«Static» production optimization

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Course material:

-http://www.ipt.ntnu.no/~stanko/files/Courses/PetCyb/2024/

Agenda

- Introduction to production optimization
  - Practical meaning
  - Time scales
  - Model-based optimization
  - Types
- Example: two gas-lifted wells
- Exercise: two gas-lifted wells
- Discrete variables
  - Exercise: routing 5 wells to 2 separators
- How do solvers work?
- Multi-objective optimization
  - Constraint method
  - Linear scalarization
- Effect of uncertainties
- Proxy modeling using tables
  - Example: Gas-lifted well
- Proxy modeling using NN
  - Exercise in python
- Limitations and pitfalls of production optimization

Production optimization – what is it?

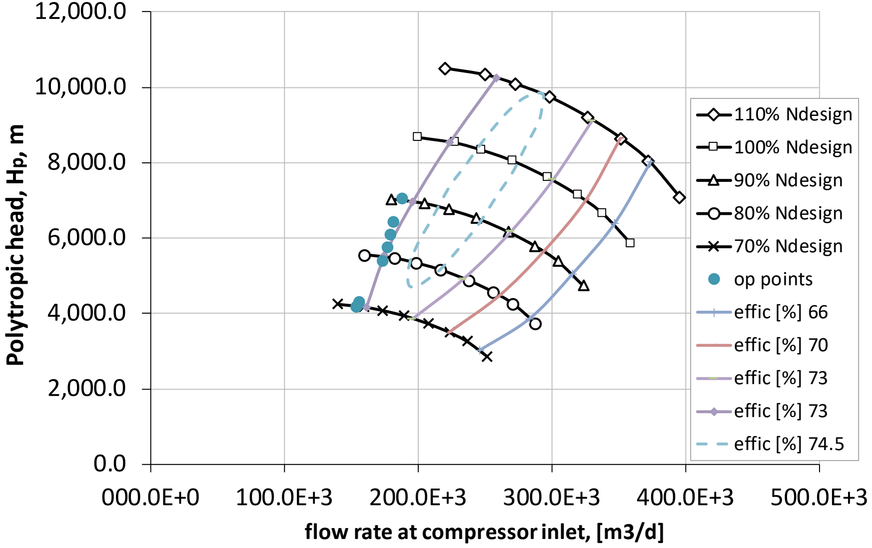
VS.

Examples of «production optimization»

- Detect locations in the system with abnormally high-pressure loss and flow restrictions

Examples of «production optimization»

- Verification of equipment design conditions vs actual operating conditions

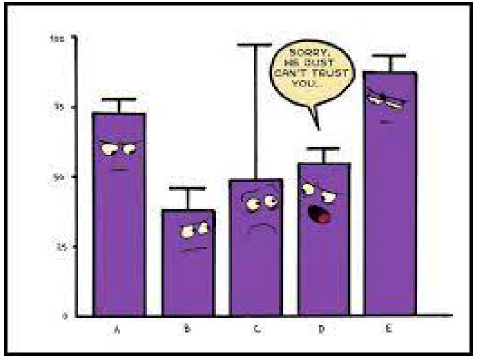


Examples of «production optimization»

- Identification and addressing fluid sources that have “disadvantageous” characteristics (e.g. high water cut, high H_2S content)
- Identify and correct system malfunctions and unintended behavior
- Analyze and improve the logistics and planning of maintenance, replacement and installation of equipment or in the execution of field activities.

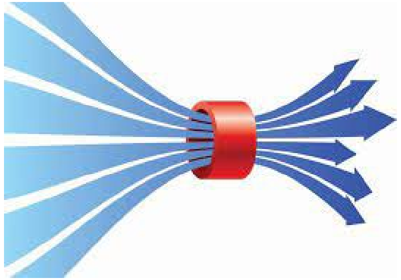
Production optimization – what is it?

- Review the occurrence of failures and recognize patterns (data analytics)
- Calibration of instrumentation
- Identification of operational constraints (e.g. water handling capacity, power capacity)



Production optimization – what is it?

- Identify bottlenecks
- Identifying and monitoring Key Performance Indicators (KPIs)



Production optimization – what is it?

- Find:
  - Control settings of equipment
  - System characteristics (design)

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    - Maximize a KPI

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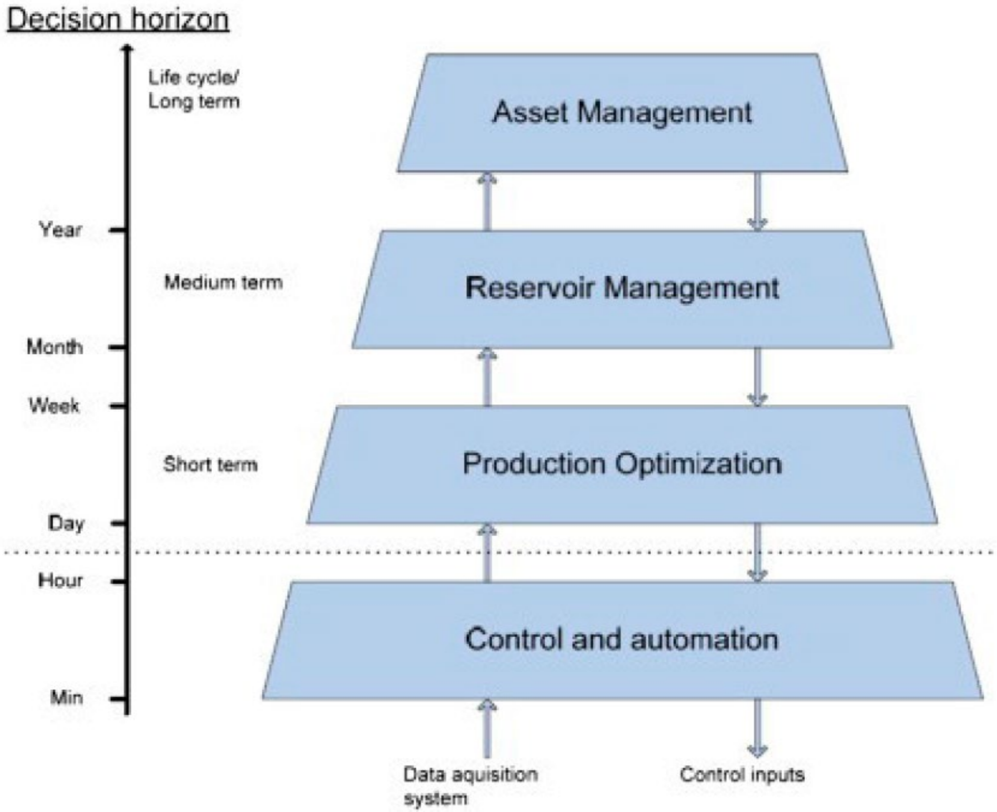
Time scales of production optimization

Long term	Short term	Shorter term
• Years, months	• Daily, weekly	• Seconds, minutes, hours

