally	ug	0.071	m/s
Oil velocity horizontally	uo	0.042	m/s
Water velocity horizontally	uw	0.000	m/s

Relative velocity calculations			
Hydraulic diameter	D_H	3.405	m
Reynolds film number	N_ref	1.50E+05	-
Interfacial viscosity number	N_my	5.01E-03	-

Maximum gas velocity	u_g_ma	1.916	m/s

Residence Time			
Residence time gas	t_r,g	210.42	s
Residence time oil	t_r,o	357.05	s
Residence time water	t_r,w	65021.59	s

Settling Time			
Settling time oil in gas	t_og	14.08	s
Settling time water in oil	t_wo	128.64	s
Settling time oil in water	t_ow	68.53	s

Mean Separator Diameter			
Mean Separator Diameter	Dm	4.081	m

The last table from the main sheet is Table 4.11. It includes the the separator manufacturing cost which is used to optimize the separator. The optimizing intends to make the cost value as small as possible.

Table 4.11: Separator manufacturing cost.

Cost			
Separator manufactoring cost	**C**	**1 014 389**	**$**

4.1.2 Sheet for calculating velocities

The second sheet serves to calculate the settling velocity of the different phases. As there are three phases, there are 6 different settling velocities. But as mentioned in Section 2.1.1 there is only 3 relevant settling velocities.

In Table 4.12 the different settling velocities are presented. In the top row is the phases. Below are the settling velocities, the number of iterations used, the drag coefficient, the Reynolds number and the check.

Table 4.12: Settling velocities.

Calculation of settling velocities								
Phase		Oil in gas	Water in oil	Oil in water	Water in gas	Gas in oil	Gas in water	
Settling velocity	u	**0.180**	**0.008**	**0.013**	0.515	0.025	0.043	m/s
Number of iterations	n	20	28	24	13	25	20	-
Drag coefficient	Cd	1.68	13.86	4.21	0.65	5.20	1.76	-
Reynolds number	N_re	30.33	2.10	8.46	216.70	6.52	28.13	-
Check		3.2E-10	8.0E-10	8.4E-10	1.7E-10	7.4E-10	4.5E-10	-

The 3 settling velocities that are used in the model, oil in gas, water in oil and oil in water, are in bold. The check has to be smaller than the constraint in Table 4.13.

Table 4.13 contain the inputs used to calculate the settling velocities. The size of the droplets, densities, viscosities, initial drag coefficient estimate and the constraint that must be fulfilled.

Table 4.13: Inputs used to calculate the settling velocities in the different phases.

Constants			
Droplet oil in gas	dog	1.00E-04	m
Droplet water in oil	dwo	2.50E-04	m
Droplet oil in water	dow	2.50E-04	m
Gas density	ρg	18	kg/m3
Oil density	ρo	767.7	kg/m3
Water density	ρw	974.6	kg/m3
Gas viscosity	µg	1.07E-05	Pas
Oil viscosity	µo	7.30E-04	Pas
Water viscosity	µw	3.70E-04	Pas
Gravitational acceleration	g	9.81	m/s2
Drag coefficient initial	Cd_0	0.34	-
Constraint	eps	1.00E-09	

Thus, by obtaining these inputs from the main sheet, this "Velo"-sheet calculate the settling velocities and return them to the main sheet. The settling velocities can be found in the main sheet in Table 4.1.

4.1.3 Sheet for calculating height

The sheet for calculating height is called "Height(2)". It takes in the areas calculated with the Equations (3.3) - (3.10) and gives the corresponding height back to the main sheet. The procedure is described in Section 3.1.5. Table 4.14 contains dimensionless heights (c) and the corresponding areas (Ad). The dimensionless heights go from 0 to 1 with steps of 0.001. For each height the corresponding area is calculated with Equation (2.57).

Table 4.14: Table with dimensionless height and corresponding dimensionless area.

c	Ad
-	-
0.000	0.000
0.001	0.000
0.002	0.000
0.003	0.000
0.004	0.000
0.005	0.001
0.006	0.001
0.007	0.001
0.008	0.001
0.009	0.001
0.010	0.002
0.011	0.002
0.012	0.002
0.013	0.003
0.014	0.003
0.015	0.003
0.016	0.003
0.017	0.004
0.018	0.004
0.019	0.004

Table 4.14 give the polynomial in Table 4.15. As described in the table y is the height (c) and x is the area (Ad).

Table 4.15: Polynomial of 5 degrees calculated from Table 4.14.

y=ax^5-bx^4+cx^3+dx^2+ex+f					
y = height			x = area		
a	b	c	d	e	f
3.7995495	-9.4989	9.18909	-4.284761	1.765	0.01499848

Table 4.16 contains the areas calculated with the Equations (3.3) - (3.10) in the second column. In the third column the corresponding dimensionless areas are listed. Next is the dimensionless heights calculated with the polynomial, and in the last column is the heights with dimensions that are sent back to the main sheet.

Table 4.16: Contains areas, dimensionless areas, dimensionless heights and heights for the different constraints. In the top is also the inner diameter.

Di	2.408

Step E-3, Polynomial of degree 5				
	Area	Area	Height	**Height**
	m2	-	-	**m**
TV	4.555	1.000	0.985	2.372
HHLL_time	3.538	0.777	0.724	1.743
HLL_time	3.111	0.683	0.647	1.558
NLL	2.685	0.589	0.572	1.378
LLL_time	2.259	0.496	0.497	1.196
LLLL_time	1.832	0.402	0.421	1.014
HHIL_time	0.595	0.131	0.190	0.458
HIL_time	0.526	0.116	0.174	0.420
NIL	0.458	0.100	0.157	0.379
LIL_time	0.389	0.085	0.140	0.337
LLIL_time	0.321	0.070	0.121	0.292

HLL_slug	3.217	0.706	0.666	1.603
LLL_surge	2.153	0.473	0.478	1.151
HIL_slug	0.559	0.123	0.182	0.438
LIL_surge	0.357	0.078	0.131	0.316

Figure 4.1 show the plot of Table 4.14. It is plotted as the blue line (c/Ad). The liquid levels are plotted as red points (LL) and the interface levels are marked as black point (IL). A polynomial of degree 5 (*Quintic function* 2022) based on Table 4.14 is plotted with a dotted blue line.

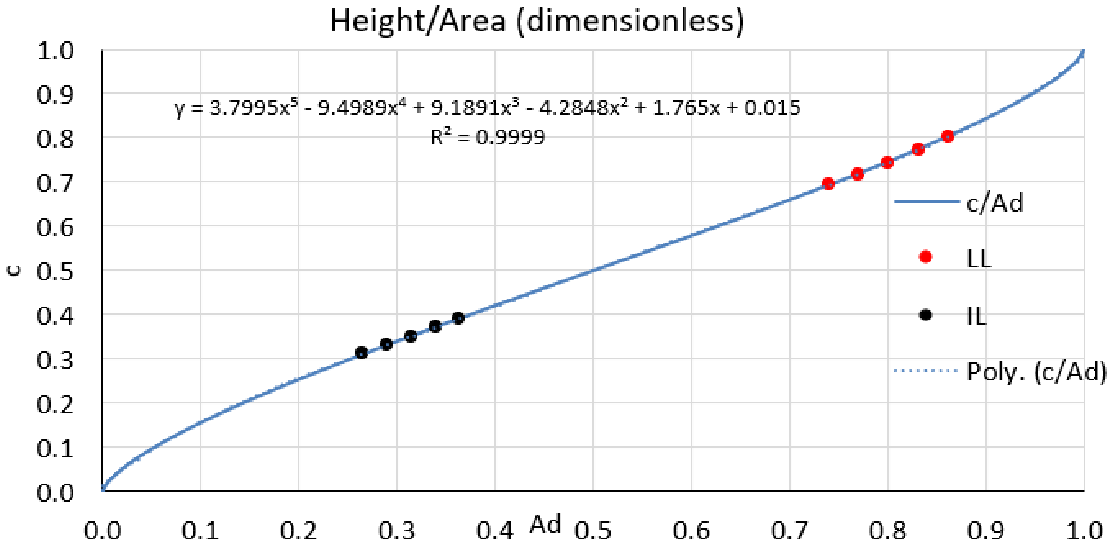

Figure 4.1: Plot of data in Table 4.14 with polynomial of 5 degrees and the liquid and interface levels marked. Both axes are dimensionless.

It is possible to see the polynomial plot in the top right corner and in the bottom left corner, but most of the time it is behind the plot "c/Ad". That shows that the polynomial is a good fit. The equation for the polynomial is also written in Figure 4.1. The values there match the values in Table 4.15 confirming that the "Linest"-function give a good polynomial. Below the function the R^2 is written. The R^2 "can be interpreted as the proportion of the variance in the dependent variable that is predictable from the independent variables" (Chicco et al. 2021). That means that the R^2 is a measure of how many points that falls on the regression line . A polynomial 3 degrees gave R^2 the value of 0.9996, which means 99.96% of all points are on the line. A polynomial of 4 degrees gave no difference, but with 5 degrees R^2 got a value of 0.9999 (99.99%) and no difference in run-time. That means that there is very small difference between polynomial of 3 and 5 degrees, but with no difference in run-time the polynomial of 5 degrees was selected. In very big samples 0.03% can make a difference, but it will not be very significant.

4.1.4 How the solver performs?

The solver converge to the same values for the optimized variables for different initial guesses. A solution is found after a couple of seconds. Sometimes the solver can struggle to find a solution and give an error message. Most of the time a restart of the solver fixes the problem. If that do not work, changing the value of one of the optimized variables often fixes the problem. It is recommended to try to decrease the normal liquid level first. That is because the error most of often is caused by the lack of space for the high and high-high liquid levels. If the normal liquid level is too high there will not be enough space. If that do not work the guess of the normal interface level should be changed.

4.2 Improvements

The changes from version 1 of the tool to version 2 will be presented in this section. There are two main differences. First some new constraints and variables are introduced. Second a new sheet is used to easier compare results of different simulations. In this sheet there is also some changes in the optimization.

4.2.1 Constraints and variables

In version 1 of the tool the gas capacity is calculated from Equation (2.14). The equation give the minimum length of the effective separation section required to perform the separation in the gas phase at a satisfactory extent, Le_g. In version 2 the K-value is used to calculate the gas capacity from Equation (2.18). This is added as a new constraint in addition to the ones that were in version 1.

In version 1 of the tool the maximum relative velocity is used as an upper bound on the slenderness ratio. But the slenderness ratio is not calculated. When calculating the slenderness ratio of some of the designs proposed it looks like it often is a bit high. Instead of being between 3 and 5 most of the designs from version 1 of the tool give slenderness ratio of around 6. Therefore two additional constraints are added in version 2. One for the minimum value of the slenderness ratio, 3, and one for the maximum value, 5.

In Table 4.17 the three new constraints can be viewed. They are just below the other constraints in the sheet showed in Table 4.8. As for the other constraints the unused capacity is also calculated and can be seen to the right of the table. Since the slenderness ratio does not only have an upper limit or a lower limit but both, there is two values for unused capacity.

Table 4.17: Constraints for K-value and slenderness ratio.

K-value				Unused capacity		
K-value	K	0.016	m/s	0.13	m/s	

Slenderness Ratio				Unused capacity	
Slenderness Ratio	SR	4.96	-	0.04	1.96
				Max	Min

The calculation of the K-value requires the introduction of the maximum gas velocity which can be found in Table 4.18.

Table 4.18: The maximum gas velocity which is needed to calculate the K-value.

Gas velocity, Di-HLL	ug	0.110	m/s

The limits of the constraint in Table 4.17 is viewed in Table 4.19. One for K-value and two for the slenderness ratio. In version 2 of the tool this table is placed just below Table 4.9 which include the other limits for the constraints.

Table 4.19: The limits of the K-value and slenderness ratio for version 2 of the tool.

Max K_value			
K_value	K_max	0.15	m/s

Slenderness Ratio			
Minimum Slenderness Ratio	SL_min	3	-
Maximum Slenderness Ratio	SL_max	5	-

Table 4.20 includes the variables for calculating the weight of the separator. The equations and theory behind is presented in Section 2.1.12.

Table 4.20: Volume and weight of the separator.

Volume			
Volume head sections	V_head	4.50	m3
Volume shell	V_shell	133.95	m3
Total volume vessel	V_sep	142.96	m3

Weight					
Shell+head	W_sh	15 701	kg	15.7	ton
Nozzle+saddle	W_ns	3 925	kg	3.9	ton
Internal	W_int	1 570	kg	1.6	ton
Total dry	W_dry	21 196	kg	21.2	ton
Water, filled separator	W_water	142 956	kg	143.0	ton
Full of water	W_full	164 152	kg	164.2	ton

Table 4.21 contains the footprint of the separator.

Table 4.21: Footprint of the separator.

Footprint			
Footprint of separator	Fp	51.87	m2

4.2.2 Sheet for results

In Version 2 a new sheet is introduced. The sheet can be used to run multiple simulations, compare results and easier make changes to input variables in the simulation.

In Table 4.22 the first part of the "Results"-sheet is viewed.

Table 4.22: The input part of the "Results"-sheet.

			Input					
Case Name	Solver Output	Optimized /Verified	Separator Condition		Rate			Nr of separators
			Temperature K	Pressure bar	Gas m3/s	Oil m3/s	Water m3/s	-
BASE CASE	0	Optimized	350	20	1.501	0.226	0.041	1

The first column contains the *Case Name*. Here the name of the case is written manually. After that is the *Solver Output* which is a return value that says something about how and if the problem was solved. The two most frequently outputs are 0 and 5 even though the output can be all numbers between 0 and 20. 0 means "solver found a solution. All constraints and optimality conditions are satisfied." 5 means "solver could not find a feasible solution". (*Define and solve a problem by using Solver* 2021) The other output variables values can be found in Appendix A.2. *Optimized/Verified* tells if the case has been optimized or verified.

The input variables include the separation conditions, the rate of the different phases and how many separators that are used. The values that are to be used in the simulation have to be written here.

Table 4.23 contains some of the variables that are recorded after the optimization. First is the residence time and settling time for all three phases. Then are the length of the effective section, the length of the end section and the total length. The last variables recorded are the inner and total diameter.

Table 4.23: The residence and settling times, lengths and diameters recorded in the "Results"-sheet.

Residence Time			Settling Time			Length			Diameter	
Gas s	Oil s	Water s	Oil in gas s	Water in oil s	Oil in water s	Effective m	End section m	Total m	Inner m	Total m
20.4	164.4	185.2	6.9	164.4	35.7	16.61	1.18	20.00	2.40	2.47

Table 4.24 contains more variables from the optimization. The height of the weir is the first variable recorded. Then comes the constraints. The values of unused capacity from Table 4.8 are recorded here. If the design is fulfilling the constraints the value should be more or equal 0. So the capacity for the gas, oil and water are first recorded. Then the re-entrainment constraint, and the different height limits are recorded.

Table 4.24: The height of the weir and the unused capacity of the constraints recorded in the "Results"-sheet.

Output							
Height	Constraints						
	Capacity			Re-	Outlet		
Weir	Gas	Oil	Water	entrainme	Oil out Gas	Gas out Oil	Oil out water
m	m	m	m	m/s	m	m	m
0.78	11.03	0.00	13.41	0.000	0.21	0.19	0.17

Table 4.25 continue recording the unused capacity of the constraints. The difference between the normal levels and the constraints for total length and diameter are all recorded here. The last value recorded is the cost of the separator.

