Sheet Version: 1.1, (**TwoOilReservoirs**)

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Description:

A typical design issue in the early phase of the development of offshore oil and gas fields is to define production and drilling schedules that maximize the net present value of the project. This Excel sheet uses integer-nonlinear numerical optimization to solve this problem. The optimization problem is defined using the interface of the Excel Solver.

The size of the problem exceeds the limits of the Solver included by default in Excel (provided by the company Frontline), thus the open source OpenSolver (https://opensolver.org) is used instead, with the BONMIN solver.

The Excel sheet also allows to evaluate the effect of uncertainty on the results. Uncertainties considered are yearly oil prices, initial oil in place of the reservoirs, well productivity of reservoirs and cost. Samples are generated using Latin-Hypercube sampling (LHS) and optimizations are run with these inputs. Results are then processed and statistical parameters such as median, mean, P10, P90, quartiles, etc. are computed.

The study case solved is an offshore oil field with two reservoirs in the Norwegian Continental Shelf that produce independently to the processing facilities through subsea networks. The details of the case are reported by Alkindira (2020).

The performance of the production system comprising reservoir, wells and gathering network is modeled using production potential curves computed from dimensionless production potential curves as described by Stanko (2021). The dimensionless production potential curve is represented with a fifth-order polynomial.

Requirements:

- This workbook requires OpenSolver Advanced (non-linear) v2.9.3, a free Excel addin available at https://opensolver.org/installing-opensolver/. Download, unpack, open OpenSolver.xlam and then open the Excel sheet. It might be necessary to activate this add-in by going into the main menu of Excel – Options – Add-in and selecting opensolver.
- Allow VBA macros
- This sheet has been tested in Windows 10 and on a 64-bit Excel version.

Sheet structure:

Color code: cells with red font can be modified, cells with blue font are usually calculated and cells with violet font are optimization variables.

The sheet “Data_and_Model” contains the main model used for optimization. It also has buttons that trigger VBA scripts to perform the following tasks:

- Initialize: assigns initial seeds for the optimization variables. Before running the optimization, it is important that the optimization variables do not violate the constraints, otherwise the solver will fail.
- Optimize: optimizes the model shown in the sheet using opensolver and the BONMIN solver.
- Run specified cases and store results: this script copies data from the sheets “Uncertainty-LHS” and “Oil_Price” to the sheet “Data_and_Model”, then initializes the variables, runs the optimization, and

[1] https://opensolver.org

copies the results to the sheet "Results". This is done on a case by case basis. The range of cases to run are specified in the cells U4 and V4 of the sheet "Data_and_Model". Make sure that there is data in the sheets "Uncertainty-LHS" and "Oil_Price" for at least the number of cases indicated.

- Run specific case: this script is similar to Run probabilistic analysis, but it runs the case specified in cell U3.

This sheet also contains computation of ultimate recovery factor for both reservoirs and plots of the drilling and production schedule of the two reservoirs and the field.

The sheet "Uncertainty-LHS" generates random samples using Latin-Hypercube sampling of probabilistic distributions of the following 5 variables:

- Initial oil in place of reservoirs 1 and 2
- Well productivity of wells in reservoirs 1 and 2
- Cost factor (that affects DRILLEX, CAPEX and OPEX)

Probability distributions available are LogNormal, Normal, Uniform and Triangular. Samples taken from the distributions are bounded with the minimum and maximum specified. To generate the samples, use the button "Generate Samples"

The sheet "Oil_Price" has a script to generate oil price trajectories using the model by Schwartz and Schmidt. It also computes statistical variables P10, P90 and mean per year of the trajectories generated. Trajectories are plotted in the chart "OilPriceTrajec" (maximum 255 series, due to Excel limitations). The P10, P90 and mean of the trajectories generated is plotted in the chart "OilPriceTrajecP90P10".

Warning: The Schwartz and Schmidt model must be tuned to historic data to determine the model parameters.

The sheet "DimProdPot" allows to compute the constants of the dimensionless production potential curve using simulation data (maximum rate of oil vs cumulative production and initial oil in place). When pasting new data in columns A and B, make sure to 1) extend or reduce columns C,D and E correspondingly and 2) modify cells G3:G7 accordingly.

The sheet "Results" has all results product of a probabilistic analysis triggered in sheet "Data and Model". The cumulative distribution function of NPV is computed and plotted in the chart "NPV_cdf". The minimum, maximum, median, and 25% and 75% quartiles of number of producer wells and oil rate for each year are calculated for field, reservoir 1 and reservoir 2. These values are plotted in the charts:

- qo_f_vs_time
- Nwpf_vs_time
- qo_1_vs_time
- Nwp1_vs_time
- qo_2_vs_time
- Nwp2_vs_time

Before running a new probabilistic analysis, run the script "Clear Results" in this sheet.