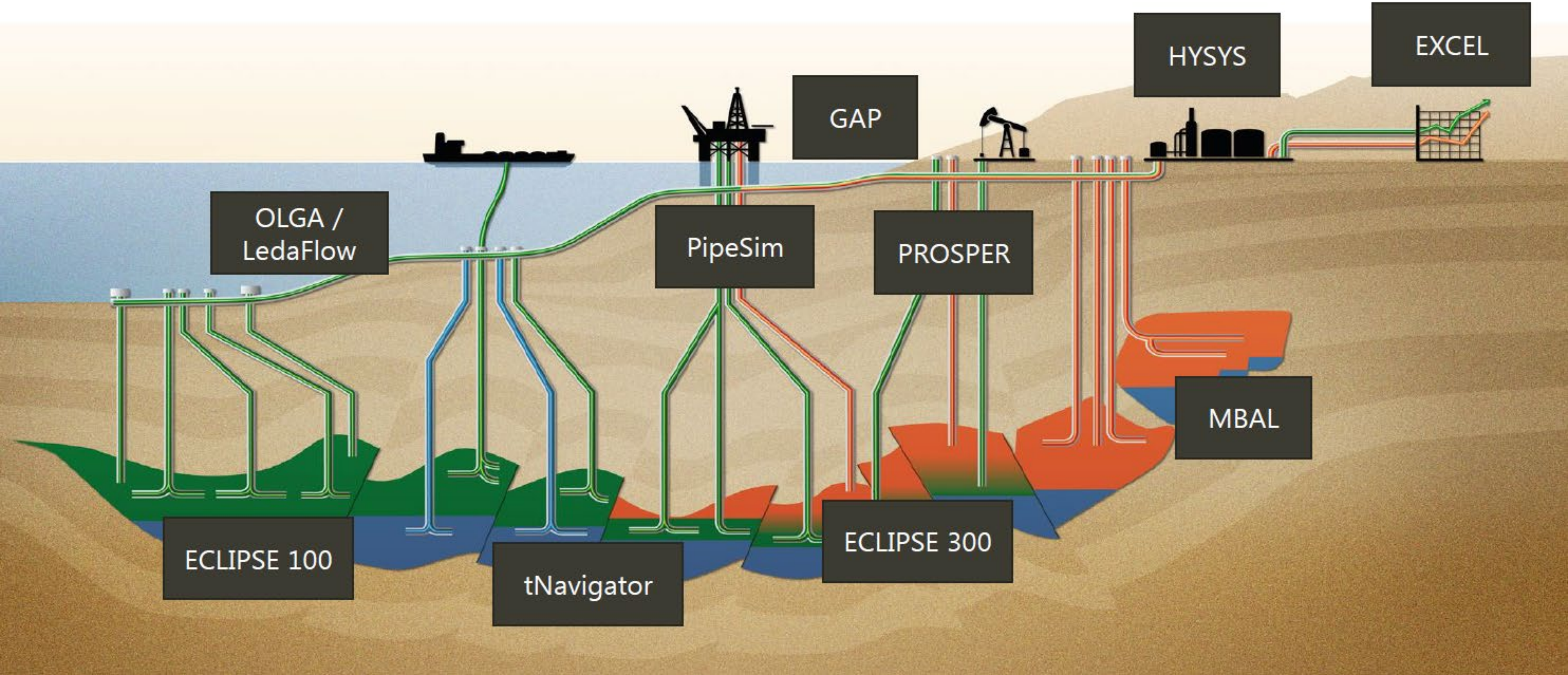
OPTIMIZATION TIMESCALES



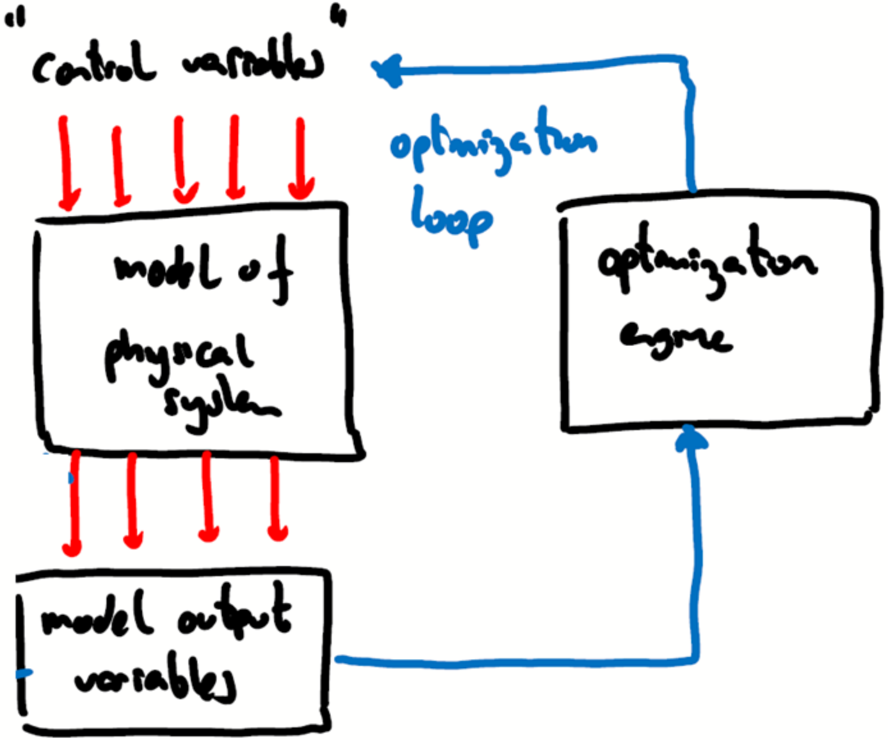
Time scales of production optimization and models

Long term	Short term	Shorter term
Years, months	Daily, weekly	Seconds, minutes, hours
-Models are highly uncertain (limited data) -Models are typically transient (reservoir model) + steady-state models	-There is data to tune models -Models are typically steady state (network, well, processing plant)	-Transient/steady state -Model/real system

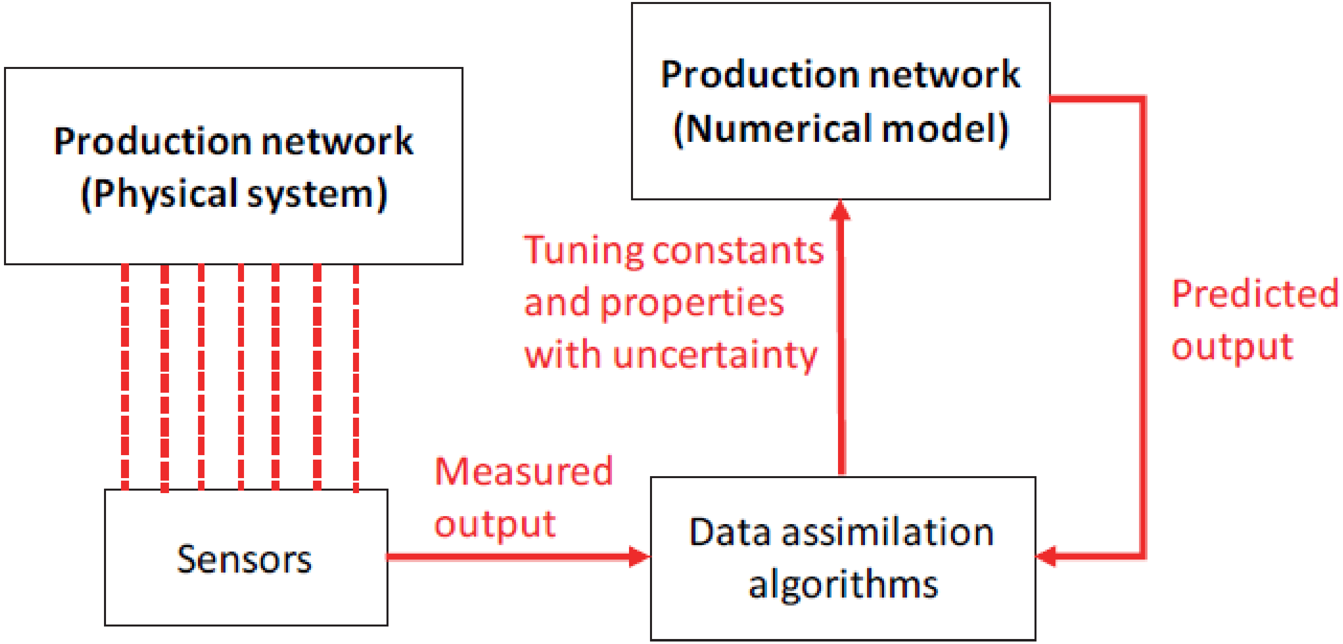
Integrated asset modeling



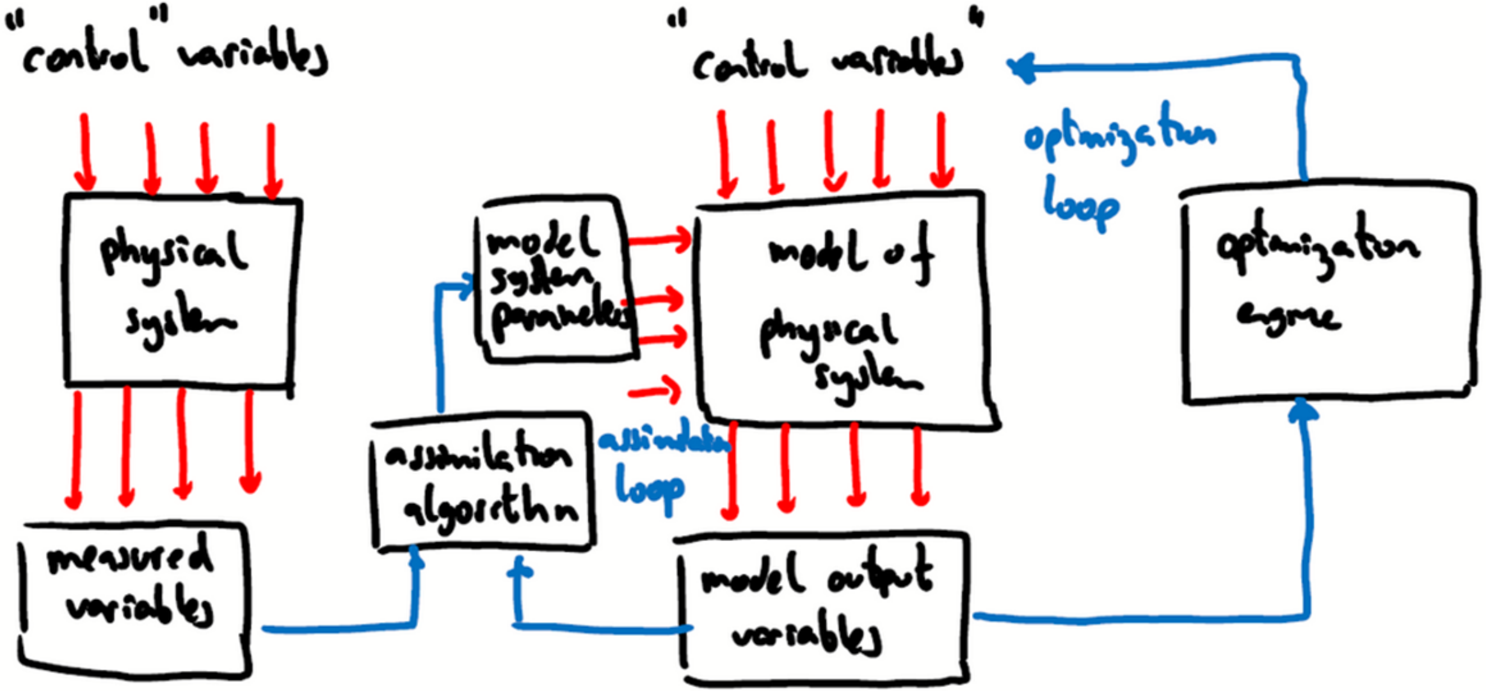
Model-based production optimization



Ensuring fidelity in model-based production optimization



Model-based production optimization workflow

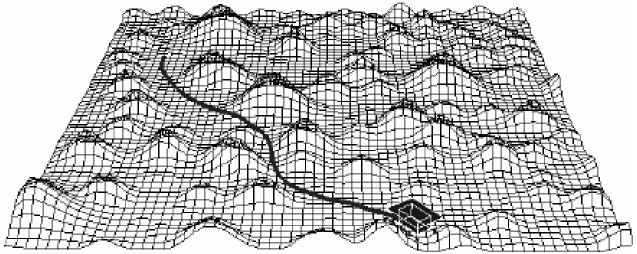


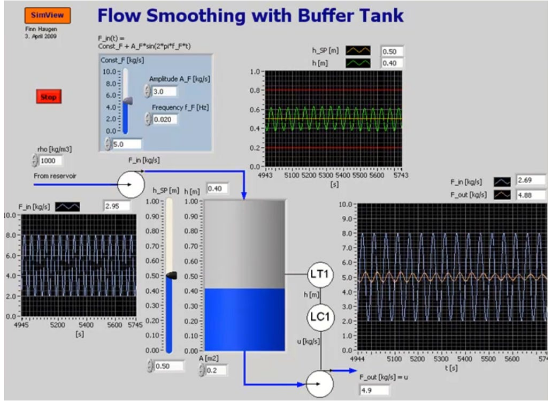
Time scales of production optimization and examples

Long term	Short term	Shorter term
-Find: -well placement, well rates, field development strategy -That: -maximize recovery factor, NPV, reduce water cut and GOR	-Find: Choke opening, gas lift rate, pump frequency -That: -Maximize oil production, condensate production, gas production, revenue	-Find: -Control choke opening, gas lift rate, control valve position -That: -Maximize production, revenue, reduce and mitigate fluctuations