Table 4.25: The unused capacity of normal levels and diameters as well as the cost are recorded in the "Results"-sheet.

Normal	Total		Cost of
levels	Length	Diameter	separator
m	m	m	$
0.58	0.00	2.03	225 306

For all the output variables in the "Results"-sheet, Table 4.23-4.25, the value will change colour to red if the value is below 0. That will make it easier to see when the tool can not find a design that fulfills all the constraints.

Table 4.22 - 4.25 are side by side with Table 4.22 to the left and Table 4.25 all the way to the right.

The results presented in this section above has only described the tables and which variables that are present and where they are located. But the key element for this sheet is to connect it to the "Main"-sheet. Table 4.26 shows control panel of the "Results"-sheet. The panel is located in the top of the sheet.
The values of the cells to the right are changed to optimize or verify the rows that the user wants. The "AddOne" and "SubtractOne" buttons can be used to change the values in the cells. A single row can be optimized or verified, or multiple rows can be optimized

Table 4.26: The control panel of the "Results"-sheet.

Optimize Cost	Optimize Footprint	ROWS		AddOne
		From	54	
Verify Cost	Verify Footprint	To	54	SubtractOne

or verified at the same time. If multiple rows are to be optimized or verified they have to be listed one after the other, without blank rows in between. Also only one action can be performed at once, meaning that either the rows are optimized or they are verified. The optimize buttons is used to optimize the rows that are listed to the right, while the verify buttons are used to verify the rows the listed rows. The user can select between optimizing or verifying the cost or the footprint of the separator.

5 Results and discussion - Case studies

In this section the results from the three different case studies will be presented and discussed.

5.1 Case from Grødal and Realff

In this section the results that Grødal and Realff report from their model are presented. Then the results from using the tool developed are presented, before the difference between them are presented.

In Table 5.1 the results Grødal and Realff report are presented.

Table 5.1: Values of variables that are reported from Grødal & Realff (1999).

Grødal/Realff SOLUTION									
C	225480	$	h_LLL	1.164	m	Pd	2200000	Pa
			h_LLLL	0.985	m	tcs	0.0320	m
			h_NIL	0.378	m	t_r,g	20.4	s
			h_NLL	1.386	m	t_r,o	166.0	s
D	2.474	m	h_WH	0.588	m	t_r,w	185.00	s
Dh	2.812	m	L	20.000	m	t_og	6.8	s
Di	2.410	m	Lb	0.907	m	t_ow	36.0	s
Dmean	2.44	m	Le	16.550	m	t_wo	166.0	s
d_n,g	0.403	m	Lh	0.635	m	ug	0.812	m/s
d_n,o	0.403	m	Ln	1.181	m	uo	0.100	m/s
d_n,w	0.182	m	Lvx	0.815	m	uw	0.090	m/s
h_HHIL	0.538	m	Lvz	0.961	m	uog	0.182	m/s
h_HHNL	1.811	m	N_ref	2.97E+05	-	uow	0.013	m/s
h_HIL	0.458	m	N_re,og	29.7	-	uwo	0.008	m/s
h_HLL	1.614	m	N_re,ow	8.43	-	u_g_max	1.920	m/s
h_LIL	0.298	m	N_re,wo	2.10	-	u_r_max	0.712	m/s
h_LLIL	0.218	m	N_my	0.0050	-			

The first thing they report is the cost, C. Then below is the total diameter of the separator D, Dh is the hydraulic diameter, Di is the inner separator diameter, $Dmean$ is the mean separator diameter, d_n is the size of the nozzles and h is the height. L is the total length of the separator, Lb is the length between the baffle plates, Le is the length of the gravity separation section, Lh is the the length of the head section, Ln is the length of the end section, Lvx and Lvz are the length and width of the vane demister. N_{ref} is the Reynolds film number, $N_{re,og}$ and $N_{re,og}$ is the droplet and bubble Reynolds number and N_{my} is the interfacial viscosity number. P_d is the design pressure, tcs is the wall thickness of the cylindrical section, t_r is the residence time and t is the settling time. u is the horizontal velocity, u_{gmax} is the maximum gas velocity and u_r max is the maximum relative velocity.

Table 5.2 shows the same variables as Table 5.1, but from the tool that has been developed.

Table 5.2: Values of the variables when optimizing with same inputs as used in paper by Grødal & Realff (1999).

OVERALL SOLUTION

C	225306	$	h_LLL	1.156	m	Pd	2200000	Pa
			h_LLLL	1.019	m	tcs	0.0314	m
			h_NIL	0.378	m	t_r,g	20.4	s
			h_NLL	1.379	m	t_r,o	164.4	s
D	2.467	m	h_WH	0.588	m	t_r,w	185.22	s
Dh	2.709	m	L	20.000	m	t_og	6.9	s
Di	2.404	m	Lb	0.907	m	t_ow	35.7	s
Dmean	2.44	m	Le	16.611	m	t_wo	164.4	s
d_n,g	0.403	m	Lh	0.601	m	ug	0.813	m/s
d_n,o	0.403	m	Ln	1.180	m	uo	0.101	m/s
d_n,w	0.182	m	Lvx	0.816	m	uw	0.090	m/s
h_HHIL	0.538	m	Lvz	0.960	m	uog	0.182	m/s
h_HHLL	1.749	m	N_ref	2.88E+05	-	uow	0.013	m/s
h_HIL	0.458	m	N_re,og	29.7	-	uwo	0.008	m/s
h_HLL	1.609	m	N_re,ow	8.456	-	u_g_max	1.916	m/s
h_LIL	0.298	m	N_re,wo	2.10	-	u_r_max	0.712	m/s
h_LLIL	0.218	m	N_my	0.0050	-			

Table 5.3 shows the difference between Table 5.1 and Table 5.2 in percentages.

Table 5.3: Difference between the values Grødal and Realff report and the values when optimizing with the same inputs.

Difference % (OVERALL - Grødal/Realff)					
C	-0.08 %	h_LLL	-0.71 %	Pd	0.00 %
		h_LLLL	3.44 %	tcs	-1.77 %
		h_NIL	0.00 %	t_r,g	0.17 %
		h_NLL	-0.50 %	t_r,o	-0.96 %
D	-0.27 %	h_WH	0.00 %	t_r,w	0.12 %
Dh	-3.66 %	L	0.00 %	t_og	0.98 %
Di	-0.23 %	Lb	0.04 %	t_ow	-0.93 %
Dmean	-0.16 %	Le	0.37 %	t_wo	-0.96 %
d_n,g	0.05 %	Lh	-5.34 %	ug	0.11 %
d_n,o	-0.03 %	Ln	-0.08 %	uo	1.04 %
d_n,w	0.08 %	Lvx	0.12 %	uw	0.21 %
h_HHIL	0.00 %	Lvz	-0.11 %	uog	-0.08 %
h_HHLL	-3.42 %	N_ref	-3.08 %	uow	0.32 %
h_HIL	0.00 %	N_re,og	-0.09 %	uwo	-0.07 %
h_HLL	-0.31 %	N_re,ow	0.31 %	u_g_max	-0.21 %
h_LIL	0.00 %	N_re,wo	-0.17 %	u_r_max	-0.02 %
h_LLIL	0.00 %	N_my	0.15 %		

Table 5.3 shows that the optimization gives a cost that is less than 1% lower than Grødal and Realff report. The diameter is also lower, but it is well under 1% difference. The hydraulic diameter is 3.7% shorter in the optimization. The difference for inner diameter and the nozzle sizes are also very small. The high-high liquid level is 3.4% lower for the optimization and the low-low liquid level is 3.4% higher. The other levels have a deviation below 1%.

The height of the weir, the total length, the length between the baffle plates and the effective separation length all have small deviations. The length of the head sections has a deviation of 5%. Grødal and Realff write that the length of the head section is calculated with Equation (2.54) in their article. But the value they report do not match with the equation so it could be that the wrong number were reported.

The length of the end section has a deviation of -5.3%, but this equals to less than 0.1 meter. Since the value of the length is a small number, the deviation will be look larger than for a variable with a larger value. So even though -5.3% indicate a significant deviation, the deviation is small.

The length and width of the vane demisters have small deviation. The Reynolds film number has a deviation of -3%. The Reynolds film number is used to calculate the relative velocity, but the deviation for the relative velocity is less than a percentage. Therefore the deviation in the Reynolds film number is not considered significant. The Reynolds numbers used to calculate the settling velocities, the interfacial Reynolds number and the design pressure have deviations below 1%. The wall thickness has a deviation of -1.8%.

But the deviation is explained by rounding. Grødal and Realff report the wall thickness to be 0.032 while the optimization give it to be 0.0315. The residence and settling times all have small deviations below 1%. The same applies for gas and oil horizontal velocity. Water horizontal velocity has a deviation of 1%, or 0.001 m/s, and is due to rounding. The settling velocities, the maximum horizontal gas velocity and the maximum relative velocity all have deviation less than 1%.

So the results show that there is small differences between what Grødal and Realff report and what is obtained from the tool. The tool recreates the results that Grødal and Realff reports to a satisfying extent. This proves the tool works good for this specific case.

5.2 Volve Field

5.2.1 Find design for 5 individual cases

Table 5.4 show input values that will be used for the case study of the Volve field. There is data from five different times in during the life of the Volve field.

Table 5.4: Input values for the Volve field case study.

Case Name	Input					
	Separator Condition		Rate			Nr of separators
	Temperature K	Pressure bar	Gas m3/s	Oil m3/s	Water m3/s	-
2008 Des	362.15	32.5	0.561	0.122	0.000	1
2009 Des	362.15	32.5	0.486	0.109	0.028	1
2010 Nov	362.15	32.5	0.227	0.047	0.077	1
2012 Jul	362.15	32.5	0.121	0.024	0.086	1
2014 Sep	362.15	32.5	0.137	0.028	0.102	1

The temperature and pressure is assumed to be constant and not change during the life of the field. The rates change over time as indicated in the table. In *December 2008* the gas and oil rates are high while there are next to no water. In *December 2009* the gas and oil rate is still high but has decreased compared to *December 2008*. The water rate however has increased to a significant amount. In *November 2010* the trend continues. The oil and gas rate decreases while the water rate increases. The water rate is now the dominant phase. In *July 2012* the water rate is somewhat higher while the gas and oil rates have decreased further. *September 2014* give the maximum water rate while the oil and gas rate still are on a low level. The last column indicate that all the optimizations have been run with 1 separator.

Table 5.5 contains some of the outputs from the optimization of the five cases: the residence and settling times, lengths and diameters.

Table 5.5: Residence and settling time, lengths and diameters for the Volve field case study.

Residence Time			Settling Time			Length			Diameter	
Gas s	Oil s	Water s	Oil in gas s	Water in oil s	Oil in water s	Effective m	End section m	Total m	Inner m	Total m
30.9	302.1	13706.0	4.2	302.1	37.1	11.32	0.05	**14.28**	2.60	**2.70**
34.2	277.2	275.3	4.3	277.2	48.6	10.80	0.05	**13.98**	2.54	**2.64**
76.6	648.9	203.7	4.1	345.1	100.1	11.42	0.05	**14.66**	2.67	**2.77**
171.4	2197.0	395.8	3.6	426.8	147.9	13.87	0.06	**17.28**	3.14	**3.27**
151.2	1932.1	342.4	3.6	429.8	149.5	13.89	0.06	**17.37**	3.16	**3.29**

The gas residence time is at the lowest in *December 2008*, but gets higher. The oil residence time follows a similar pattern but is at the lowest in *December 2009*. The water residence time is at the highest in *December 2008* and decreases. For the first case where the water rate is very low, the water residence time is around 45 times higher than the oil. The gas residence time is around 10 times smaller than the oil residence time. The ratio between oil and gas residence time is roughly the same for all the cases. In *December 2009* the water and oil residence time is the same before the water residence time becomes smaller compared to the oil residence time for the last two cases.

For all five cases the residence time are equal or higher than the corresponding settling time. For example the oil residence time in *December 2009* is $277s$, which is the same as the settling time for water in oil. This means that the water droplets of the given size ($250\mu m$) have enough time to reach the water phase before leaving the separator. The oil in gas settling time is highest in *December 2009* and lowest in *July 2012* and *September 2014*. For the water in oil settling time the maximum is in *September 2014* while the minimum is in *December 2009*. The settling time for oil in water is highest in *September 2014* and lowest in *December 2008*.

The effective lengths vary between $10.8m$ and $13.9m$ for the five cases. The shortest length is for *December 2009* when the the oil in gas settling time is also lowest. The longest effective length is for *September 2014* when the settling times for water in oil is highest. This can indicate that the oil in gas settling time restrain the effective length.

The length of the end section give the same results in all the cases. The total length follow the same pattern as the effective length. It is smallest in *December 2009* and largest in *July 2012*. This is reasonable as the total length depends on the length of the inlet section, effective length and end section length. The length of the inlet section is a constant while the length of the end section do not change much between the cases.

The total diameter corresponds to the inner diameter. Both have the highest value in *September 2014* and the lowest value in *December 2009*. So the inner diameter and the effective length has the highest value for the same case. The total diameter and inner diameter had the lowest value in *December 2009*.

Table 5.6 contains the output variables such as the K-value, the slenderness ratio and some of the constraint variables. The constraint variables are the variables that record how much unused capacity there is for a given constraint. The constraint variables in Table 5.6 are the gas, oil and water capacity and the re-entrainment.

Table 5.6: K-value, slenderness ratio, gas, oil and water capacity, and re-entrainment for the Volve field case study.

K-value	Slenderness Ratio	Capacity			Re-entrainment
		Gas	Oil	Water	
m/s	-	m	m	m	m/s
0.00	5.00	9.78	0.00	11.29	2.411
0.00	5.00	9.45	0.00	8.89	2.463
0.00	5.00	10.81	5.35	5.81	2.608
0.00	5.00	13.58	11.18	8.69	2.665
0.00	5.00	13.56	10.80	7.83	2.655

The K-value is for all cases very low with values between $0.001m/s$ and $0.004m/s$. The slenderness ratio is for all cases at the maximum limit. This is because the cost function is increasing quadratic with the inner diameter and linear with the length for the shell section of the separator. The cost of the head section is a function of the inner diameter and not connected to the length. This and the factor for constructing head section (F_h) will increase the tendency to mover towards a long and slim design. The results from the capacity variable show that there is capacity for more gas and more water for all cases. The oil capacity restrain the optimization in the first two cases while it is capacity for more in the last three cases. The re-entrainment constraint is not restraining the design in any of the cases. There is around $2.5m/s$ from breaching the capacity limit for all cases. This indicates that the design can take a higher gas rate compared to the oil rate and still fulfill the re-entrainment constraint.

As mentioned in Section 2.1.10 there should be a a safety distance to avoid unwanted conditions. Table 5.7 contain the results from the constraints related to which outlets the fluids use to get out of the separator.

Table 5.7: Constraints for height difference for outlets for the Volve field case study.