Model:

The objective function to maximize is the net present value (NPV) of the project:

$$NPV = \sum_{t \in T} DCF_t \qquad \text{Eq. 1}$$

Where "t" is a given year, T is the total number of years and DCF is the yearly discounted cash flow:

$$DCF_t = \frac{1}{(1+i)^t}\left(P_{o,t} \cdot \Delta N_{p,f,t} - CAPEX_{SUBSEA+TOPSIDE,t} - DRILLEX_t - OPEX_t - TAX_t\right) \quad \text{Eq. 2}$$

"i" is the discount rate

It is assumed that all field revenues come from oil sales. $\Delta N_{p,f,t}$ is the oil produced by the field in year "t", calculated by summing the production from all reservoirs:

$$\Delta N_{p,f,t} = \sum_{r=1}^{N_R} \Delta N_{p,r,t} \quad \text{Eq. 3}$$

N_R is the total number of reservoirs in the field. A given reservoir is denoted with the letter "r".

$P_{o,t}$ is oil price in time. The value is input in USD/bbl and then converted to Norwegian Kroner using an exchange rate.

Drilling expenditures are:

$$DRILLEX_t = \sum_{r=1}^{N_R} \Delta N_{w,p,r,t} \cdot \left(1 + N_{\frac{inj}{prod},r}\right) \cdot a_{DRILLEX} \quad \text{Eq. 4}$$

$N_{\frac{inj}{prod},r}$ is the number of injectors per producer in reservoir "r". $\Delta N_{w,p,r,t}$ is number of new producer wells in reservoir "r" in year "t". It is expressed with the number of producer wells in reservoir "r" ($N_{w,p,r}$) at end of times "t" and "t-1"

$$\Delta N_{w,p,r,t} = N_{w,p,r,t} - \Delta N_{w,p,r,t-1} \quad \text{Eq. 5}$$

Warning: It could happen that the total number of new wells in a given reservoir or in the field at a time "t" gives a value which is a fraction. The number of producers will always be an integer, but the number of injectors might not necessarily be.

Capital expenditures (CAPEX) take into account the total cost of processing facilities, offshore structure and subsea system. It is a function of the total number of wells in the field, and the maximum oil, gas and water rates of the field. The maximum oil, gas and water rates of the field are computed with the maximum oil, gas and water rates of the reservoirs. The maximum gas and water rates of the reservoir are expressed as a function of the maximum oil rate and a maximum gas oil ratio ($GOR_{r,max}$) and a maximum water cut ($WC_{r,max}$).

$$CAPEX_{SUBSEA+TOPSIDE} = N_{w,f,max} \cdot a_{CAPEX} + \sum_{r=1}^{N_R} q_{o,r,max} \cdot \left(b_{CAPEX} + \frac{c_{CAPEX}}{1 - WC_{r,max}} + GOR_{r,max} \cdot d_{CAPEX}\right) + e_{CAPEX} \quad \text{Eq. 6}$$

Warning: This expression assumes that the maximum oil rate of both reservoirs will occur at the same time, which might not always be the case.

The maximum number of wells in the field is the sum of with the maximum number of wells in each reservoir.

$$N_{w,f,max} = \sum_{r=1}^{N_R} N_{w,p,r,max} \cdot \left(1 + N_{\frac{inj}{prod},r}\right) \quad \text{Eq. 7}$$

CAPEX is paid in parts over a finite amount of years. The CAPEX per year is calculated using a split factor for the year and the total CAPEX amount:

$$CAPEX_{SUBSEA+TOPSIDE,t} = F_t \cdot CAPEX_{SUBSEA+TOPSIDE} \quad \text{Eq. 8}$$

Operational expenditures are a function of the field oil rate at the end of year and the total operative number of wells in the field at the end of year

$$OPEx_t \ = a_{opex} + b_{opex} \cdot q_{o,f,t} + c_{opex} \cdot N_{w,f,t} \quad \text{Eq. 9}$$

The number of wells of the field at the end of year "t" is the sum of the wells in each reservoir at end of year "t" (including injectors and producers).

$$N_{w,f,t} = \sum_{r=1}^{N_R} N_{w,r,t} \quad \text{Eq. 10}$$

Warning: Operating expenses are calculated with the oil production and number of wells at end of year. In reality, oil production and number of wells at the beginning of the year should be considered as well.