Optimization types

- Parametric (static) – using a model
- Dynamic (control) – using a model, physical system, or a combination of both





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Milan

Optimization types

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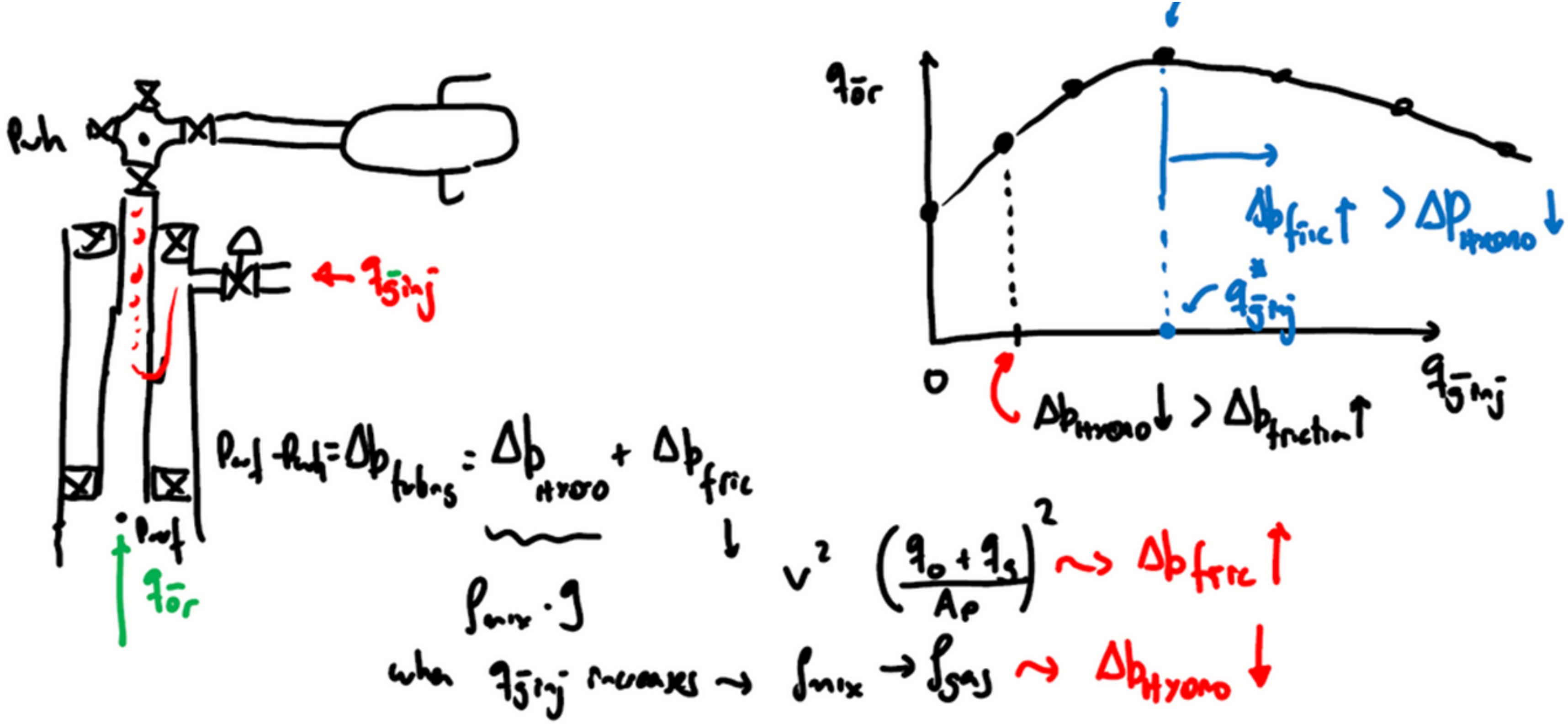
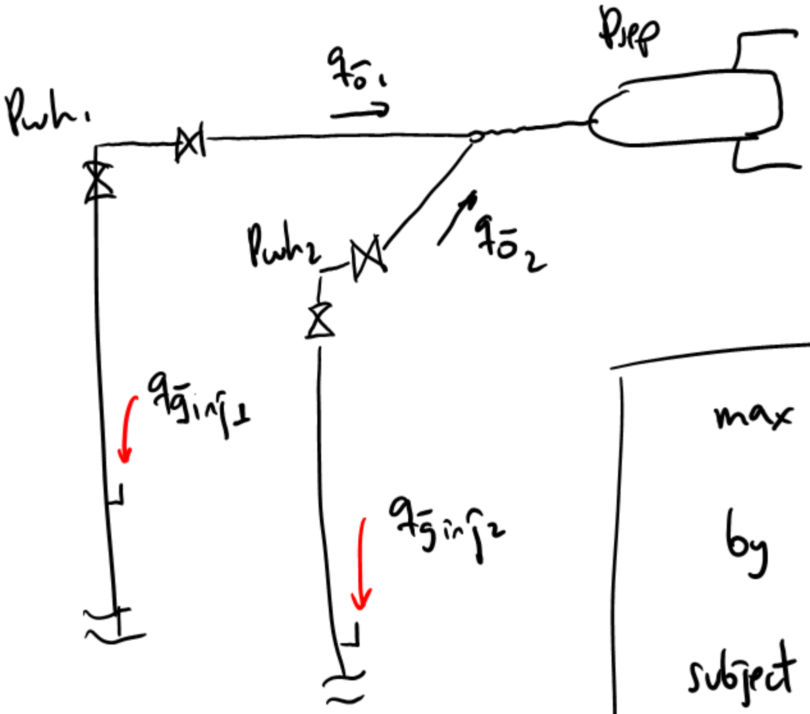
Alexey

Example: two gas-lifted wells

System description



System sketch (2 wells to one separator)



$P_{wh1} \approx P_{wh2} \approx P_{sep}$

$\bar{o}, \bar{g}$ standard conditions rate Sm^3/d

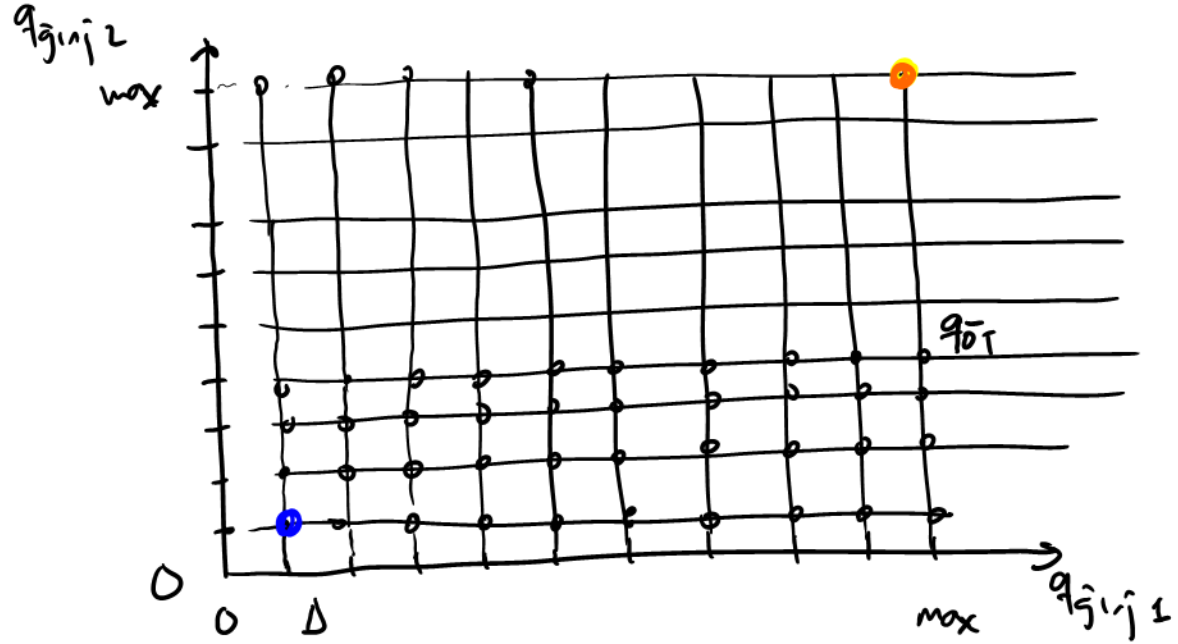
max $q_{\bar{o}T} = q_{\bar{o}1} + q_{\bar{o}2}$