Outlet			
Oil out Gas	Gas out Oil	Water Out Oil	Oil out water
m	m	m	m
0.00	0.35	0.35	0.18
0.00	0.24	0.24	0.27
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00

In *December 2008* and *December 2009* the constraints for oil in gas outlet restrain the design. The rest of the constraints have more capacity. For the last three cases all the constraints are restraining the design. The main difference between the first two cases and the last three is that there is a much lower water rate for the first two. Lower water rate means that there will be more space in the separator for the other two phases. But there is still some minimum heights that has to be respected. Therefore the design in the first two cases have more space while the last three cases give a design that have safety heights at minimum.

Table 5.8 contains the constraint variables for normal levels, the total length and diameter, K-value and slenderness ratio.

Table 5.8: Constraints for normal levels distance, size of separator, K-value and slenderness ratio for the Volve field case study.

Normal levels	Total		K-value	Slenderness Ratio	
	Length	Diameter		Min	Max
m	m	m	m/s	-	-
0.92	5.72	2.30	0.15	2.00	0.00
0.74	6.02	2.36	0.15	2.00	0.00
0.61	5.34	2.23	0.15	2.00	0.00
0.83	2.72	1.73	0.15	2.00	0.00
0.83	2.63	1.71	0.15	2.00	0.00

For all cases the constraint for the distance between the normal liquid level and normal interface levels are fulfilled and the constrain does not restrain the design. The case from *November 2010* records the smallest distance. The constraints for total length and total diameter are not restraining the design in any of the cases. As discussed earlier the largest separator is for *July 2012* and this is where the total length and total diameter constraints are closest to the limit. This can be seen in Table 5.8 as they have the lowest value for this case. The K-value are far from the limit for all cases while the slenderness ratio is at the maximum value for all cases. The reason for the slenderness ratio to go towards the upper limit is explain by the cost function (Equation (2.66)). The cost function is a function of both length and diameter, but the cost increases linear with the length and quadratic with the diameter (Bogen 2021). This means that the optimization will go towards a long and thin separator to keep the cost low.

Table 5.9 contains the cost of the separator, dry and wet weight and the footprint of the separator.

Table 5.9: The cost, weight and footprint of the separator for the Volve field case study.

Cost of separator	Weight		Footprint
	Dry	Wet	
$	ton	ton	m2
321 181	69.48	150.14	35.06
301 401	65.20	140.79	33.58
347 164	75.10	162.43	36.97
562 604	121.71	264.54	51.30
571 789	123.69	268.90	51.87

The cost, which is the variable that is optimized, has the lowest value in *December 2009* and the highest value in *September 2014*. The minimum and maximum values for the three other variables in the table are also obtained in the same years. This indicate that they correspond. The cost function is a function of the weight. If the cost factors are removed from the cost function, the expression that is left is the expression for the dry weight. So a higher weight give a higher cost. Also the footprint is closely connected to the cost. The footprint is a function of diameter and length. Larger diameter and length give a larger footprint. And larger diameter and length give higher cost.

Figure (5.1) show the heights of the diameter, liquid and interface levels for each of the 5 cases. In the bottom is the interface levels which are brown. The low-low interface level is dark brown and the high-high interface level is light brown. The levels get a brighter colour for each new level. The low-low liquid level is light blue and the other liquid levels get darker for each new level. The black part is the space from the high-high liquid level to the top of the vessel.

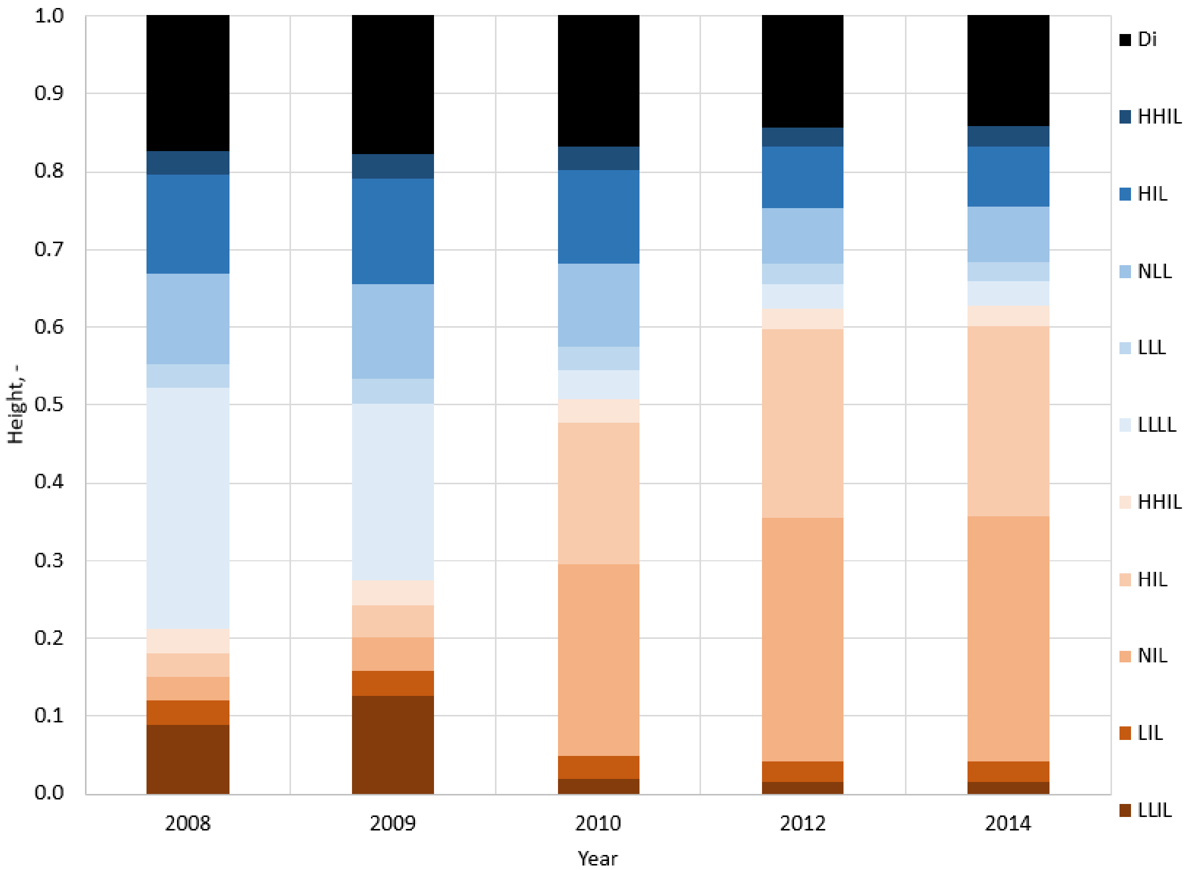

Figure 5.1: Diameter, liquid and interface levels for the Volve field case study. The heights are dimensionless and the figure with dimensions can be found in Appendix A.4.

In *December 2008* and *December 2009* the liquid levels take up most of the space. The interface levels are low compared to the other cases. That indicate that water take up a small part of the vessel. As these two cases have a low water rate this is reasonable results. In *November 2010* the liquid and interface levels take up more similar space. This indicate that the rates of the different phases are more equivalent. In the last two cases the interface levels take up a larger part of the vessel. This indicate that the water phase take up a larger part of the vessel. This is reasonable as these cases have the largest water rates. For all cases the black part (distance from high-high liquid level to inner diameter) has the same size. That indicates that the vane demisters take up the same space for all cases.

All cases have now been optimized. For each case the optimal design has been found. The cheapest design was obtained for the *December 2009* case where the length and diameter also was the smallest. The most expensive design was obtained for the *September 2014* case where the length and diameter had the highest values. This case had the highest water rate and while the gas and oil rate were low, another case had a lower gas and oil rates.

Each case has given a different design. It is not feasible to make five different separators for the same field. Therefore a design that can fulfill all constraints for all cases has to be found.

5.2.2 Find design for field lifetime

All cases were verified against the other cases as Figure 3.4 shows. That means that in addition to the 5 cases already run and optimized, 20 more simulations have been run. In Table 5.10 the results from the verifying process are listed. The table only include results of how much capacity the constraints have left before they are violated. This is because they are the most interesting variables. These variables have to be fulfilled to make the design work.

As mentioned earlier all variables for the unused capacity constraints should be equal or more than 0 if the corresponding constraint is fulfilled. If not the design is not feasible for the case in question. To make it easier to visualize, all values below 0 is marked with red in Table 5.10.

Table 5.10: Result of the constraints after verifying all the cases against each other as shown in Figure 3.4. The table is divided in 5 sections downwards. In the top of each section is the results of the optimized cases before the results of the verifying is in the 4 rows below.

Case Name	Optimized /Verified	Constraints													
		Capacity			Re-	Outlet				Normal	Total		K-value	Slenderness Ratio	
		Gas	Oil	Water	entrainm	Oil out Gas	Gas out Oil	Water Out Oil	Oil out water	levels	Length	Diameter		Min	Max
		m	m	m	m/s	m	m	m	m	m	m	m	m/s	-	-
2008 Des	Optimized	9.78	0.00	11.29	2.411	0.00	0.35	0.35	0.18	0.92	5.72	2.30	0.15	2.00	0.00
2009 Des	Verified	9.99	0.96	9.08	2.456	0.01	0.34	0.34	0.13	0.92	5.48	2.30	0.15	2.09	-0.09
2010 Nov	Verified	10.70	4.67	4.75	2.607	0.00	0.00	0.00	-0.26	0.65	5.47	2.30	0.15	2.09	-0.09
2012 Jul	Verified	10.99	2.30	0.00	2.669	0.00	-0.30	-0.30	-3.96	0.65	5.55	2.30	0.15	2.06	-0.06
2014 Sep	Verified	10.94	1.03	-1.08	2.660	0.00	-0.34	-0.34	-3.63	0.60	5.49	2.30	0.15	2.09	-0.09
2009 Des	Optimized	9.45	0.00	8.89	2.463	0.00	0.24	0.24	0.27	0.74	6.02	2.36	0.15	2.00	0.00
2008 Des	Verified	9.24	-1.03	10.76	2.419	0.00	0.32	0.32	0.15	0.88	6.27	2.36	0.15	1.90	0.10
2010 Nov	Verified	10.17	3.07	2.26	2.609	0.00	0.00	0.00	-0.74	0.71	6.02	2.36	0.15	2.00	0.00
2012 Jul	Verified	10.46	0.00	-0.16	2.671	0.00	-0.42	-0.42	-4.23	0.52	6.10	2.36	0.15	1.97	0.03
2014 Sep	Verified	10.42	-0.90	-0.38	2.664	0.00	-0.51	-0.51	-3.09	0.39	6.03	2.36	0.15	2.00	0.00
2010 Nov	Optimized	10.81	5.35	5.81	2.608	0.00	0.00	0.00	0.00	0.61	5.34	2.23	0.15	2.00	0.00
2008 Des	Verified	10.00	0.02	11.40	2.469	0.10	0.16	0.16	0.57	0.52	5.58	2.23	0.15	1.91	0.09
2009 Des	Verified	10.20	1.26	10.01	2.507	0.10	0.16	0.16	0.57	0.52	5.34	2.23	0.15	2.00	0.00
2012 Jul	Verified	11.10	4.20	1.67	2.669	0.00	-0.28	-0.28	-2.87	0.65	5.41	2.23	0.15	1.97	0.03
2014 Sep	Verified	11.05	2.90	0.00	2.659	0.00	-0.29	-0.29	-2.94	0.64	5.35	2.23	0.15	2.00	0.00
2012 Jul	Optimized	13.58	11.18	8.69	2.665	0.00	0.00	0.00	0.00	0.83	2.72	1.73	0.15	2.00	0.00
2009 Des	Verified	12.70	6.06	12.79	2.442	0.00	0.34	0.34	0.91	0.83	2.65	1.73	0.15	2.02	-0.02
2008 Des	Verified	12.64	5.13	13.86	2.466	0.13	0.29	0.29	0.91	0.71	2.89	1.73	0.15	1.95	0.05
2010 Nov	Verified	13.37	9.84	10.30	2.628	0.14	0.16	0.16	0.62	0.71	2.64	1.73	0.15	2.03	-0.03
2014 Sep	Verified	13.54	10.73	7.78	2.655	0.00	-0.01	-0.01	0.00	0.81	2.66	1.73	0.15	2.02	-0.02
2014 Sep	Optimized	13.56	10.80	7.83	2.655	0.00	0.00	0.00	0.00	0.83	2.63	1.71	0.15	2.00	0.00
2008 Des	Verified	12.66	5.21	13.88	2.466	0.14	0.29	0.29	0.92	0.72	2.86	1.71	0.15	1.93	0.07
2009 Des	Verified	12.83	6.15	12.82	2.504	0.14	0.29	0.29	0.92	0.72	2.62	1.71	0.15	2.00	0.00
2010 Nov	Verified	13.40	9.90	10.36	2.628	0.14	0.16	0.16	0.64	0.72	2.62	1.71	0.15	2.00	0.00
2012 Jul	Verified	13.60	11.24	8.73	2.665	0.00	0.01	0.01	0.00	0.85	2.69	1.71	0.15	1.98	0.02

Verifying design from *December 2008*

In the first section of the table is the *December 2008*-case optimized while the other cases are verified. This can also be seen in the second column named "Optimized/Verified". The *December 2009* case fulfill all constraints except one. The "Slenderness ratio" maximum limit is violated. That means that the length is too large compared to the diameter. The case from *November 2010* also violates the "Slenderness ratio" maximum limit. In addition the "Oil out water" constraint is violated. That means that the low-low interface level is too low which can lead to the oil entering the water outlet. The case from *July 2012* also violates the same two constraints as the *November 2010* case. But now the "Gas out oil" and "Water out oil" are violated as well. That means that the distance between the low-low liquid level and the weir height, and the high-high interface level and the weir height is too low. This can result in gas and water entering the oil outlet.

The safety margin is not respected. The last case, from *September 2014*, violates the same constraints as the previous case as well as the "Water capacity" constraint. When the "Water capacity" constraint is violated the residence time for water is lower than the settling time for oil in water. That means that there will be oil droplets larger than the 100µm that is supposed to be separated in the water phase.

None of the other cases fulfill all the constraints for the design from *December 2008*. But that is expected as the results from the optimization show that the case from *December 2008* give the second smallest footprint and second cheapest design. The "Oil out water" constraint seems to be the biggest problem, especially for the two cases from the latest period of the lifetime. For those cases the "Oil out water" constraint are exceeded with more than $3.5m$. The other constraints are exceeded with less margin and therefore not as significant. There is a reason for why the "Oil out water" constraint are the most frequently violated constraint of the four safety margin constraints. The constraints are set up in the solver from top to bottom of the separator. That means that the design is first customized for the "Oil out gas" constraint, then for the "Gas out oil" constraint, then for the "Water out oil" constraint and finally for the "Oil out water" constraint. That means that the "Water out oil" constraint is the first of the four to being violated. For all cases the "Gas out oil" and "Water out oil" constraints have the same values in Table 5.10. That is because the constraints are used to calculate the weir height with Equation (2.48) and (2.49). This give two values for the weir height and the average of these are used.