Yearly tax (TAX_t) is calculated by computing taxable income of the year and multiplying by the tax rate. Tax is calculated only if the taxable income is positive.

$$TAX_t = TAX\_INC_t \cdot TAXRATE \quad \text{Eq. 11}$$

The taxable income of the year is the yearly revenue from hydrocarbon sales minus the depreciation of the year.

$$TAX\_INC_t = P_{o,t} \cdot \Delta N_{p,f,t} - DEP_t \quad \text{Eq. 12}$$

The depreciation of the year is calculated with the CAPEX and DRILLEX of the previous "N" number of years:

$$DEP_t = \sum_{t-N-1}^{t} \frac{CAPEX_{SUBSEA+TOPSIDE,t} + DRILLEX_t}{N} \quad \text{Eq. 13}$$

For each reservoir:

Oil cumulative production of year t is expressed with the production at end of years "t" and "t-1":

$$\Delta N_{p,t} = \left(q_{o,t} + q_{o,t-1}\right) \cdot \Delta t \cdot t_{up} \quad \text{Eq. 14}$$

Δt is one year, and t_{up} is the number of operational days in a year.

Reservoir production ($q_{o,t}$) and number of producer wells ($N_{w,p,t}$) at end of year are the independent variables to optimize. Some constraints on these variables are:

No oil has been produced at initial time:

$$N_{p,t=0} = 0 \quad \text{Eq. 15}$$

Cumulative oil production always increases:

$$\Delta N_{p,t} \geq 0 \quad \text{Eq. 16}$$

The oil production at a given end of year "t" must be less or equal to the production potential $q_{pp,t}$ at end of year.

$$q_{o,t} \leq q_{pp,t} \quad \text{Eq. 17}$$

The production potential at end of year “t” is a function of number of producer wells and cumulative production at end of year:

$$q_{pp,t} = q_{pp}\left(N_{p,t}, N_{w,p,t}\right) = q_{pp,max,reservoir,t} \cdot \left(a_{DIMPOT} \cdot \left(\frac{N_{p,t}}{N}\right)^5 + b_{DIMPOT} \cdot \left(\frac{N_{p,t}}{N}\right)^4 + c_{DIMPOT} \cdot \left(\frac{N_{p,t}}{N}\right)^3 + d_{DIMPOT} \cdot \left(\frac{N_{p,t}}{N}\right)^2 + e_{DIMPOT} \cdot \left(\frac{N_{p,t}}{N}\right) + 1\right) \quad \text{Eq. 18}$$

With:

$$N_{p,t} = N_{p,t-1} + \Delta N_{p,t} \quad \text{Eq. 19}$$

$$q_{pp,max,reservoir,t} = N_{w,p,t} \cdot q_{pp,max,well} \cdot F_{Pancake}{}^{N_{w,p},t-1} \quad \text{Eq. 20}$$

This expression assumes that producer wells in each reservoir are identical.

The factor $F_{Pancake}$ is added to capture the effect that the total rate from a reservoir is not equal to the multiplication of the well rate times the number of producers, but that there is some loss of production due to the presence of the subsea network.

Other relevant constraints:

$\Delta N_{w,p,t} \geq 0$ producer wells cannot be “undrilled” Eq. 21

$\Delta N_{w,p,f,t} \leq y$ It is only possible to drill “y” new producer wells every year in the field Eq. 22

$\Delta N_{w,p,t} \leq x$ It is only possible to drill “x” new producer wells every year in a given reservoir. Eq. 23

$$q_{o,max} = \max\left(q_{o,t}\right) \quad \text{Eq. 24}$$

$$N_{w,p,max} = \max\left(N_{w,p,t}\right) \quad \text{Eq. 25}$$

Implementation details:

1. Eq. 24 and Eq. 25 are enforced by adding two additional optimization variables for each reservoir, one continuous $q_{o,max}$ and one integer $N_{w,p,max}$ (both used in the cost functions) and enforcing the constraints:

$$q_{o,max} \geq q_{o,t} \quad \text{Eq. 26}$$

$$N_{w,p,max} \geq N_{w,p,t} \quad \text{Eq. 27}$$

2. The condition to calculate the tax only if the taxable income is positive is enforced in the following manner:

$$TAX_t = 0.5 \cdot TAXRATE \cdot \left(\frac{|TAX\_INC_t|}{TAX\_INC_t} + 1\right) \quad \text{Eq. 28}$$

Warning: This equation will be undefined if the taxable income is equal to zero.

About modifications:

If you wish to do significant modifications to this Excel sheet for your specific case, because changing the input in red is not enough, keep in mind the following:

- You will most likely have to modify some blue cells in the sheet "Data_and_Model". Avoid using logical functions like "IF" because most optimizers are not compatible with them
- You will most likely have to update the optimization problem using the interface of the Excel Solver
- You will most likely have to modify some VBA scripts like "Initialize", "Run specified cases and store results" and "Run Specific Case" in the sheet "Data and Model"
- The sheet "Results" and "Oil_Price" are made for a maximum of 50 years. If you want to run for longer periods, you will have to modify these sheets and their scripts.

Disclaimer:

- The author of disclaims any warranty, expressed or implied, as to the accuracy or reliability of the data or calculations contained therein.
- The tool is not a substitute for sound professional judgment.

Acknowledgments:

- The Oil price model of Schwartz and Schmidt has been coded by Leonardo Sales

References:

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