by changing $q_{\bar{g}inj1}$, $q_{\bar{g}inj2}$

subject to a constraint $q_{\bar{g}inj\,TOTAL} \leq q_{\bar{g}inj\,max}$

$q_{\bar{g}inj\,TOTAL} = q_{\bar{g}inj1} + q_{\bar{g}inj2}$

Brute force solution



90 combinations of $q_{\bar{j}_1, j_1}$ and $q_{\bar{j}_2, j_2}$ to test

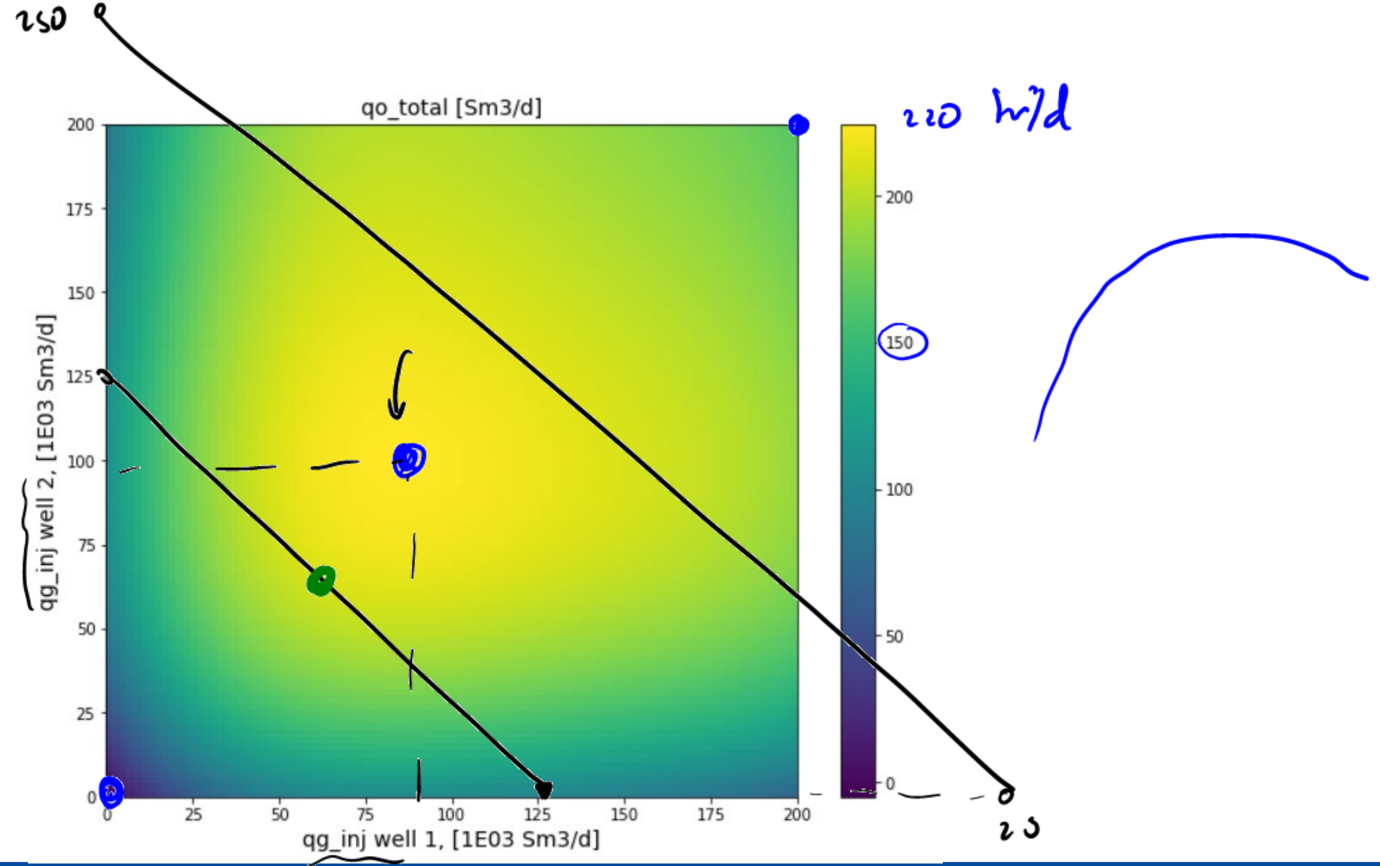
Color map of total oil production versus gas lift rates