Verifying design from *December 2009*

The second section of Table 5.10 contains the *December 2009* case optimized while the other cases are verified. The *December 2008* case violates the "Oil capacity" constraint with more than a meter. That means that there will be larger water droplets in the oil than what it is designed for. The residence time for water is smaller than the water in oil settling time. The case from *November 2012* fulfill the "Oil capacity" constraint but violates the "Oil out water" constraint. The "Slenderness ratio" maximum limit is also violated but with less than "0.01 m". The *July 2012* case fulfill the "Slenderness ratio" constraint but not the "Oil out water" constraint. In addition, the "Gas out oil", "Water out oil" and "Water capacity" constraints are violated. There is not enough safety margin for the oil phase and the effective separation length is too short to separate the oil droplets out of the water phase. The case from *September 2014* violates the same constraints as the case from *July 2012* but in addition the "Oil capacity" and "Water capacity" constraints are also violated. That means there is not enough space for the liquid phases.

As for the previous design, none of the cases fulfill all the constraints for the design from *December 2009*. The design for *December 2009* is the cheapest design and has the smallest footprint. Interestingly the *December 2008* case violates the "Oil capacity" constraint which means that the separator should be longer. When the *December 2009* case were verified for the *December 2008* design, the "Slenderness ratio" constraint were violated. This indicate that the *December 2008* case need a shorter length or a longer diameter of the separator. The cases last in the lifetime also indicate that the design is too short by violating the capacity constraints. This is further confirmed when looking at the results from the optimization. The effective length is shortest for design for *December 2009*.

Verifying design from *November 2010*
The third section of Table 5.10 contains the *November 2010* case optimized while the other cases are verified. The *December 2008* case and the *December 2009* case do not violate any of the constraints when verified against the design from the *November 2010* case. The constraints closest to being violated are the "Oil capacity", the "Oil out gas" and the "Slenderness ratio" constraints. The cases from *July 2012* and *September 2014* do not fulfill the constraints. The "Gas out oil", the "Water out oil" and the "Oil out water" constraints are all violated for both cases. The safety margin is not respected. This is reasonable as the constraints can be fulfilled by increasing the diameter of the separator. The design from the optimization of the *November 2010* case has a diameter that is $0.5m$ shorter than the designs from the optimizations of the *July 2012* and *September 2014* cases.

The verifying of the design for *November 2010* give that the constraints are fulfilled for two cases in addition to the *November 2010* case. The two cases are from the early period of the lifetime. The verifying process show that the design can be used in these early periods. However the design violates several constraints for the last two cases and can therefore not be used for the whole lifetime.

Verifying design from *July 2012*
The fourth section of Table 5.10 contains the *July 2012* case optimized while the other cases are verified. Note that in this section of the table the data from case *December 2009* is presented before the data from case *December 2008*, in contrary to the other sections. The case from *December 2008* is fulfilling all constraints. The "Slenderness ratio" constraint is closest to being violated. The *December 2009* case is violating the "Slenderness ratio" maximum limit for the design for the *July 2012* case. That can be solved either be decreasing the length or increasing the diameter of the separator. The *November 2010* case is like the *December 2009* case also violating the "Slenderness ratio" maximum limit. All other constraints are fulfilled. The case from *September 2014* is also violating the "Slenderness ratio" constraint as well as the "Gas out oil" and "Water out oil" constraints. All these constraints can be fulfilled by increasing the diameter of the separator.

The design for this case is not fulfilling the constraints for more than one of the other cases. So that means that it gives worse results than the previous design. However the constraints are violated with a smaller margin than in the previous design. That means that small changes would help a lot for the constraints to be fulfilled. There are three constraints that are violated and increasing the diameter would fulfill all constraints.

Verifying design from *September 2014*
The last section of Table 5.10 contains the *September 2014* case optimized while the other cases are verified. The *December 2008* case fulfill all the constraints. The "Slenderness ratio" constraint is closest to being violated. The cases from *December 2009* and *November 2010* violate the "Slenderness ratio" constraint. But the constraint is violated with less than $0.01m$. Therefore a small increase in the diameter of the separator would make the constraints fulfilled. The *July 2012* case is fulfilling all constraints. For this case the "Slenderness ratio" and the four safety margins ("Oil out gas", "Gas out oil",

"Water out oil", and "Oil out water") are the constraints that are closest to being violated.

The design for the *September 2014* case is fulfilling all the constraints for three of the five cases. The two cases that are violating the "Slenderness ratio" constraint can fulfill the design if the diameter is increased slightly. Therefore a design that fulfills all constraints for all cases can be found. This give a good indication of how a separator for the Volve field should be designed to separate at a satisfactory extent during the lifetime of the field.

5.3 Comparing with Equinor tool

Table 5.11 contains the input data used: the operating pressure and gas, oil and water rates. The upper row of the results contain the variables from the Equinor tool while the row below contain the variables from Version 2 of the tool described in this thesis. The case run is the "September 2014" case from the Volve field also used in the previous section. For all tables in this section the values of the variables from the Equinor tool is the one at the top while the values from Version 2 is at the bottom.

Table 5.11: Input for the case study to compare Version 2 and the tool of Equinor.

Case	Operating Pressure	Rate		
		Gas	Oil	Water
	bar	m3/s	m3/s	m3/s
Equinor	35.75	0.137	0.028	0.102
Version 2	35.75	0.137	0.028	0.102

In the tool of Equinor the temperature is not used a an input. It is not used for further calculations in the tool implemented in this thesis either. It is however important to consider how the fluid properties change with the temperature.

Table 5.12 contains the liquid levels. The values from the Equinor tool on the top and from Version 2 below.

Table 5.12: Liquid level calculated from the case study to compare Version 2 and the tool of Equinor.

Liquid Level				
High-high	High	Normal	Low	Low-low
m	m	m	m	m
2.708	2.558	2.355	2.205	2.055
2.707	2.627	2.382	2.159	2.079

The high-high liquid level is very similar with only 0.001m difference. The results from Equinor give that the high and normal liquid level is lower for Equinor than in Version 2. The same goes for the low-low liquid level but the low liquid level from Equinor is higher than what Version 2 predicts. Both models calculate the normal level first and then the other levels. The tool from Equinor has a smaller difference between normal and high liquid level than Version 2, but larger intervals between the other liquid levels. The reason could be that the high liquid level for Equinor should be able to handle slug. None of the other levels have to handle slug. Version 2 however consider slug and surge for all alarm levels (high and low).

Table 5.13 contain the interface levels. The values from the Equinor tool on the top and from Version 2 below.

Table 5.13: Interface level calculated from the case study to compare Version 2 and the tool of Equinor.

Interface Level				
High-high m	High m	Normal m	Low m	Low-low m
1.353	1.203	1.053	0.903	0.753
1.979	1.899	1.128	0.130	0.050

The Equinor tool give that high-high, high and normal interface levels are lower than in Version 2, while the low and low-low interface levels are higher. The intervals between the alarm levels (high and low) and the shut-down levels (high-high and low-low) are larger for the Equinor tool. Between the normal and alarm levels the Version 2 have a larger difference. The reason the large difference could be that Version 2 consider slug and surge while the Equinor tool does not.

Table 5.14 contains the lengths, inner diameter, the K-value and the slenderness ratio. The values from the Equinor tool on the top and from Version 2 below.

Table 5.14: Lengths, inner diameter, K-value and slenderness ratio calculated from the case study to compare Version 2 and the tool of Equinor.

Length			Inner diameter	K-value	Slenderness Ratio
Effective m	End section m	Tan-tan m	m	m/s	-
13.086	1.309	16.358	3.272	0.015	5.00
13.89	0.89	17.372	3.157	0.004	5.00

The effective length calculated with the tool from Equinor is almost a meter shorter than what Version 2 give. The end section from Equinor is almost half a meter larger than the end section from Version 2. In the Equinor tool the end section is calculated from the inner diameter while it is calculated from the rates in Version 2. But compared to the effective length the end section has small significance to the tan-tan length. The length of the tan-tan section is a meter shorter from the Equinor tool. The inner diameter is $0.1m$ higher for the Equinor tool. The K-value is a lot higher for the Equinor tool, while the slenderness ratio for both are 5.

Table 5.15 contains the dry and wet (filled with water) weights as well as the footprint. The values from the Equinor tool on the top and from Version 2 below.
The weights give similar results both for dry and wet weight. The dry weight for the Equinor tool is less than the for Version 2 while it is the opposite for wet weight. The reason for this is because in the Equinor tool the density of water is set to $1000kg/m^3$ while it is set at $1101kg/m^3$ in Version 2. The Equinor tool give a larger footprint which is caused by the differences in lengths and diameter.

For Version 2 there is, as mentioned earlier, three heights that is calculated for each alarm level (high and low liquid and interface level) and two heights for each shut-down

Table 5.15: Weights and footprint calculated from the case study to compare Version 2 and the tool of Equinor.

Weight		Footprint
Dry ton	Wet ton	m2
123.08	269.75	55.53
123.69	268.90	51.87

level (high-high and low-low liquid and interface level). The most extreme of these are selected for all levels, meaning the maximum for the high and high-high levels and the minimum for the low and low-low levels. If one only look at the height calculated from the "height interval NORSOK standard" the smallest inner diameter can be formulated with Equation (5.1).

$$D_{i,\ \min} = h_{vd} + 4\Delta h_s + 8\Delta h_{NOR} = 1.24m \tag{5.1}$$

$D_{i,\ \min}$ is the minimum diameter, h_{vd} is the height of the vane demister. The height of the vane demister is the distance between the high-high liquid level and the top of the separator. In the tool from Equinor the same constant is used to calculate the distance between the different liquid levels and the interface levels, and between the interface level and weir height. The minimum diameter is given with Equation (5.2).

$$D_{i,\ \min} = L_{GB} + 13\Delta h_{\min} = 2.21m \tag{5.2}$$

L_{GB} is the minimum length of the vane demisters and $\Delta h_{\min}$ is the height interval. As observed the to tool give a very similar minimum height for a separator with only $0.03m$ difference. This further confirm that the tools give similar results.

To conclude and summarize the two tools give similar results for the design for the *September 2014* case. There are some differences but they give two designs that overall are matching quite good. However, as only one case has been run that is a small sample. More cases should be run to better evaluate the tool implemented. This has not been done due to time limitations.

6 Conclusion

- A tool to optimize the design of a separator based on a paper from Grødal & Realff (1999) has been implemented with the use of Excel VBA. The tool optimizes the cost of a separator by adjusting the value of four design variables. The design variables are the inner diameter, the length of the gravity separation section (effective length), the normal liquid level and the normal interface level. A set of constraints are used to find designs that are physically possible and give good separation conditions. This version of the tool is called Version 1.
- The original tool was improved by introducing other relevant constraints and equations. Some of the new parameters are the weight and footprint of the separator as well as variables needed to calculate the weight and footprint. In addition new constraints have also been introduced. These constraints are connected to the K-value and the slenderness ratio. This version of the tool is called Version 2.
- A method is proposed to determine an optimized separator design for varying inlet conditions. First each of the cases is optimized separately before the cases are verified against each other. The verifying is performed in the same manner as the optimization but with the inner diameter and the length of the gravity separation section constant. At the end of this process one should select the design that does not violate any constraint for any case and gives optimum objective function (cost, weight or footprint).

Three case studies were evaluated with the tool:

- The original case presented by Grødal and Realff was optimized with version 1 of the tool. The results obtained are very similar. Version 1 of the tool gives a cost which is less than 1% below the cost the Grødal and Realff report. Most variables have a deviation of less than 1%.
- Separator designs are found for the Volve field using the published production data. Five cases were taken from different periods of the field lifetime. The five cases were first optimized separately. Then the cases were verified against the designs from the optimization. By increasing the inner diameter slightly in the design from the *September 2014* case a design that fulfills all constraints for all cases was found.
- Have compared Version 2 of the tool with a similar tool from Equinor. The case *September 2014* from the Volve field was used as input. The tools overall give similar results. The dry weight is for both tools calculated to be *123 ton*. The tan-tan length is calculated to be a meter shorter and the inner diameter is *0.1 m* longer for the Equinor tool.

7 Further work

- Make an option for the tool to change between finding the optimal design for a two phase or a three phase separator. This option will then merge the work done in this thesis and in the project report by Bogen (2021). Only a single Excel spreadsheet is needed.

- Update how variables are calculated as new and better correlations and equations may have been proposed since Grødal & Realff (1999) wrote their paper (based on input from Equinor in meeting, 09.06.2022).

  - Make the tool consider that there could be different lengths for the gas, oil and water layers.
  - Add the inlet length as a variable depending of which technology used as inlet device. For example, it could be a function of the diameter.
  - Adjust how the length of the end section is calculated. It could for example, only depend on the size of the oil nozzle and not the water nozzle. Where the end section starts and where the effective length ends should then be adjusted.
  - There are other technologies that for the gas outlet besides vanes. The type should be considered in the tool. The orientation of the vanes should also be included in the design.
  - Update the NORSOK standards in the tool.
  - Introduce a constraint for maximum wall thickness due to manufacturing.

- Perform a more comprehensive case study to evaluate the tool against other tools.

- Perform a case study of how the optimizing the of footprint compare to other tools.

- Perform a case study where data from an early phase of the field development are used to design a separator. In this thesis data of actual production have been used. But from early phases of the production there are large uncertainties for the design parameters. Therefore it should be tested with data from early phases of the field development.

- To find an optimal design for all times you could make a large optimization problem including all 5 cases simultaneously (but changing a unique L and D, but 5 sets of levels).

- Make a similar tool for optimizing design of vertical separators.

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A Appendix

A.1 Equation Dimensionless Area

The dimensionless area of a pipe section A_D, is derived by Equation (A.1).

$$
\begin{aligned}
A =& \left(h_1 - \frac{D_i}{2}\right)\sqrt{D_i h_1 - h_1^2} + \frac{D_i^2}{4}\sin^{-1}\left(\frac{2h_1}{D_i} - 1\right) + \frac{\pi D_i^2}{8} \\
A_D =& \frac{A}{A_T} = \frac{A}{\frac{\pi D_i^2}{4}} = \frac{\left(h_1 - \frac{D_i}{2}\right)\sqrt{D_i h_1 - h_1^2}}{\frac{\pi D_i^2}{4}} + \frac{\frac{D_i^2}{4}\sin^{-1}\left(\frac{2h_1}{D_i} - 1\right)}{\frac{\pi D_i^2}{4}} + \frac{1}{2} \\
A_D =& \frac{4\left(h_1 - \frac{D_i}{2}\right)}{\pi_i}\frac{\sqrt{D_i h_1 - h_1^2}}{D_i} + \frac{\sin^{-1}\left(\frac{2h_1}{D_i} - 1\right)}{\pi} + \frac{1}{2} \\
A_D =& \frac{4}{\pi}\left(\frac{h_1}{D_i} - \frac{1}{2}\right)\sqrt{\frac{D_i h_1 - h_1^2}{D_i^2}} + \frac{\sin^{-1}\left(\frac{2h_1}{D_i} - 1\right)}{\pi} + \frac{1}{2} \\
A_D =& \frac{4}{\pi}\left(\frac{h_1}{D_i} - \frac{1}{2}\right)\sqrt{\frac{h_1}{D_i} - \left(\frac{h_1}{D_i}\right)^2} + \frac{\sin^{-1}\left(2\frac{h_1}{D_i} - 1\right)}{\pi} + \frac{1}{2} \\
A_D =& \frac{4}{\pi}\left(c - \frac{1}{2}\right)\sqrt{c - (c)^2} + \frac{\sin^{-1}(2c - 1)}{\pi} + \frac{1}{2}
\end{aligned}
\tag{A.1}
$$

The constant c is given in Equation (A.2).

$$
0 \leq c = \frac{h_1}{D_i} \leq 1 \tag{A.2}
$$

A.2 Solver Output

Return Value	Message
0	Solver found a solution. All constraints and optimality conditions are satisfied.
1	Solver has converged to the current solution. All constraints are satisfied.
2	Solver cannot improve the current solution. All constraints are satisfied.
3	Stop chosen when the maximum iteration limit was reached.
4	The Objective Cell values don't converge.
5	Solver could not find a feasible solution.
6	Solver stopped at user's request.
7	The linearity conditions required by this LP Solver are not satisfied.
8	The problem is too large for Solver to handle.
9	Solver encountered an error value in a target or constraint cell.
10	Stop chosen when the maximum time limit was reached.
11	There is not enough memory available to solve the problem.
13	Error in model. Please verify that all cells and constraints are valid.
14	Solver found an integer solution within tolerance. All constraints are satisfied.
15	Stop chosen when the maximum number of feasible [integer] solutions was reached.
16	Stop chosen when the maximum number of feasible [integer] subproblems was reached.
17	Solver converged in probability to a global solution.
18	All variables must have both upper and lower bounds.
19	Variable bounds conflict in binary or all different constraint.
20	Lower and upper bounds on variables allow no feasible solution.

Figure A.1: Overview over what the different values of the return variable from the solver means.

A.3 Algorithm to verify a case against a design from another case

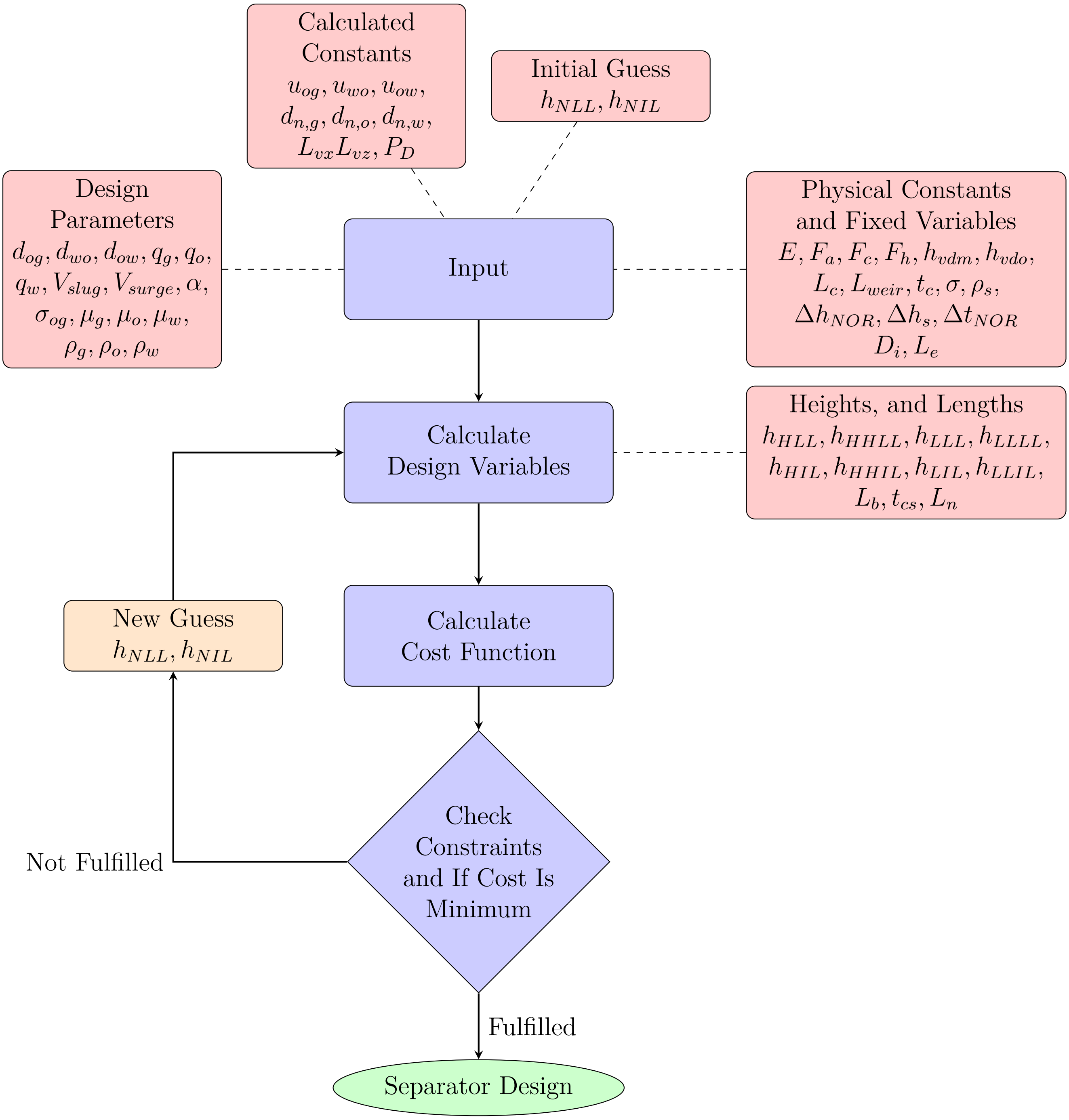

Figure A.2: Algorithm for verifying design of separator for different properties. (Grødal & Realff 1999)

A.4 Diameter, liquid and interface levels for the Volve field case study.

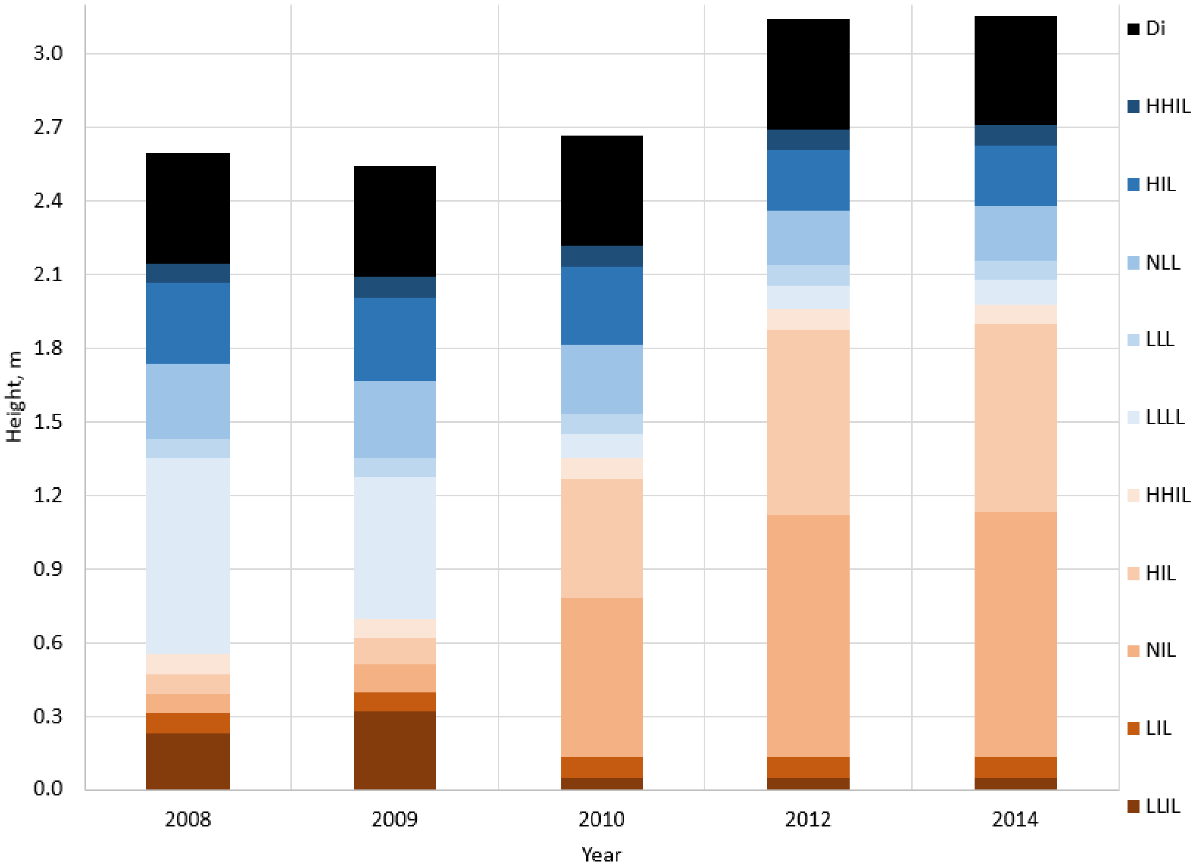

Figure A.3: Diameter, liquid and interface levels for the Volve field case study.