$q_{g_{inj},1} + q_{g_{inj},2} \le a$

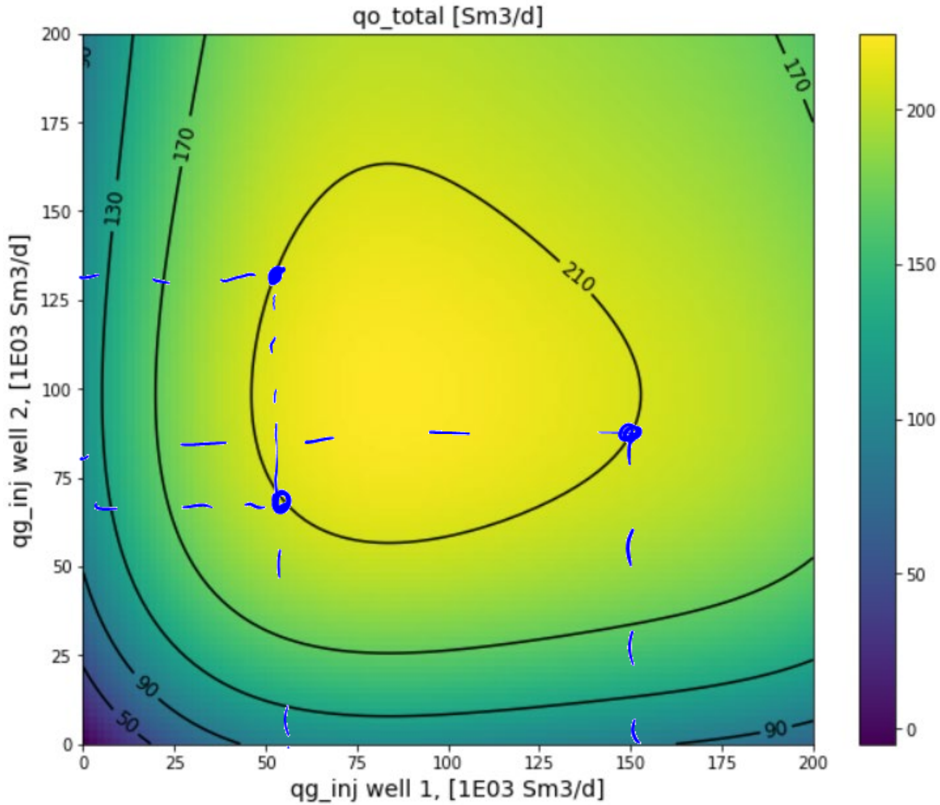
$y \le a - x$

$a = 125$ Sm³/d

$a = 250$ Sm³/d

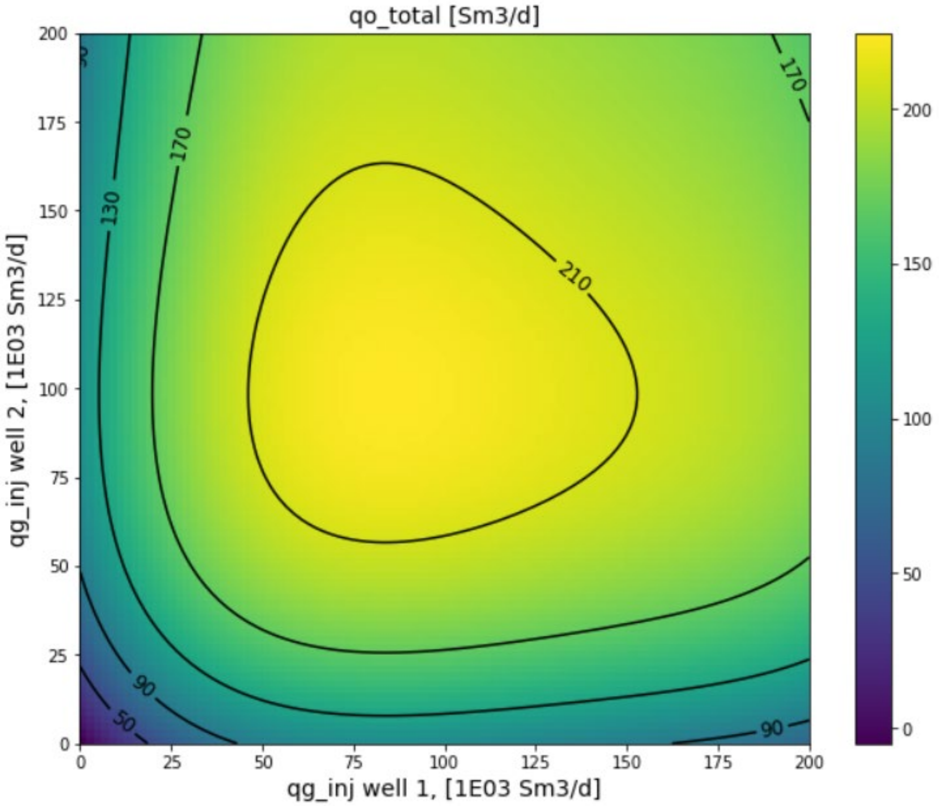


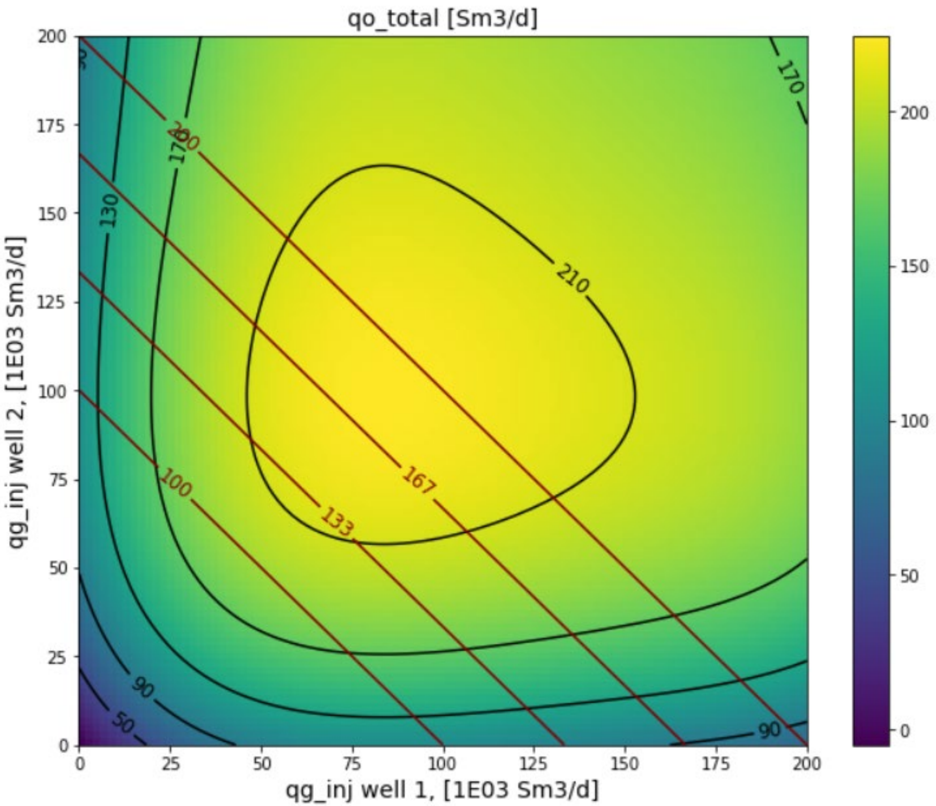
Contour lines of total oil production



Constraints in available gas

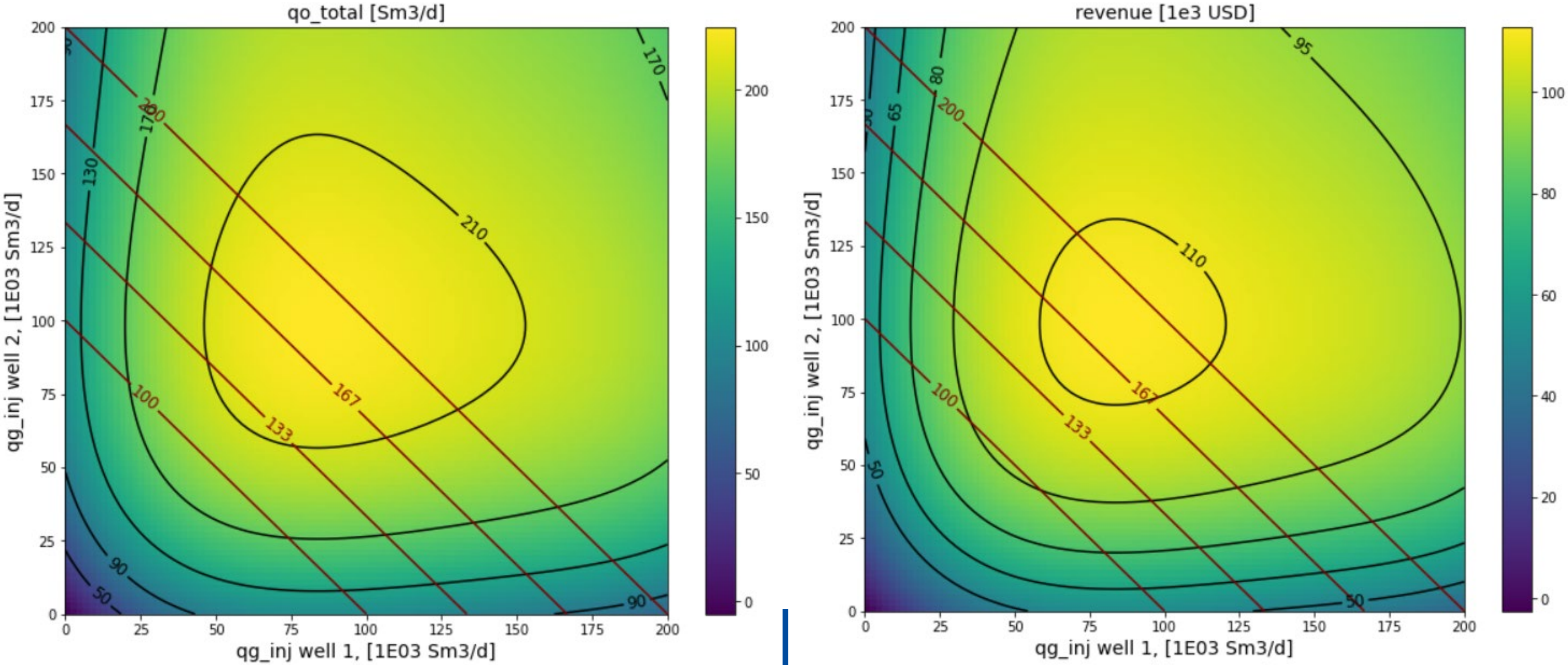
Effect of constraints





Maximizing profit instead of total oil production

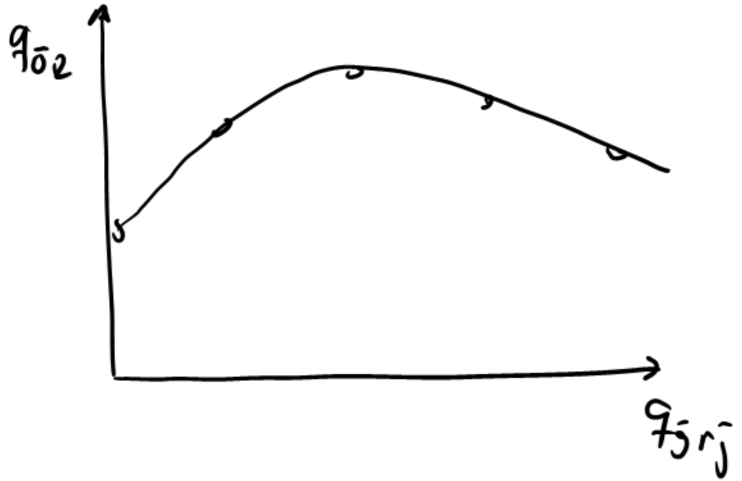
Maximizing profit instead of total oil production



Exercise: optimization of two gas-lifted wells

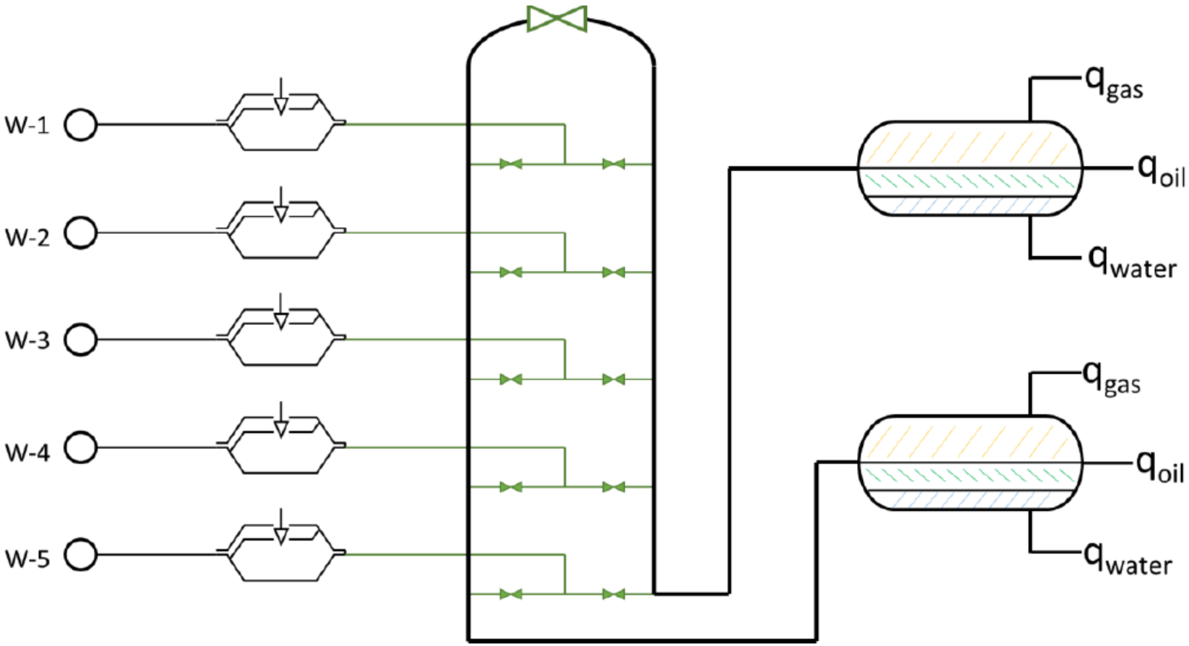
Equation for gas lift performance curve

$$q_{oil} = a\, q_{ginj}^4 + b\, q_{ginj}^3 + c\, q_{ginj}^2 + d\, q_{ginj} + e$$



Discrete variables in production optimization
Exercise: well routing to separators

System sketch



Estimating number of combinations

$q_{o,well} = f(\text{choke, } C.O)$

objective: $\max(q_{oT})$

by changing: ~~choke opening of wells~~ well oil rate of wells {1, 2, 3, 4, 5} — continuous, 0 → 100%

separator selection for wells {1, 2, 3, 4, 5} — {sep A, sep B} — discrete, binary variable

$2^{(N_{wells})} = 32$

subject to: sep A, sep B

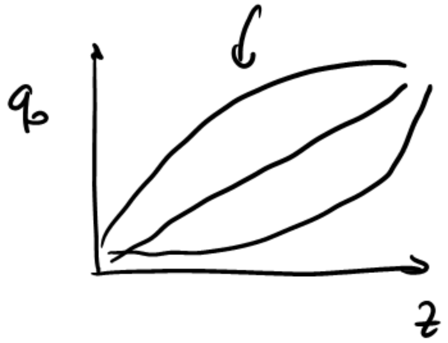
$q_{o,TOTAL} \leq q_{o,max}$

$q_{w,TOTAL} \leq q_{w,MAX}$

$q_{o,well} \geq 50\ \text{Sm}^3/\text{d}$ {1, 2, 3, 4, 5} choke model

choke opening $z \begin{cases} 1 & \text{open} \\ \vdots \\ 0 & \text{closed} \end{cases}$

$$q_{\bar{o}\,well} = q_{\bar{o}\,max\,well} \cdot \tilde{z}$$



Separator assignment $\begin{cases} 0 \\ ① \end{cases}$

0 is assigned to sep B (2)

1 is assigned to sep A (1)

$$q_{\bar{o}\,well_1,\,sep\,A} = q_{\bar{o}\,well_1} \cdot (x) \cdot \quad x$$

$$q_{\bar{o}\,well_1,\,sep\,B} = q_{\bar{o}\,well_1} \cdot (1-x) \quad ✓$$

Separator Constraints table					
Separator 1			Separator 2		
qo	qg	qw	qo	qg	qw
Sm3/D	Sm3/D	Sm3/D	Sm3/D	Sm3/D	Sm3/D
	250.0E+3	400		200.0E+3	380

qomin [Sm3/d] 50

Calculat

Optimize

Well	q_{maxo} Sm3/D	f_w fraction	GOR Sm3/m3	Sep assign	qo Sm3/D	Separator 1 qo Sm3/D	Separator 1 qg Sm3/D	Separator 1 qw Sm3/D	Separator 2 qo Sm3/D	Separator 2 qg Sm3/D	Separator 2 qw Sm3/D
1	636	0.20	142								
2	795	0.43	214								
3	477	0.31	267								
4	636	0.47	356								
5	318	0.10	249								
				SUM=							