B Macros

B.1 Functions used to calculate variables in Excel sheet

Listing B.1: Equations made in the visual basic for application and used in the model

```
Function u_settling(d, rho1, rho2, Cd, g)
    'u_settling - Settling velocity, m/s
    'd - Diameter droplet or bubble, m
    'rho1 - Density bubble or droplet, kg/m3
    'rho2 - Density continous phase, kg/m3
    'CD - Spherical drag coefficiant, -
    'g - Gravitational acceleration, m/s^2

        If rho1 > rho2 Then
            rhoEX = ((rho1 - rho2) / rho2)
        Else:
            rhoEX = ((rho2 - rho1) / rho2)
        End If

    u_settling = (4 / 3 * d / Cd * g * rhoEX) ^ 0.5

End Function

Function N_re(rho, u_settling, d, my)
    'N_re - Reynolds number droplet or bubble, -
    'rho - Density continous phase, kg/m3
    'u_settling - Settling velocity, m/s
    'd - Diameter bubble or droplet, m
    'my - Dynamic viscosity continous , kg/(m*s)

    N_re = rho * u_settling * d / my
End Function

Function Cd(N_re)
    'CD - Spherical drag coefficiant, -
    'N_re - Dropplet or bubble Reynolds number, -

    Cd = 24 / N_re + 3 / (N_re) ^ (1 / 2) + 0.34
End Function

Function u_settling_iterative1(d, rho1, rho2, Cd0, g, my, eps) As Variant
    'u_settling_iterative1 - Settling velocity calculated with iteration, m/s
    'd - Diameter droplet or bubble, m
    'rho1 - Density bubble or droplet, kg/m3
    'rho2 - Density continous phase, kg/m3
    'Cd0 - Spherical drag coefficiant, -
    'g - Gravitational acceleration, m/s^2
    'my - Dynamic viscosity continous , kg/(m*s)
    'eps - Constraint, -

        Dim arr(4) As Variant


        Cd1 = Cd0
        Check = 1
        n = 0

        u_0 = u_settling(d, rho1, rho2, Cd1, g)
        N_re1 = N_re(rho2, u_0, d, my)


        While Check >= eps

        n = n + 1

            Cd2 = Cd(N_re1)
```

```
            u_settling_iter = u_settling(d, rho1, rho2, Cd2, g)

            N_re1 = N_re(rho2, u_settling_iter, d, my)

            Check = Abs(Cd2 / Cd1 - 1)

            Cd1 = Cd2

        Wend

        arr(0) = u_settling_iter
        arr(1) = n
        arr(2) = Cd2
        arr(3) = N_re1
        arr(4) = Check

    u_settling_iterative1 = arr
End Function

Function d_n(q, rho)
    'd_n - Minimum nozzle size, m^0.25*s^0.5/kg^0.25
    'q - Volumetric flow rate, m3/s
    'rho - Density, kg/m3

    d_n = 0.161 * (q * (rho) ^ 0.5) ^ 0.5
End Function

Function p_D(p)
    'p_D - Design pressure, Pa
    'p - Operating pressure, Pa

    p_D1 = p + 200000    '2 bar
    p_D2 = p * 1.1       '10%
    If p_D1 < p_D2 Then
        p_D = p_D2
    Else: p_D = p_D1
    End If
End Function


Function Lvz(Di, h_vdm)
    'Lvz - Length of vane demister, m
    'Di - Inner diameter separator, m
    'h_vdm - Height vane demister mounting point, m

    Lvz = 2 * (Di * h_vdm - (h_vdm) ^ 2) ^ (0.5)
End Function


Function LvxLvz(qg, rhoo, rhog, sig_og)
    'LvxLvz - Product of length and width of vane demister, m2
    'rhoo - Density oil, kg/m3
    'rhog - Density gas, kg/m3
    'sig_og - Surface tension between oil and gas, kg/s2

    g = 9.81 'm/s2
    LvxLvz = qg / (2.38) * (rhoo / (sig_og * g)) ^ 0.25 * (rhog / (rhoo - rhog)) ^ 0.5
End Function


Function tcs(p_D, Di, sig, E, tc)
    'tcs - Wall thickness cylindrical section, m
    'p_D - Design pressure, Pa
    'Di - Inner separator diameter, m
    'sig - Tensile strength, Pa
    'E - Joint efficiency
    'tc - Wall thickness of cylindrical section

    tcs = p_D * Di / (2 * sig * E - 1.2 * p_D) + tc
End Function

Function teh(p_D, Di, sig, E, tc)
    'tcs - Wall thickness cylindrical section, m
```

```
    'p_D - Design pressure, Pa
    'Di - Inner separator diameter, m
    'sig - Tensile strength, Pa
    'E - Joint efficiency
    'tc - Wall thickness of cylindrical section

    teh = p_D * Di / (2 * sig * E - 0.2 * p_D) + tc
End Function

Function LiqLev_A_top(A_bot, qo, qw, del_t_NOR, Lc, Ln, Le)
    'LiqLev_A_top - Area from top height and to bottom of separator, m2
    'A_bot - Area from bottom height and to bottom of separator, m2
    'qo - Voluetric rate oil, m3/s
    'qg - Voluetric rate gas, m3/s
    'del_T_NOR - Time inteval NORSOK standard, s
    'Lc - Length inlet section, m
    'Ln - Length end section, m
    'Le - Length gravity separation section, m

    LiqLev_A_top = A_bot + ((qo + qw) * del_t_NOR) / (Lc + Le + Ln)
End Function

Function LiqLev_A_bot(A_top, qo, qw, del_t_NOR, Lc, Ln, Le)
    'LiqLev_A_bot - Area from bottom height and to bottom of separator, m2
    'A_top - Area from top height to bottom of separator, m2
    'qo - Voluetric rate oil, m3/s
    'qg - Voluetric rate gas, m3/s
    'del_T_NOR - Time inteval NORSOK standard, s
    'Lc - Length inlet section, m
    'Ln - Length end section, m
    'Le - Length gravity separation section, m

    LiqLev_A_bot = A_top - (qo + qw) * del_t_NOR / (Lc + Le + Ln)
End Function

Function IntLev_A_top(A_bot, qw, del_t_NOR, Lc, Le, d_n_w)
    'IntLev_A_top - Area from top height and to bottom of separator, m2
    'A_bot - Area from bottom height and to bottom of separator, m2
    'qg - Voluetric rate gas, m3/s
    'del_T_NOR - Time inteval NORSOK standard, s
    'Lc - Length inlet section, m
    'Le - Length gravity separation section, m
    'd_n_w - Size water outlet

    IntLev_A_top = A_bot + qw * del_t_NOR / (Lc + Le + 2 * d_n_w)
End Function

Function IntLev_A_bot(A_top, qw, del_t_NOR, Lc, Le, d_n_w)
    'IntLev_A_bot - Area from bottom height and to bottom of separator, m2
    'A_top - Area from top height and to bottom of separator, m2
    'qg - Voluetric rate gas, m3/s
    'del_T_NOR - Time inteval NORSOK standard, s
    'Lc - Length inlet section, m
    'Le - Length gravity separation section, m
    'd_n_w - Size water outlet

    IntLev_A_bot = A_top - qw * del_t_NOR / (Lc + Le + 2 * d_n_w)
End Function

Function A_pipe(h1, Di)
    'A_pipe - Cross-sectional area from h1 to bottom, m
    'h1 - Height, m
    'Di - Inner separator diameter, m

    Pi = Atn(1) * 4
    A_pipe = (h1 - Di * 0.5) * (Di * h1 - h1 ^ 2) ^ 0.5 + Di ^ 2 * 0.25 * Application.
        WorksheetFunction.Asin(2 * h1 / Di - 1) + Pi * (Di ^ 2) / 8
End Function

Function A_HLL_slug(A_NLL, V_slug, Lc, Le, Ln)
    'A_HLL_slug - Area from HLL and to bottom of separator, m2
    'A_NLL - Area from NLL and to bottom of separator, m2
    'V_slug - Slug volume, m3
```

```
    'Lc - Length inlet section, m
    'Le - Length gravity separation section, m
    'Ln - Length end section, m

    A_HLL_slug = A_NLL + V_slug / (Lc + Le + Ln)
End Function

Function A_LLL_surge(A_NLL, V_surge, Lc, Le, Ln)
    'A_LLL_surge - Area from LLL and to bottom of separator, m2
    'A_NLL - Area from NLL and to bottom of separator, m2
    'V_surge - Surge volume, m3
    'Lc - Length inlet section, m
    'Le - Length gravity separation section, m
    'Ln - Length end section, m

    A_LLL_surge = A_NLL - V_surge / (Lc + Le + Ln)
End Function

Function A_HIL_slug(A_NIL, V_slug, qw, qo, Lc, Le, d_n_w)
    'A_HIL_slug - Area from HIL and to bottom of separator, m2
    'A_NIL - Area from NIL and to bottom of separator, m2
    'V_slug - Slug volume, m3
    'qw - Water rate, m3/s
    'qo - Oil rate, m3/s
    'Lc - Length inlet section, m
    'Le - Length gravity separation section, m
    'd_n_w - Size water nozzle, m

    A_HIL_slug = A_NIL + V_slug * (qw / qo) / (Lc + Le + 2 * d_n_w)
End Function

Function A_LIL_surge(A_NIL, V_surge, qw, qo, Lc, Le, d_n_w)
    'A_LIL_surge - Area from LIL and to bottom of separator, m2
    'A_NIL - Area from NIL and to bottom of separator, m2
    'V_surge - Surge volume, m3
    'qw - Water rate, m3/s
    'qo - Oil rate, m3/s
    'Lc - Length inlet section, m
    'Le - Length gravity separation section, m
    'd_n_w - Size water nozzle, m

    A_LIL_surge = A_NIL - V_surge * (qw / qo) / (Lc + Le + 2 * d_n_w)
End Function

Function Ad(c)
    'Ad = A_pipe/A_tot, dimensionless version of A_pipe
    'c = h1/Di, dimensionless version of h1

    Pi = Atn(1) * 4
    Ad = 4 / Pi * (c - 1 / 2) * (c - (c) ^ (2)) ^ 0.5 + Application.WorksheetFunction.
        Asin(2 * c - 1) / Pi + 1 / 2
End Function

Function Lb(alfa, hu, hv)
    'Lb - Length between baffle plates, m
    'alfa - Pitch angle, degree
    'hu - Upper height, m
    'hv - Lower height, m

    Radi = alfa * WorksheetFunction.Pi / 180
    Lb = 2 * (hu - hv) / (Tan((Radi)))
End Function

Function Le_g(qg, Di, h_LLL, uog, A_TV, A_NLL)
    'Le_g - Length gravity separation section gas constrain, m
    'qg - Voluetric rate gas, m3/s
    'Di - Inner separator diameter, m
    'h_LLL - Height low liquid level, m
    'uog - Settling velocity oil in gas, m/s
    'A_TV - Area from top of vessel to bottom, m2
    'A_NLL - Area from normal liquid level to bottom, m2

    Le_g = qg * (Di - h_LLL) / (uog * (A_TV - A_NLL))
```

```
End Function

Function Le_o_2ph(qo, h_HLL, ugo, A_NLL)
    'For 2 phase separators
    'Le_o - Length gravity separation section oil constrain, m
    'qo - Volumetric rate oil, m3/s
    'A_HLL - Area from high liquid level to bottom, m2
    'ugo - Settling velocity gas in oil, m/s
    'A_NLL - Area from normal liquid level to bottom, m2

    Le_o_2ph = qo * h_HLL / (ugo * A_NLL)
End Function

Function Le_o_3ph(qo, h_HLL, h_LIL, uwo, A_NLL, A_NIL)
    'For 3 phase separators
    'Le_o_3ph - Length gravity separation section oil constrain, m
    'qo - Volumetric rate oil, m3/s
    'h_HLL - Height high liquid level, m
    'h_LIL - Height low interface level, m
    'uwo - Settling velocity water in oil, m/s
    'A_NLL - Area from normal liquid level to bottom, m2
    'A_NIL - Area from normal infterfacelevel to bottom, m2

    Le_o_3ph = qo * (h_HLL - h_LIL) / (uwo * (A_NLL - A_NIL))
End Function

Function Le_w(qw, h_HIL, uow, A_NIL)
    'Le_w - Length gravity separation section water constrain, m
    'qw - Voluetric rate water, m3/s
    'h_HIL - Height high interface level, m
    'uow - Settling velocity oil in water, m/s
    'A_NIL - Area from normal interface level to bottom, m2

    Le_w = qw * h_HIL / (uow * A_NIL)
End Function

Function uo(qo, A_NLL, A_NIL)
    'uo - Horizontal velocity oil, m/s
    'A_NLL - Area from normal liquid level to bottom, m2
    'A_NIL - Area from normal interface level to bottom, m2

    uo = qo / (A_NLL - A_NIL)
End Function

Function ug(qg, A_NLL, A_TV)
    'ug - Horizontal velocity gas, m/s
    'A_NLL - Area from normal liquid level and to bottom, m2
    'A_TV - Area from top of vessel to bottom, m2

    ug = qg / (A_TV - A_NLL)
End Function

Function uw(qw, A_NIL)
    'uw - Horizontal velocity water, m/s
    'A_NIL - Area from normal interface level to bottom, m2

    uw = qw / A_NIL
End Function

Function tr(u, Le)
    'tr - Retention time, s
    'u - Horizontal velocity, m/s
    'Le_o - Length gravity separation section, m

    tr = Le / u
End Function

Function tsettling(u_set, h_top, h_bot)
    'tsettling - Settling time, s
    'u_set - Settling velocity, m/s
    'h_top - Height top of phase, m
    'h_bot - Height bottom of phase, m
```

```
    tsettling = (h_top - h_bot) / u_set
End Function

Function D_H(Di, h_HLL, A_HLL)
    'D_H - Hydraulic Diameter, m
    'Di - Inner separator diameter, m
    'h_HLL - Height of high liquid level, m
    'A_HLL - Area from high liquid level to bottom of separator, m2

    P_HLL = Di * Application.WorksheetFunction.Acos(1 - 2 * h_HLL / Di)
    D_H = 4 * A_HLL / P_HLL
End Function

Function N_ref(rhoo, uo, D_H, myo)
    'N_ref - Reynolds film number, -
    'rhoo - Density oil, kg/m3
    'uo - Horizontal velocity oil, m/s
    'D_H - Hydraulic Diameter, m
    'myo - Dynamic viscosity oil,kg/(m*s)

    N_ref = rhoo * uo * D_H / myo
End Function

Function N_my(myo, rhoo, rhog, sig_og)
    'N_my - Interfacial viscosity number, -
    'myo - Dynamic viscosity oil,kg/(m*s)
    'rhoo - Density oil, kg/m3
    'rhog - Density gas, kg/m3
    'sig_og - Surface tension between oil and gas, kg/s2

    g = 9.81
    N_my = myo / (rhoo * sig_og * (sig_og / (g * (rhoo - rhog))) ^ 0.5) ^ 0.5
End Function

Function u_r_max1(N_ref, N_my, rhoo, rhog, myo, sig_og)
    'u_r_max1 - Maximum relative velocity between oil and gas, m/s
    'N_ref - Reynolds film number, -
    'N_my - Interfacial viscosity number, -
    'rhoo - Density oil, kg/m3
    'rhog - Density gas, kg/m3
    'myo - Dynamic viscosity oil,kg/(m*s)
    'sig_og - Surface tension between oil and gas, kg/s2

    If N_ref < 160 Then
        u_r_max1 = 0.4572 * (sig_og / myo) * (rhoo / rhog) ^ 0.5 * N_ref ^ (-0.5)
    ElseIf N_ref >= 160 And N_ref <= 1635 Then
        If N_my <= 1 / 15 Then
            u_r_max1 = 3.5905 * (sig_og / myo) * (rhoo / rhog) ^ 0.5 * N_my ^ 0.8 *
                N_ref ^ (-1 / 3)
        Else
            u_r_max1 = 0.4115 * (sig_og / myo) * (rhoo / rhog) ^ 0.5 * N_ref ^ (-1 / 3)
        End If
    Else
        If N_my <= 1 / 15 Then
            u_r_max1 = 0.3048 * (sig_og / myo) * (rhoo / rhog) ^ 0.5 * N_my ^ 0.8
        Else
            u_r_max1 = 0.03493 * (sig_og / myo) * (rhoo / rhog) ^ 0.5
        End If
    End If
End Function

Function u_r(qg, qo, A_TV, A_NLL, A_NIL)
    'u_r - Relative velocity between oil and gas, m/s
    'qo - Voluetric rate oil, m3/s
    'qg - Voluetric rate gas, m3/s
    'A_TV - Area from top of vessel to bottom, m2
    'A_NLL - Area from normal liquid level and to bottom, m2
    'A_NIL - Area from normal interface level to bottom, m2

    u_r = qg / (A_TV - A_NLL) - qo / (A_NLL - A_NIL)
End Function
```

```
Function L_sep(Lc, Le, Ln, Lh, tcs)
    'L_sep - Total length of separator, m
    'Lc - Length inlet section, m
    'Ln - Length end section, m
    'Le - Length gravity separation section, m
    'Lh - Length head section, m
    'tcs - Wall thickness of cylindrical section

    L_sep = Lc + Le + Ln + 2 * Lh + 2 * tc
End Function

Function D_sep(Di, tcs)
    'D_sep - Total diameter of separator, m
    'Di - Inner diameter of separator, m
    'tcs - Wall thickness of cylindrical section

    D_sep = Di + 2 * tc
End Function

Function Dm(Di, tcs)
    'Dm - Mean separator diameter, m
    'Di - Inner diameter separator, m
    'tcs - Wall thickness cylindrical section, m

    Dm = (((Di) ^ (2) + (Di + 2 * tcs) ^ (2)) / 2) ^ (1 / 2)
End Function

Function Cost(tcs, Fc, rhos, Dm, Lc, Le, Ln, Fa, Fh)
    'Cost - Cost of separator, $
    'tcs - Wall thickness cylindrical section, m
    'Fc - Cost factor per unit mass to manufacture a vessel shell, $/kg
    'rhos - Density steel, kg/m3
    'Dm - Mean separator diameter, m
    'Lc - Length inlet section, m
    'Ln - Length end section, m
    'Le - Length gravity separation section, m

    Lt = Lc + Le + Ln
    Cost = tcs * Fc * rhos * (WorksheetFunction.Pi * Dm * Lt + 2 * Fa * Fh * (Dm) ^ (2)
        )
End Function

Function Weight_dry1(tcs, rhos, Dm, L_TT, Fa)
    'Weight_dry - Dry weight of separator, kg
    'tcs - Wall thickness cylindrical section, m
    'rhos - Density steel, kg/m3
    'Dm - Mean separator diameter, m
    'Lc - Length inlet section, m
    'Ln - Length end section, m
    'Le - Length gravity separation section, m

    Weight_dry1 = tcs * rhos * (WorksheetFunction.Pi * Dm * L_TT + 2 * Fa * (Dm) ^ (2))
End Function

Function Weight_wet1(Weight_dry, Vol, rhow)
    'Weight_wet1 - Weight of separator full with water, kg
    'Weight_dry - Dry weight of separator, kg
    'V - Volume of separator, m3
    'rhow - Density of water, kg/m3

    Weight_wet1 = Weight_dry + Vol * rhow
End Function

Function K_value(u_gas, rhog, rhol)
    'K_value - Gas load K-value, m/s
    'u_gas - Horizontal velocity gas, m/s
    'rhog - Density gas, kg/m3
    'rhol - Density liquid, kg/m3

    K_value = u_gas * (rhog / (rhol - rhog)) ^ (1 / 2)
End Function

Function Footprint(Di, tcs, L_TT)
```

```
    'Footprint - Footprint of separator, m2
    'Di - Inner diameter of separator, m
    'L_TT - Length tan tan, m
    'tcs - Wall thickness cylindrical section, m

    Footprint = (Di + 2 * tcs) * L_TT
End Function

Function Vol_Head(h, Di)
    'Vol_Head - Volume of head section, m3
    'h - Height, m
    'Di - Inner diameter of separator, m

    Vol_Head = (Di) ^ (3) * WorksheetFunction.Pi / 24 * (3 * (h / Di) ^ (2) - 2 * (h /
        Di) ^ (3))
End Function

Function Vol_Shell(h, Di, L_TT)
    'Vol_shell - Volume shell, m3
    'Di - Inner diameter of separator, m
    'h - Height, m
    'L_TT - Length tan tan, m

    Vol_Shell = WorksheetFunction.Pi * (Di) ^ (2) / 4 * L_TT
End Function

Function Shell_Head_Weight(rhos, L_TT, Di, tcs)
    'Shell_Head_Weight - Weight of shell and head
    'rhos - Density of steel, kg/m3
    'L_TT - Length tan tan, m
    'Di - Inner diameter of separator, m
    'tcs - Wall thickness cylindrical section, m

    Pi = WorksheetFunction.Pi
    Shell_Head_Weight = rhos * (Pi / 4 * L_TT * ((Di + 2 * tcs) ^ (2) - (Di) ^ (2))) +
        rhos * (Pi / 12 * ((Di + 2 * tcs) ^ (3) - (Di) ^ (3)))
End Function
```

B.2 Subs for optimizing and verify designs in Excel sheet

Listing B.2: Subs to optimize and verify for cost and footprint

```
Sub Macro8wi()
'
' Macro8wi Solve for cost
'
    Worksheets("3-phase calc").Activate

    'Reset solver
    SolverReset

    'Goal: Get cost as low as possible by changing Le, Di, h_NLL and h_NIL
    SolverOk SetCell:="$C$111", MaxMinVal:=2, ValueOf:=0, ByChange:="$V$15:$V$18", _
        Engine:=1, EngineDesc:="GRG Nonlinear"


        'Constraints

        'Gas capacity constraint: Le_g < Le
        SolverAdd CellRef:="$C$71", Relation:=1, FormulaText:="$J$72"

        'Oil capacity constraint: Le_o < Le
        SolverAdd CellRef:="$C$74", Relation:=1, FormulaText:="$J$72"

        'Water capacity constraint: Le_w < Le
        SolverAdd CellRef:="$C$77", Relation:=1, FormulaText:="$J$72"

        'Re-entrainment constraint: u_r_act < u_r_max
        SolverAdd CellRef:="$C$80", Relation:=1, FormulaText:="$J$75"

        'Oil out gas outlet constraint: hvdi - h_HHLL >= delta_h_s
        SolverAdd CellRef:="$C$83", Relation:=3, FormulaText:="$J$78"

        'Gas out oil outlet constraint: h_LLLL - h_WH >= delta_h_s
        SolverAdd CellRef:="$C$86", Relation:=3, FormulaText:="$J$78"

        'Water out oil outlet constraint: h_WH-HHIL >= delta_h_s
        SolverAdd CellRef:="$C$89", Relation:=3, FormulaText:="$J$78"

        'Oil out water outlet constraint: h_LILL >= delta_h_s
        SolverAdd CellRef:="$C$92", Relation:=3, FormulaText:="$J$78"

        'Normal levels apart constraint: h_NLL-h_NIL>= 4*delta_h_NOR+2*delta_h_s
        SolverAdd CellRef:="$C$95", Relation:=3, FormulaText:="$J$81"

        'Separator length constraint: Lsep < 20 m
        SolverAdd CellRef:="$C$98", Relation:=1, FormulaText:="$J$84"

        'Separator diameter constraint: Dsep < 4.5 m
        SolverAdd CellRef:="$C$101", Relation:=1, FormulaText:="$J$87"

        'K-value constraint: K_value < 0.15 m/s
        SolverAdd CellRef:="$C$104", Relation:=1, FormulaText:="$J$90"

        'Slenderness Ratio constraint: 3 < SL < 5
        SolverAdd CellRef:="$C$107", Relation:=1, FormulaText:="$J$94"
        SolverAdd CellRef:="$C$107", Relation:=3, FormulaText:="$J$93"

        'Variables always positive: Di,Le,h_NLL >= 0
        SolverAdd CellRef:="$V$15:$V$18", Relation:=3, FormulaText:="0"

    'Solve
    SolverSolve '(True)
End Sub

Sub Macro8(i)
'
' Macro8 Solve for cost
'
    Worksheets("3-phase calc").Activate
```

```
    'Reset solver
    SolverReset

    'Goal: Get cost as low as possible by changing Le, Di, h_NLL and h_NIL
    SolverOk SetCell:="$C$111", MaxMinVal:=2, ValueOf:=0, ByChange:="$V$15:$V$18", _
        Engine:=1, EngineDesc:="GRG Nonlinear"

    'Constraints

        'Gas capacity constraint: Le_g < Le
        SolverAdd CellRef:="$C$71", Relation:=1, FormulaText:="$J$72"

        'Oil capacity constraint: Le_o < Le
        SolverAdd CellRef:="$C$74", Relation:=1, FormulaText:="$J$72"

        'Water capacity constraint: Le_w < Le
        SolverAdd CellRef:="$C$77", Relation:=1, FormulaText:="$J$72"

        'Re-entrainment constraint: u_r_act < u_r_max
        SolverAdd CellRef:="$C$80", Relation:=1, FormulaText:="$J$75"

        'Oil out gas outlet constraint: hvdi - h_HHLL >= delta_h_s
        SolverAdd CellRef:="$C$83", Relation:=3, FormulaText:="$J$78"

        'Gas out oil outlet constraint: h_LLLL - h_WH >= delta_h_s
        SolverAdd CellRef:="$C$86", Relation:=3, FormulaText:="$J$78"

        'Water out oil outlet constraint: h_WH-HHIL >= delta_h_s
        SolverAdd CellRef:="$C$89", Relation:=3, FormulaText:="$J$78"

        'Oil out water outlet constraint: h_LILL >= delta_h_s
        SolverAdd CellRef:="$C$92", Relation:=3, FormulaText:="$J$78"

        'Normal levels apart constraint: h_NLL-h_NIL>= 4*delta_h_NOR+2*delta_h_s
        SolverAdd CellRef:="$C$95", Relation:=3, FormulaText:="$J$81"

        'Separator length constraint: Lsep < 20 m
        SolverAdd CellRef:="$C$98", Relation:=1, FormulaText:="$J$84"

        'Separator diameter constraint: Dsep < 4.5 m
        SolverAdd CellRef:="$C$101", Relation:=1, FormulaText:="$J$87"

        'K-value constraint: K_value < 0.15 m/s
        SolverAdd CellRef:="$C$104", Relation:=1, FormulaText:="$J$90"

        'Slenderness Ratio constraint: 3 < SL < 5
        SolverAdd CellRef:="$C$107", Relation:=1, FormulaText:="$J$94"
        SolverAdd CellRef:="$C$107", Relation:=3, FormulaText:="$J$93"

        'Variables always positive: Di,Le,h_NLL >= 0
        SolverAdd CellRef:="$V$15:$V$18", Relation:=3, FormulaText:="0"


    'Solve
    Solv_cst = SolverSolve(True)
    Sheets("RESULTS").Cells(i, 5).Value = Solv_cst

    'SolverOk.True
End Sub

Sub Macro10(i)
'
' Macro8 Solve for cost
'   Verify separator design

    Worksheets("3-phase calc").Activate

    'Reset solver
    SolverReset

    'Goal: Get cost as low as possible by changing Le, Di, h_NLL and h_NIL
    SolverOk SetCell:="$C$111", MaxMinVal:=2, ValueOf:=0, ByChange:="$V$17:$V$18", _
```

```
        Engine:=1, EngineDesc:="GRG Nonlinear"

     'Constraints

        'Gas capacity constraint: Le_g < Le
        SolverAdd CellRef:="$C$71", Relation:=1, FormulaText:="$J$72"

        'Oil capacity constraint: Le_o < Le
        SolverAdd CellRef:="$C$74", Relation:=1, FormulaText:="$J$72"

        'Water capacity constraint: Le_w < Le
        SolverAdd CellRef:="$C$77", Relation:=1, FormulaText:="$J$72"

        'Re-entrainment constraint: u_r_act < u_r_max
        SolverAdd CellRef:="$C$80", Relation:=1, FormulaText:="$J$75"

        'Oil out gas outlet constraint: hvdi - h_HHLL >= delta_h_s
        SolverAdd CellRef:="$C$83", Relation:=3, FormulaText:="$J$78"

        'Gas out oil outlet constraint: h_LLLL - h_WH >= delta_h_s
        SolverAdd CellRef:="$C$86", Relation:=3, FormulaText:="$J$78"

        'Water out oil outlet constraint: h_WH-HHIL >= delta_h_s
        SolverAdd CellRef:="$C$89", Relation:=3, FormulaText:="$J$78"

        'Oil out water outlet constraint: h_LILL >= delta_h_s
        SolverAdd CellRef:="$C$92", Relation:=3, FormulaText:="$J$78"

        'Normal levels apart constraint: h_NLL-h_NIL>= 4*delta_h_NOR+2*delta_h_s
        SolverAdd CellRef:="$C$95", Relation:=3, FormulaText:="$J$81"

        'Separator length constraint: Lsep < 20 m
        SolverAdd CellRef:="$C$98", Relation:=1, FormulaText:="$J$84"

        'Separator diameter constraint: Dsep < 4.5 m
        SolverAdd CellRef:="$C$101", Relation:=1, FormulaText:="$J$87"

        'K-value constraint: K_value < 0.15 m/s
        SolverAdd CellRef:="$C$104", Relation:=1, FormulaText:="$J$90"

        'Slenderness Ratio constraint: 3 < SL < 5
        SolverAdd CellRef:="$C$107", Relation:=1, FormulaText:="$J$94"
        SolverAdd CellRef:="$C$107", Relation:=3, FormulaText:="$J$93"

        'Variables always positive: Di,Le,h_NLL >= 0
        SolverAdd CellRef:="$V$15:$V$18", Relation:=3, FormulaText:="0"


    'Solve
    Solv_cst = SolverSolve(True)
    Sheets("RESULTS").Cells(i, 5).Value = Solv_cst

    'SolverOk.True
End Sub

Sub Optimize_For_Footprint(i)

' Optimize footprint

    Worksheets("3-phase calc").Activate

    'Reset solver
    SolverReset

    'Goal: Get cost as low as possible by changing Le, Di, h_NLL and h_NIL
    SolverOk SetCell:="$C$118", MaxMinVal:=2, ValueOf:=0, ByChange:="$V$15:$V$18", _
        Engine:=1, EngineDesc:="GRG Nonlinear"


     'Constraints

        'Gas capacity constraint: Le_g < Le
        SolverAdd CellRef:="$C$71", Relation:=1, FormulaText:="$J$72"
```

```
        'Oil capacity constraint: Le_o < Le
        SolverAdd CellRef:="$C$74", Relation:=1, FormulaText:="$J$72"

        'Water capacity constraint: Le_w < Le
        SolverAdd CellRef:="$C$77", Relation:=1, FormulaText:="$J$72"

        'Re-entrainment constraint: u_r_act < u_r_max
        SolverAdd CellRef:="$C$80", Relation:=1, FormulaText:="$J$75"

        'Oil out gas outlet constraint: hvdi - h_HHLL >= delta_h_s
        SolverAdd CellRef:="$C$83", Relation:=3, FormulaText:="$J$78"

        'Gas out oil outlet constraint: h_LLLL - h_WH >= delta_h_s
        SolverAdd CellRef:="$C$86", Relation:=3, FormulaText:="$J$78"

        'Water out oil outlet constraint: h_WH-HHIL >= delta_h_s
        SolverAdd CellRef:="$C$89", Relation:=3, FormulaText:="$J$78"

        'Oil out water outlet constraint: h_LILL >= delta_h_s
        SolverAdd CellRef:="$C$92", Relation:=3, FormulaText:="$J$78"

        'Normal levels apart constraint: h_NLL-h_NIL>= 4*delta_h_NOR+2*delta_h_s
        SolverAdd CellRef:="$C$95", Relation:=3, FormulaText:="$J$81"

        'Separator length constraint: Lsep < 20 m
        SolverAdd CellRef:="$C$98", Relation:=1, FormulaText:="$J$84"

        'Separator diameter constraint: Dsep < 4.5 m
        SolverAdd CellRef:="$C$101", Relation:=1, FormulaText:="$J$87"

        'K-value constraint: K_value < 0.15 m/s
        SolverAdd CellRef:="$C$104", Relation:=1, FormulaText:="$J$90"

        'Slenderness Ratio constraint: 3 < SL < 5
        SolverAdd CellRef:="$C$107", Relation:=1, FormulaText:="$J$94"
        SolverAdd CellRef:="$C$107", Relation:=3, FormulaText:="$J$93"

        'Variables always positive: Di,Le,h_NLL >= 0
        SolverAdd CellRef:="$V$15:$V$18", Relation:=3, FormulaText:="0"


    'Solve
    Solv_cst = SolverSolve(True)
    Sheets("RESULTS").Cells(i, 5).Value = Solv_cst

    'SolverOk.True
End Sub

Sub Verify_For_Footprint(i)
'
' Verify design for footprint

    Worksheets("3-phase calc").Activate

    'Reset solver
    SolverReset

    'Goal: Get cost as low as possible by changing Le, Di, h_NLL and h_NIL
    SolverOk SetCell:="$C$118", MaxMinVal:=2, ValueOf:=0, ByChange:="$V$17:$V$18", _
        Engine:=1, EngineDesc:="GRG Nonlinear"

     'Constraints

        'Gas capacity constraint: Le_g < Le
        SolverAdd CellRef:="$C$71", Relation:=1, FormulaText:="$J$72"

        'Oil capacity constraint: Le_o < Le
        SolverAdd CellRef:="$C$74", Relation:=1, FormulaText:="$J$72"

        'Water capacity constraint: Le_w < Le
        SolverAdd CellRef:="$C$77", Relation:=1, FormulaText:="$J$72"
```

```
        'Re-entrainment constraint: u_r_act < u_r_max
        SolverAdd CellRef:="$C$80", Relation:=1, FormulaText:="$J$75"

        'Oil out gas outlet constraint: hvdi - h_HHLL >= delta_h_s
        SolverAdd CellRef:="$C$83", Relation:=3, FormulaText:="$J$78"

        'Gas out oil outlet constraint: h_LLLL - h_WH >= delta_h_s
        SolverAdd CellRef:="$C$86", Relation:=3, FormulaText:="$J$78"

        'Water out oil outlet constraint: h_WH-HHIL >= delta_h_s
        SolverAdd CellRef:="$C$89", Relation:=3, FormulaText:="$J$78"

        'Oil out water outlet constraint: h_LILL >= delta_h_s
        SolverAdd CellRef:="$C$92", Relation:=3, FormulaText:="$J$78"

        'Normal levels apart constraint: h_NLL-h_NIL>= 4*delta_h_NOR+2*delta_h_s
        SolverAdd CellRef:="$C$95", Relation:=3, FormulaText:="$J$81"

        'Separator length constraint: Lsep < 20 m
        SolverAdd CellRef:="$C$98", Relation:=1, FormulaText:="$J$84"

        'Separator diameter constraint: Dsep < 4.5 m
        SolverAdd CellRef:="$C$101", Relation:=1, FormulaText:="$J$87"

        'K-value constraint: K_value < 0.15 m/s
        SolverAdd CellRef:="$C$104", Relation:=1, FormulaText:="$J$90"

        'Slenderness Ratio constraint: 3 < SL < 5
        SolverAdd CellRef:="$C$107", Relation:=1, FormulaText:="$J$94"
        SolverAdd CellRef:="$C$107", Relation:=3, FormulaText:="$J$93"

        'Variables always positive: Di,Le,h_NLL >= 0
        SolverAdd CellRef:="$V$15:$V$18", Relation:=3, FormulaText:="0"


    'Solve
    Solv_cst = SolverSolve(True)
    Sheets("RESULTS").Cells(i, 5).Value = Solv_cst

    'SolverOk.True
End Sub

Sub Optimize_1()

'Set up to optimize for cost

    Application.ScreenUpdating = False

    For_Start = Sheets("RESULTS").Cells(2, 10).Value
    For_end = Sheets("RESULTS").Cells(3, 10).Value


    For i = For_Start To For_end

       Call insertinput_1(i)

       Call Macro8(i)

       Call GetResults1(i)

       Sheets("RESULTS").Cells(i, 6).Value = "Optimized"