$$f_w = \frac{q_{\bar{w}}}{q_{\bar{o}} + q_{\bar{w}}}$$

$$GOR = \frac{q_{\bar{g}}}{q_{\bar{o}}}$$

$$f_w (q_{\bar{o}} + q_{\bar{w}}) = q_w$$

$$q_{\bar{w}} (1 - f_w) = f_w q_{\bar{o}}$$

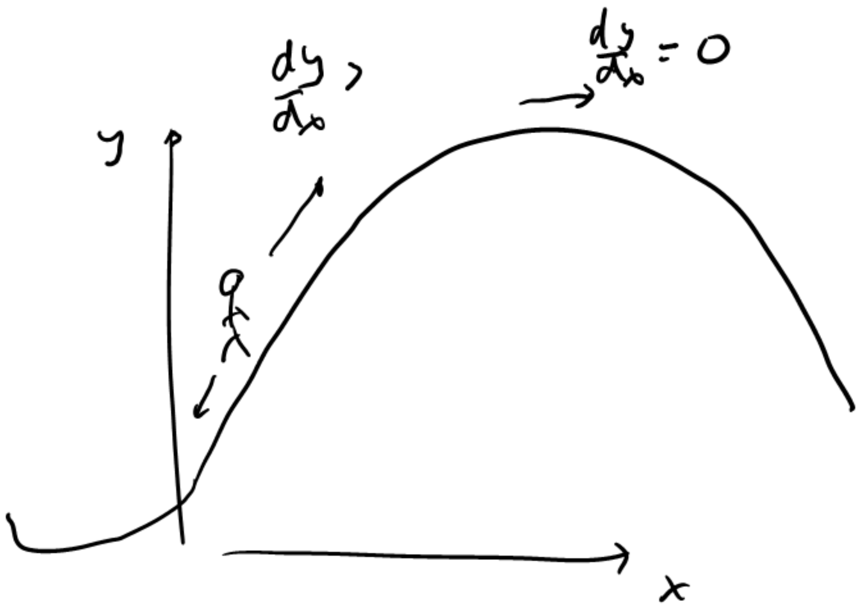
$$q_{\bar{w}} = \frac{q_{\bar{o}} f_w}{(1 - f_w)}$$

$$q_{\bar{o}_T} =$$

How do solvers work?

Optimization methods

- Simplex (linear problems)
- Derivative-based (gradients, hessians)
- Line search/ Trust region
- Heuristic



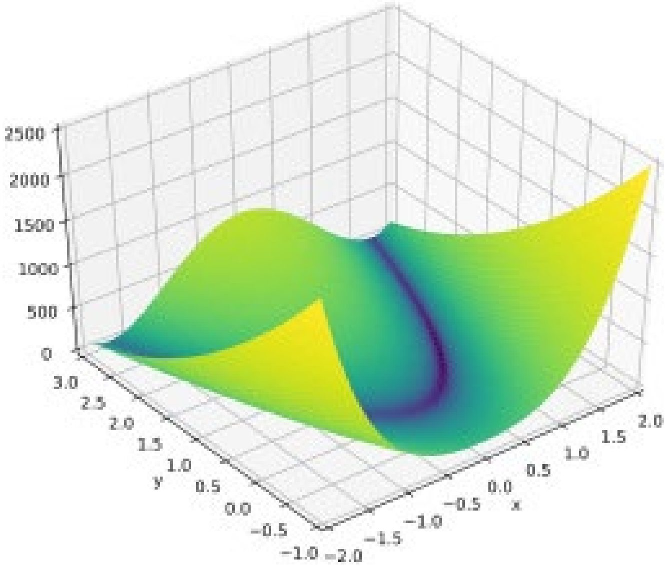
$y = a \cdot x_1 + b x_2$ Linear

$y = x_1 \cdot x_2$ non linear

Newton

$x_k + \Delta x$ **is a local extremum if:**

$$\nabla f(x_k + \Delta x) = 0$$



https://jamesmccaffrey.wordpress.com/page/2/

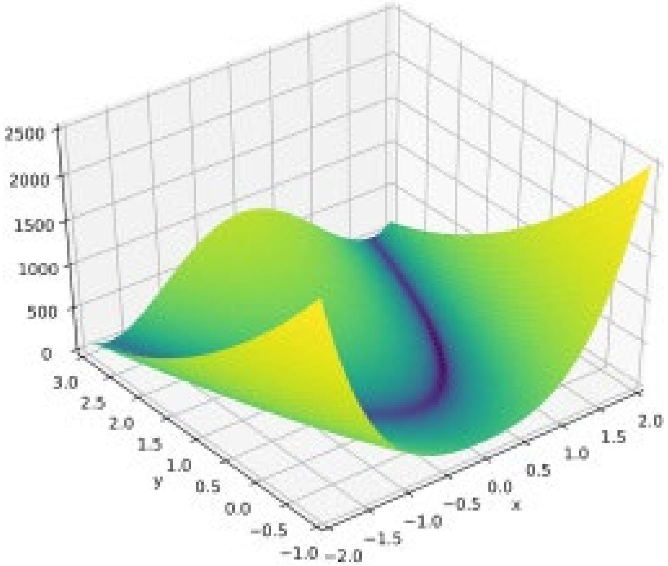
Newton

$x_k + \Delta x$ **is a local extremum if:**

$$\nabla f(x_k + \Delta x) = 0$$

$$\nabla f(x_k) + H \, . \Delta x = 0$$ **(Taylor expansion)**

$$H(f) = \begin{bmatrix} \frac{\partial^2 f}{\partial x_1^2} & \frac{\partial^2 f}{\partial x_1 \partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_1 \partial x_n} \\ \frac{\partial^2 f}{\partial x_2 \partial x_1} & \frac{\partial^2 f}{\partial x_2^2} & \cdots & \frac{\partial^2 f}{\partial x_2 \partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 f}{\partial x_n \partial x_1} & \frac{\partial^2 f}{\partial x_n \partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_n^2} \end{bmatrix}$$



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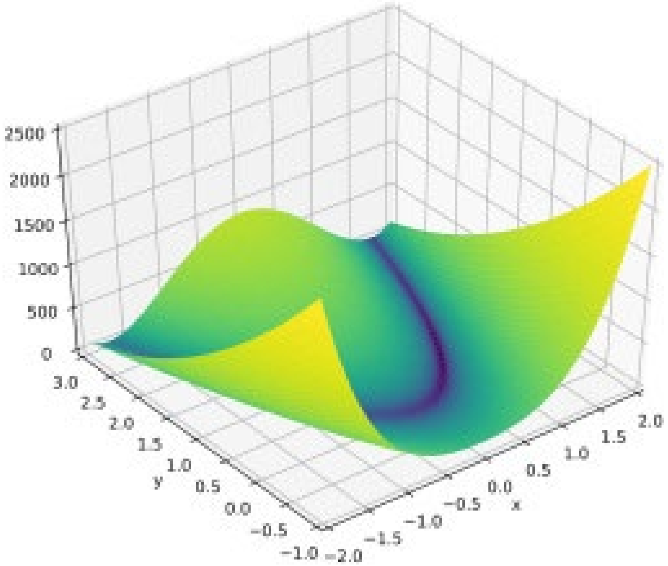

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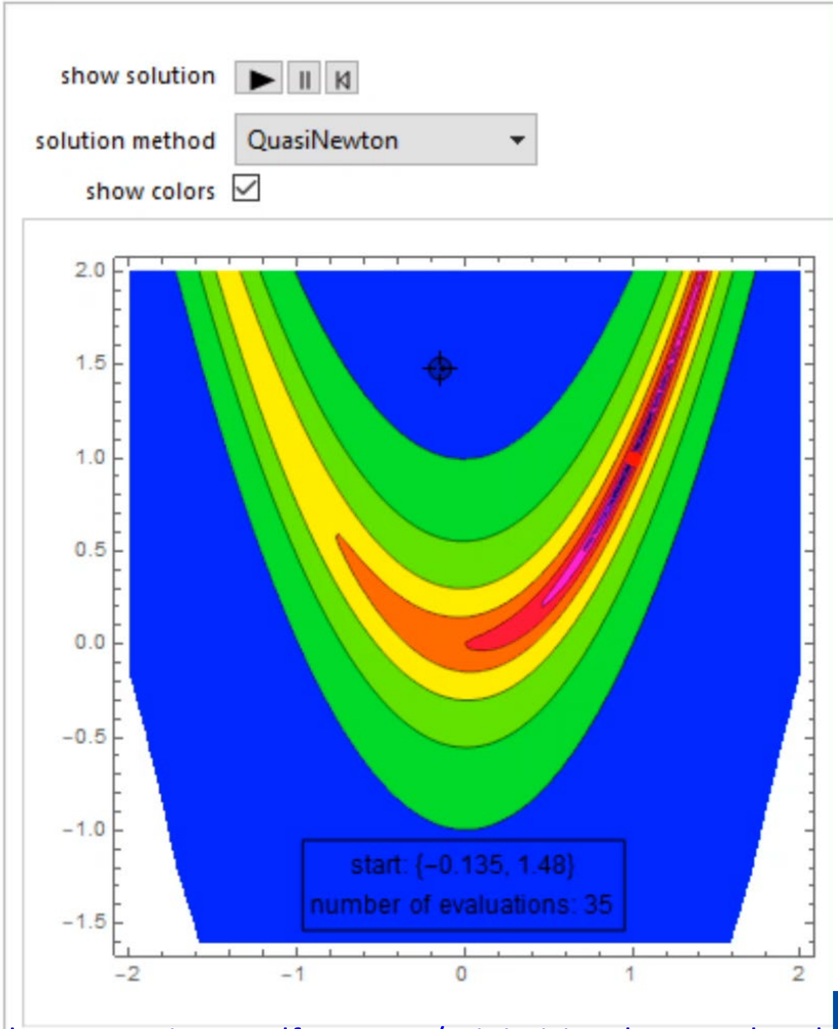
$$\Delta x = -H^{-1} . \nabla f(x_k)$$

$$x_{k+1} = x_k + \Delta x$$

Newton


show solution
solution method
QuasiNewton
show colors
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2
−1
0
1
2
start: {−0.135, 1.48}
number of evaluations: 35

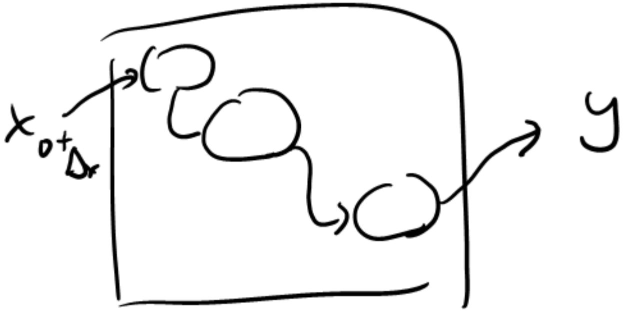
Estimation of gradient – analytical estimation

$y = x^2$

(x_1, y_1)

$$\frac{dy}{dx} = 2 \cdot x$$

Estimation of gradient – perturbation method

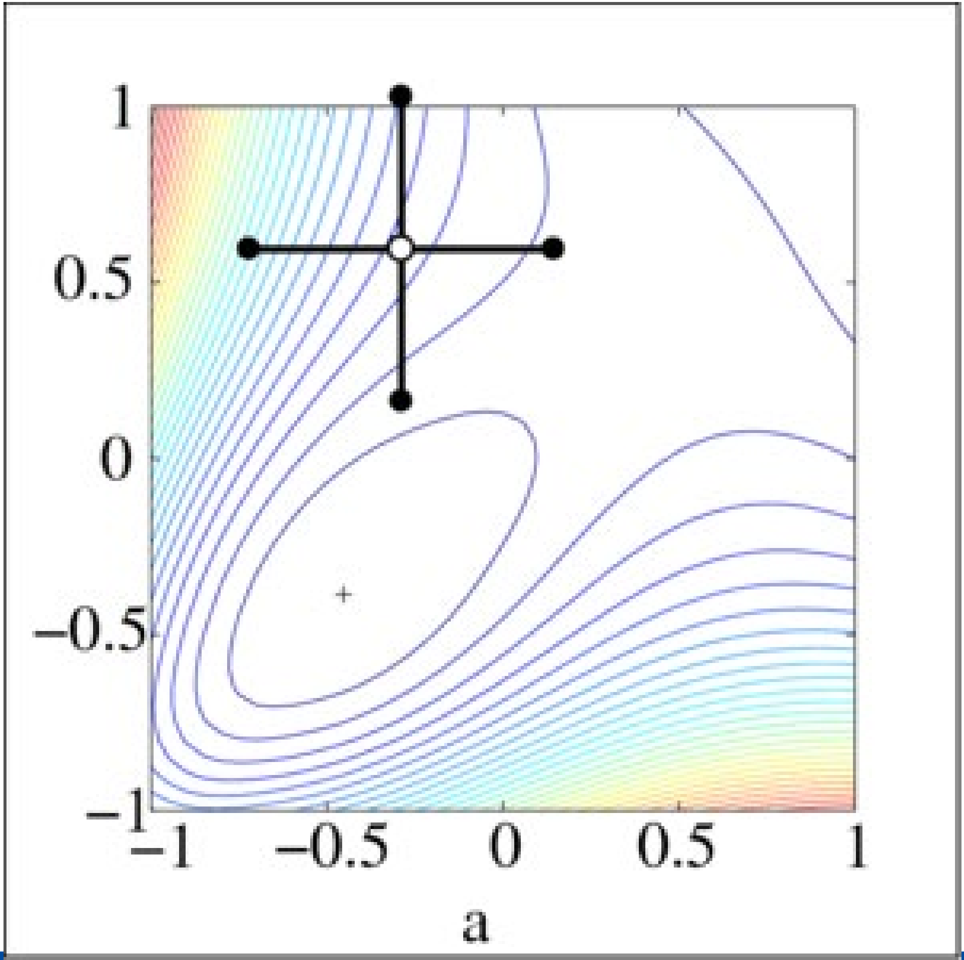


$$\left.\frac{dy}{dx}\right|_{x_0} = \frac{y(x_0+\Delta x) - y(x_0)}{\Delta x}$$

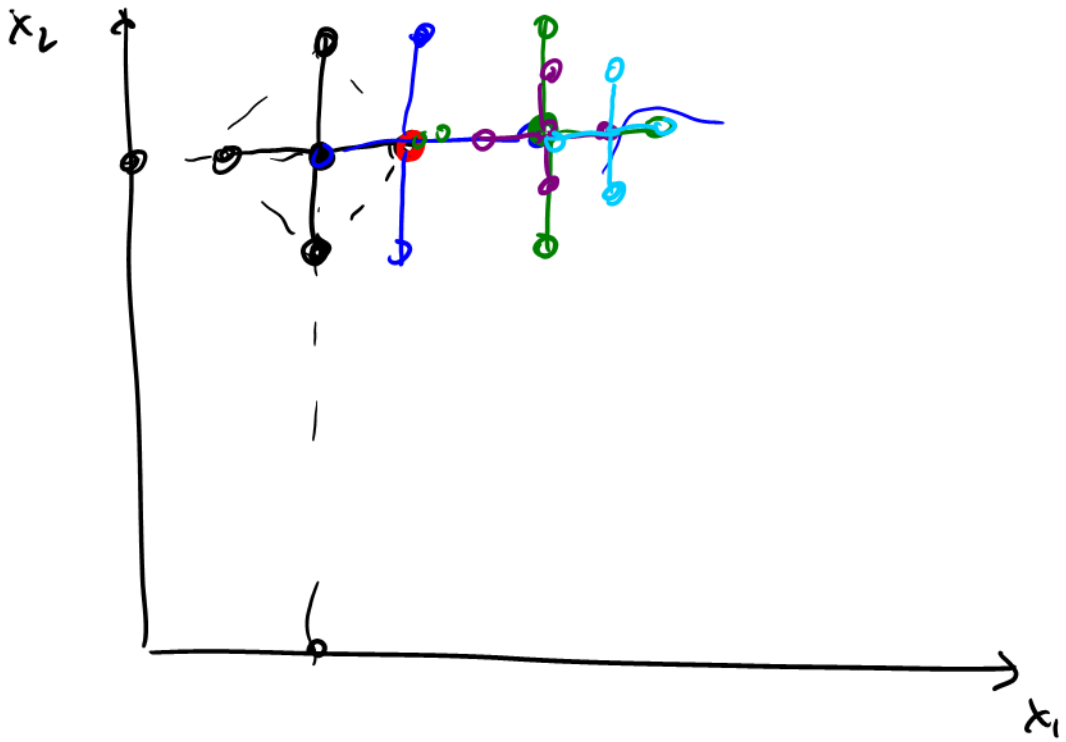
$$\frac{\partial y}{\partial x_1} = \frac{y(x_1+\Delta x) - y(x_1, x_2)}{\Delta x}$$

$$\frac{\partial y}{\partial x_2} = \frac{y(x_2+\Delta x, x_1) - y(x_2, x_1)}{\Delta x}$$

Pattern search

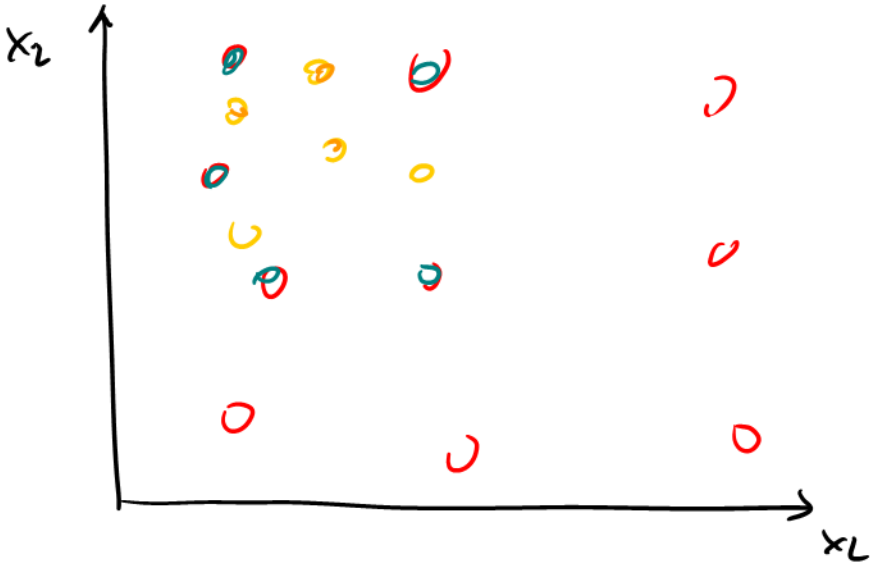


https://en.wikipedia.org/wiki/Pattern_search_(optimization)



x_2
x_1

Evolutionary algorithms (e.g. GA)



Multi-objective production optimization

DEFINITION

- More than one optimization objective (KPI), e.g.
  - Oil, condensate or gas production
  - NPV
  - Equipment efficiency
  - Energy consumption
  - Downtime
  - Maintenance cost
  - OPEX
  - CAPEX
  - CO_2 emissions

COMPLEXITIES

- Techniques are usually developed for optimizing one objective
  - When an objective is optimal **usually** all rest are not
  - → How to combine all objectives into one?

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    - → How to combine all objectives into one?

- Conflicting (non-trivial) objectives
    - High revenue → more energy usage
    - High rates → more equipment failure
    - High production → more CO_2 emissions

APPROACHES – CONSTRAINT METHOD

- Set most important KPI as objective
- Set the rest as constraints.
- Define an acceptable level for the constraints
- Run the optimization and evaluate results, adjust levels as necessary

$$
\begin{aligned}
\min \quad & f_j(x) \\
\text{s.t.} \quad & x \in X \\
& f_i(x) \leq \epsilon_i \text{ for } i \in \{1, \ldots, k\} \setminus \{j\},
\end{aligned}
$$

APPROACHES – LINEAR SCALARIZATION

- Normalize the KPIs with reference values
- Create an objective function that is the weighted sum of all KPIs

$$\min_{x \in X} \sum_{i=1}^{k} w_i f_i(x)$$

- Run the optimization and evaluate results, adjust weights as necessary

APPROACHES – LINEAR SCALARIZATION

- Normalize the KPIs with reference values
- Create an objective function that is the weighted sum of all KPIs

$$\min_{x \in X} \sum_{i=1}^{k} \widetilde{w_i} f_i(x)$$

Be careful with the signs!, squaring might be needed, changing the sign or inversion

- Run the optimization and evaluate results, adjust weights as necessary

max q_{o_T}, min CO_2 emissions $\left(a \cdot q_{o_T} + \frac{1}{CO_2 \text{ emission}} \cdot b\right)$