    Next

    Worksheets("RESULTS").Select
    Application.ScreenUpdating = True

End Sub

Sub Verify_1()
    'Verify design for cost

    Application.ScreenUpdating = False
```

```
    For_Start = Sheets("RESULTS").Cells(2, 10).Value
    For_end = Sheets("RESULTS").Cells(3, 10).Value

    For i = For_Start To For_end

       Call insertinput_2(i)

       Call Macro10(i)

       Call GetResults1(i)

       Sheets("RESULTS").Cells(i, 6).Value = "Verified"
    Next

    Worksheets("RESULTS").Select
    Application.ScreenUpdating = True

End Sub

Sub Optimize_Footprint_Get_Results()

'Set up to optimize for footprint

    Application.ScreenUpdating = False

    For_Start = Sheets("RESULTS").Cells(2, 10).Value
    For_end = Sheets("RESULTS").Cells(3, 10).Value


    For i = For_Start To For_end

       Call insertinput_1(i)

       Call Optimize_For_Footprint(i)

       Call GetResults1(i)

       Sheets("RESULTS").Cells(i, 6).Value = "Optimized"
    Next

    Worksheets("RESULTS").Select
    Application.ScreenUpdating = True

End Sub

Sub Verify_Footprint_Get_Results()

'Verify footprint set up

    Application.ScreenUpdating = False

    For_Start = Sheets("RESULTS").Cells(2, 10).Value
    For_end = Sheets("RESULTS").Cells(3, 10).Value

    For i = For_Start To For_end

       Call insertinput_2(i)

       Call Verify_For_Footprint(i)

       Call GetResults1(i)

       Sheets("RESULTS").Cells(i, 6).Value = "Verified"
    Next

    Worksheets("RESULTS").Select
    Application.ScreenUpdating = True

End Sub

Sub insertinput_1(i)
```

```
'Input data

    'Dim iInput As Integer
    'i = InputBox("Please row-number", "Create Invoice Number", 10)



        c = 7

        'Temperature
        Sheets("RESULTS").Cells(i, c).Copy
        Sheets("3-phase calc").Cells(10, 3).PasteSpecial Paste:=xlPasteValues

        'Pressure
        Sheets("RESULTS").Cells(i, c + 1).Copy
        Sheets("3-phase calc").Cells(11, 3).PasteSpecial Paste:=xlPasteValues


        'Rates
        'Gas rate
        Sheets("3-phase calc").Cells(16, 3).Value = Sheets("RESULTS").Cells(i, c + 2).
            Value / Sheets("RESULTS").Cells(i, c + 12).Value

        'Oil rate
        Sheets("3-phase calc").Cells(16, 4).Value = Sheets("RESULTS").Cells(i, c + 3).
            Value / Sheets("RESULTS").Cells(i, c + 12).Value

        'Water rate
        Sheets("3-phase calc").Cells(16, 5).Value = Sheets("RESULTS").Cells(i, c + 4).
            Value / Sheets("RESULTS").Cells(i, c + 12).Value

        'Density
        'Gas
        'Sheets("RESULTS").Cells(i, 11).Copy
        'Sheets("3-phase calc").Cells(17, 3).PasteSpecial Paste:=xlPasteValues

        'Oil
        'Sheets("RESULTS").Cells(i, 12).Copy
        'Sheets("3-phase calc").Cells(17, 4).PasteSpecial Paste:=xlPasteValues

        'Water
        'Sheets("RESULTS").Cells(i, 13).Copy
        'Sheets("3-phase calc").Cells(17, 5).PasteSpecial Paste:=xlPasteValues


        'Surface tension
        'Sheets("RESULTS").Cells(i, 14).Copy
        'Sheets("3-phase calc").Cells(20, 3).PasteSpecial Paste:=xlPasteValues


        'Viscosity
        'Gas
        'Sheets("RESULTS").Cells(i, c + 9).Copy
        'Sheets("3-phase calc").Cells(18, 3).PasteSpecial Paste:=xlPasteValues

        'Oil
        'Sheets("RESULTS").Cells(i, c + 10).Copy
        'Sheets("3-phase calc").Cells(18, 4).PasteSpecial Paste:=xlPasteValues

        'Water
        'Sheets("RESULTS").Cells(i, c + 11).Copy
        'Sheets("3-phase calc").Cells(18, 5).PasteSpecial Paste:=xlPasteValues


        'Initial Guesses
        'Diameter
        Sheets("RESULTS").Cells(4, 24).Copy
        Sheets("3-phase calc").Cells(15, 22).PasteSpecial Paste:=xlPasteValues

        'Length
        Sheets("RESULTS").Cells(4, 25).Copy
        Sheets("3-phase calc").Cells(16, 22).PasteSpecial Paste:=xlPasteValues
```

```
        'Liquid Level
        Sheets("RESULTS").Cells(4, 26).Copy
        Sheets("3-phase calc").Cells(17, 22).PasteSpecial Paste:=xlPasteValues

        'Interface Level
        Sheets("RESULTS").Cells(4, 27).Copy
        Sheets("3-phase calc").Cells(18, 22).PasteSpecial Paste:=xlPasteValues

End Sub

Sub insertinput_2(i)


'Input data for verification

    'Dim iInput As Integer
    'i = InputBox("Please row-number", "Create Invoice Number", 10)



        c = 7

        'Temperature
        'Sheets("RESULTS").Cells(i, c).Copy
        'Sheets("3-phase calc").Cells(10, 3).PasteSpecial Paste:=xlPasteValues

        'Pressure
        'Sheets("RESULTS").Cells(i, c + 1).Copy
        'Sheets("3-phase calc").Cells(11, 3).PasteSpecial Paste:=xlPasteValues


        'Rates
        'Gas rate
        Sheets("3-phase calc").Cells(16, 3).Value = Sheets("RESULTS").Cells(i, c + 2).
            Value / Sheets("RESULTS").Cells(i, c + 12).Value
        'Sheets("RESULTS").Cells(i, 8).Copy
        'Sheets("3-phase calc").Cells(16, 3).PasteSpecial Paste:=xlPasteValues

        'Oil rate
        Sheets("3-phase calc").Cells(16, 4).Value = Sheets("RESULTS").Cells(i, c + 3).
            Value / Sheets("RESULTS").Cells(i, c + 12).Value
        'Sheets("RESULTS").Cells(i, 9).Copy
        'Sheets("3-phase calc").Cells(16, 4).PasteSpecial Paste:=xlPasteValues

        'Water rate
        Sheets("3-phase calc").Cells(16, 5).Value = Sheets("RESULTS").Cells(i, c + 4).
            Value / Sheets("RESULTS").Cells(i, c + 12).Value
        'Sheets("RESULTS").Cells(i, 10).Copy
        'Sheets("3-phase calc").Cells(16, 5).PasteSpecial Paste:=xlPasteValues


        'Density
        'Gas
        'Sheets("RESULTS").Cells(i, 11).Copy
        'Sheets("3-phase calc").Cells(17, 3).PasteSpecial Paste:=xlPasteValues

        'Oil
        'Sheets("RESULTS").Cells(i, 12).Copy
        'Sheets("3-phase calc").Cells(17, 4).PasteSpecial Paste:=xlPasteValues

        'Water
        'Sheets("RESULTS").Cells(i, 13).Copy
        'Sheets("3-phase calc").Cells(17, 5).PasteSpecial Paste:=xlPasteValues


        'Surface tension
        'Sheets("RESULTS").Cells(i, 14).Copy
        'Sheets("3-phase calc").Cells(20, 3).PasteSpecial Paste:=xlPasteValues


        'Viscosity
        'Gas
        'Sheets("RESULTS").Cells(i, c + 9).Copy
```

```
        'Sheets("3-phase calc").Cells(18, 3).PasteSpecial Paste:=xlPasteValues

        'Oil
        'Sheets("RESULTS").Cells(i, c + 10).Copy
        'Sheets("3-phase calc").Cells(18, 4).PasteSpecial Paste:=xlPasteValues

        'Water
        'Sheets("RESULTS").Cells(i, c + 11).Copy
        'Sheets("3-phase calc").Cells(18, 5).PasteSpecial Paste:=xlPasteValues


        'Initial Guesses
        'Diameter
        'Sheets("RESULTS").Cells(4, 24).Copy
        'Sheets("3-phase calc").Cells(15, 22).PasteSpecial Paste:=xlPasteValues

        'Length
        'Sheets("RESULTS").Cells(4, 25).Copy
        'Sheets("3-phase calc").Cells(16, 22).PasteSpecial Paste:=xlPasteValues

        'Liquid Level
        'Sheets("RESULTS").Cells(4, 26).Copy
        'Sheets("3-phase calc").Cells(17, 22).PasteSpecial Paste:=xlPasteValues

        'Interface Level
        'Sheets("RESULTS").Cells(4, 27).Copy
        'Sheets("3-phase calc").Cells(18, 22).PasteSpecial Paste:=xlPasteValues

End Sub

Sub GetResults1(i)

    'Get outputs from "3-phase calc"-sheet to "RESULTS"-sheet

        'Liquid Levels
            A = 0
            For j = 39 To 43
                A = A + 1
                Sheets("3-phase calc").Cells(j, 3).Copy
                Sheets("RESULTS").Cells(i, 20 + A).PasteSpecial Paste:=xlPasteValues
            Next j

        'Interface Levels
        A = 0
        For j = 46 To 50
            A = A + 1
            Sheets("3-phase calc").Cells(j, 3).Copy
            Sheets("RESULTS").Cells(i, 25 + A).PasteSpecial Paste:=xlPasteValues
        Next j

        'Optimized Variables
        'a = -1
        'For j = 15 To 18
        '    a = a + 1
        '    Sheets("3-phase calc").Cells(j, 22).Copy
        '    Sheets("RESULTS").Cells(i, 24 + a).PasteSpecial Paste:=xlPasteValues
        'Next j

        'Residence Time
        A = 0
        For j = 84 To 86
            A = A + 1
            Sheets("3-phase calc").Cells(j, 16).Copy
            Sheets("RESULTS").Cells(i, 30 + A).PasteSpecial Paste:=xlPasteValues
        Next j

        'Settling Time
         A = 0
        For j = 89 To 91
            A = A + 1
            Sheets("3-phase calc").Cells(j, 16).Copy
            Sheets("RESULTS").Cells(i, 33 + A).PasteSpecial Paste:=xlPasteValues
        Next j
```

```
c = 37

'Effective length
Sheets("3-phase calc").Cells(16, 22).Copy
Sheets("RESULTS").Cells(i, c).PasteSpecial Paste:=xlPasteValues

'End section length
Sheets("3-phase calc").Cells(57, 3).Copy
Sheets("RESULTS").Cells(i, c + 1).PasteSpecial Paste:=xlPasteValues

'Total length
Sheets("3-phase calc").Cells(98, 3).Copy
Sheets("RESULTS").Cells(i, c + 2).PasteSpecial Paste:=xlPasteValues


'Inner diameter
Sheets("3-phase calc").Cells(15, 22).Copy
Sheets("RESULTS").Cells(i, c + 3).PasteSpecial Paste:=xlPasteValues

'Total diameter
Sheets("3-phase calc").Cells(101, 3).Copy
Sheets("RESULTS").Cells(i, c + 4).PasteSpecial Paste:=xlPasteValues

'Weir height
Sheets("3-phase calc").Cells(66, 3).Copy
Sheets("RESULTS").Cells(i, c + 5).PasteSpecial Paste:=xlPasteValues

'K-value
Sheets("3-phase calc").Cells(104, 3).Copy
Sheets("RESULTS").Cells(i, c + 6).PasteSpecial Paste:=xlPasteValues

'Slenderness Ratio
Sheets("3-phase calc").Cells(107, 3).Copy
Sheets("RESULTS").Cells(i, c + 7).PasteSpecial Paste:=xlPasteValues


'Gas Capacity
Sheets("3-phase calc").Cells(71, 5).Copy
Sheets("RESULTS").Cells(i, c + 8).PasteSpecial Paste:=xlPasteValues

'Oil Capacity
Sheets("3-phase calc").Cells(74, 5).Copy
Sheets("RESULTS").Cells(i, c + 9).PasteSpecial Paste:=xlPasteValues

'Water Capacity
Sheets("3-phase calc").Cells(77, 5).Copy
Sheets("RESULTS").Cells(i, c + 10).PasteSpecial Paste:=xlPasteValues

'Re-entrainment
Sheets("3-phase calc").Cells(80, 5).Copy
Sheets("RESULTS").Cells(i, c + 11).PasteSpecial Paste:=xlPasteValues

'Oil out gas outlet
Sheets("3-phase calc").Cells(83, 5).Copy
Sheets("RESULTS").Cells(i, c + 12).PasteSpecial Paste:=xlPasteValues

'Gas out oil outlet
Sheets("3-phase calc").Cells(86, 5).Copy
Sheets("RESULTS").Cells(i, c + 13).PasteSpecial Paste:=xlPasteValues

'Water out oil outlet
Sheets("3-phase calc").Cells(89, 5).Copy
Sheets("RESULTS").Cells(i, c + 14).PasteSpecial Paste:=xlPasteValues

'Oil out water outlet
Sheets("3-phase calc").Cells(92, 5).Copy
Sheets("RESULTS").Cells(i, c + 15).PasteSpecial Paste:=xlPasteValues

'Normal levels apart
Sheets("3-phase calc").Cells(95, 5).Copy
Sheets("RESULTS").Cells(i, c + 16).PasteSpecial Paste:=xlPasteValues
```

```
        'Total length
        Sheets("3-phase calc").Cells(98, 5).Copy
        Sheets("RESULTS").Cells(i, c + 17).PasteSpecial Paste:=xlPasteValues

        'Total diameter
        Sheets("3-phase calc").Cells(101, 5).Copy
        Sheets("RESULTS").Cells(i, c + 18).PasteSpecial Paste:=xlPasteValues

        'K-value
        Sheets("3-phase calc").Cells(104, 5).Copy
        Sheets("RESULTS").Cells(i, c + 19).PasteSpecial Paste:=xlPasteValues

        'Slenderness Ratio Min
        Sheets("3-phase calc").Cells(107, 6).Copy
        Sheets("RESULTS").Cells(i, c + 20).PasteSpecial Paste:=xlPasteValues

        'Slenderness Ratio Min
        Sheets("3-phase calc").Cells(107, 5).Copy
        Sheets("RESULTS").Cells(i, c + 21).PasteSpecial Paste:=xlPasteValues

        'Cost
        Sheets("3-phase calc").Cells(111, 3).Copy
        Sheets("RESULTS").Cells(i, c + 22).PasteSpecial Paste:=xlPasteValues

        'Weight Dry
        Sheets("3-phase calc").Cells(114, 5).Copy
        Sheets("RESULTS").Cells(i, c + 23).PasteSpecial Paste:=xlPasteValues

        'Weight Wet
        Sheets("3-phase calc").Cells(115, 5).Copy
        Sheets("RESULTS").Cells(i, c + 24).PasteSpecial Paste:=xlPasteValues

        'Footprint
        Sheets("3-phase calc").Cells(118, 3).Copy
        Sheets("RESULTS").Cells(i, c + 25).PasteSpecial Paste:=xlPasteValues


End Sub
```

Elias Vølstad Bogen

Optimized Design of Horizontal Gas-Oil-Water Gravity Separators

NTNU

Norwegian University of
Science and Technology