100000 stb/d

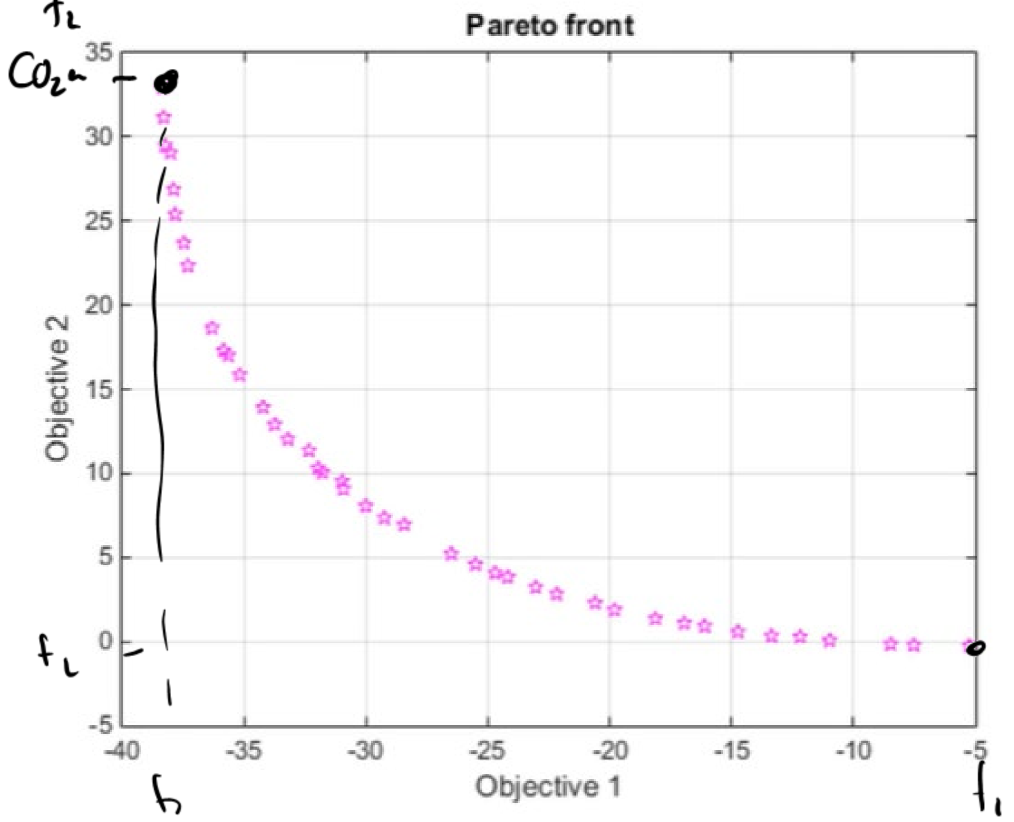
↳ chosen by the production optimizer

PARETO FRONT

max

$$f(x) = w \cdot f_1(x) + (1 - w) \cdot f_2(x)$$

with different values of w

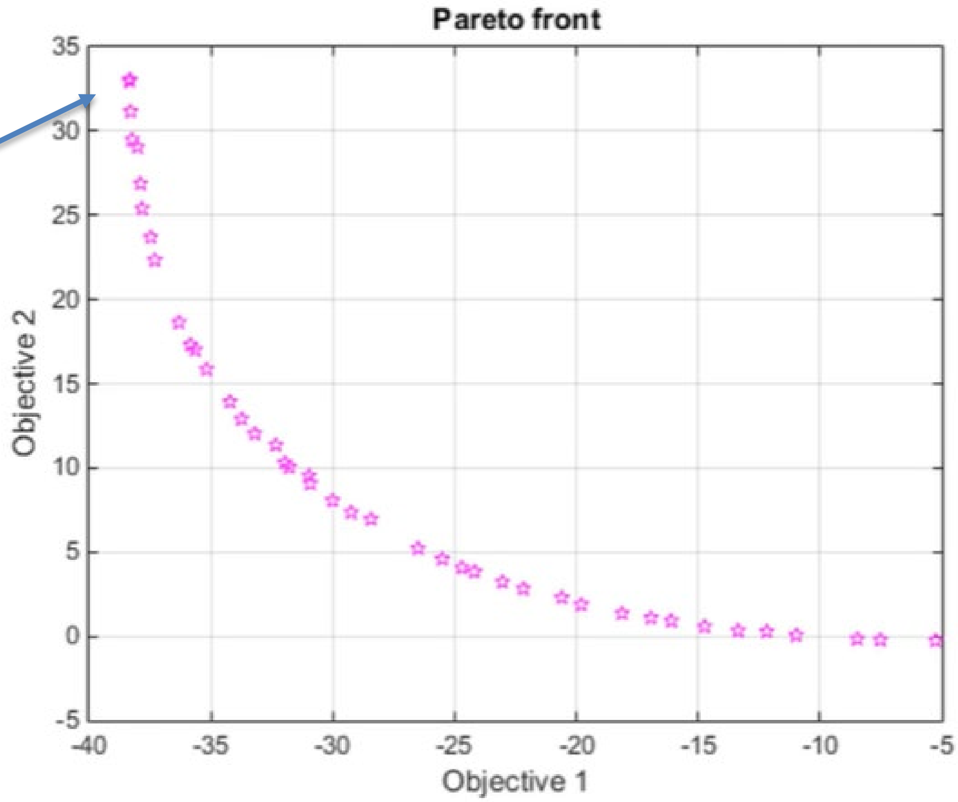


PARETO FRONT

max

$$f(x) = \mathrm{w} \cdot f_1\ (x) + (1 - w) \cdot f_2\ \ (x)$$

If w = 0

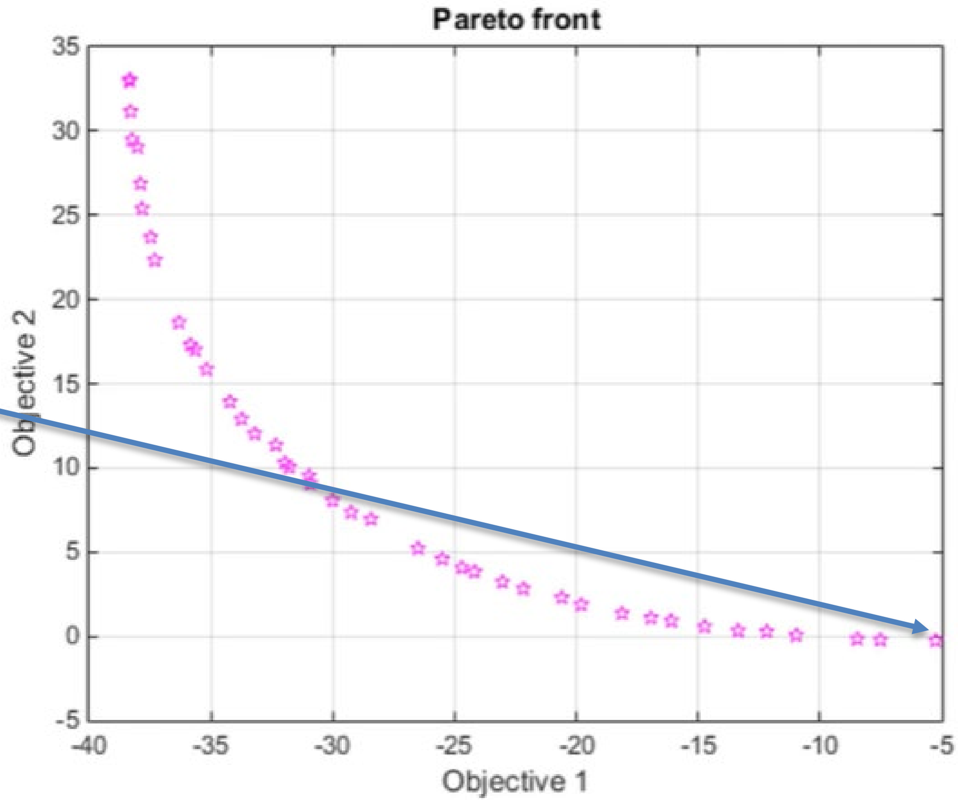


PARETO FRONT

max

$$f(x) = \mathrm{w} \cdot f_1\ (x) + (1 - w) \cdot f_2\ \ (x)$$

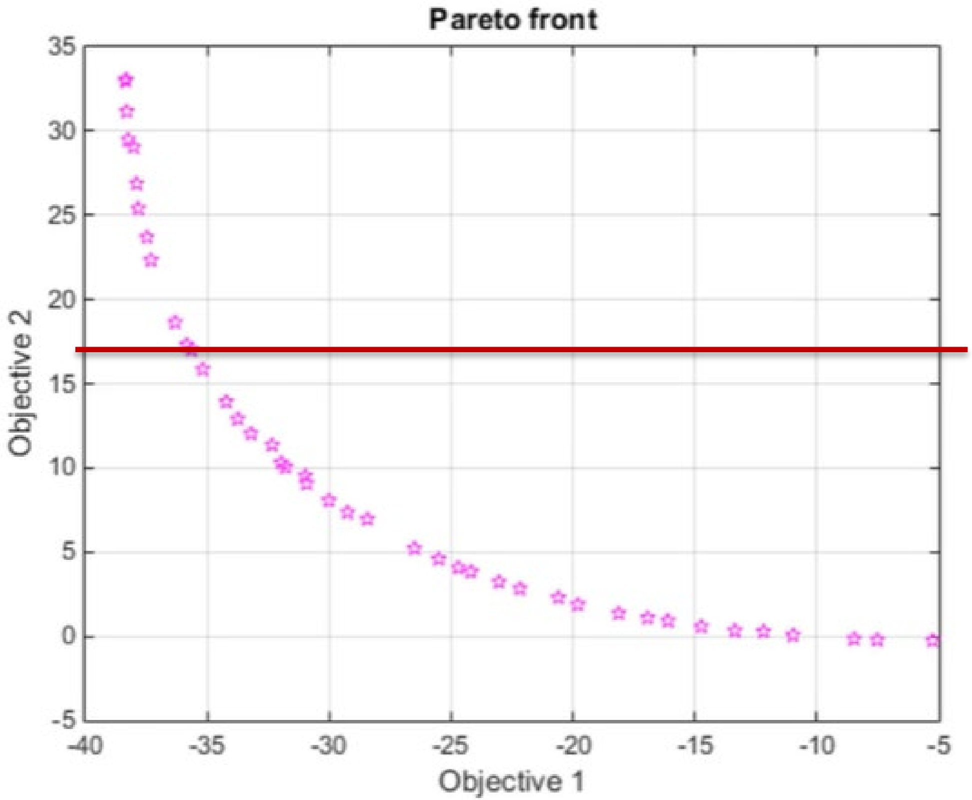
If w = 1



PARETO FRONT

max

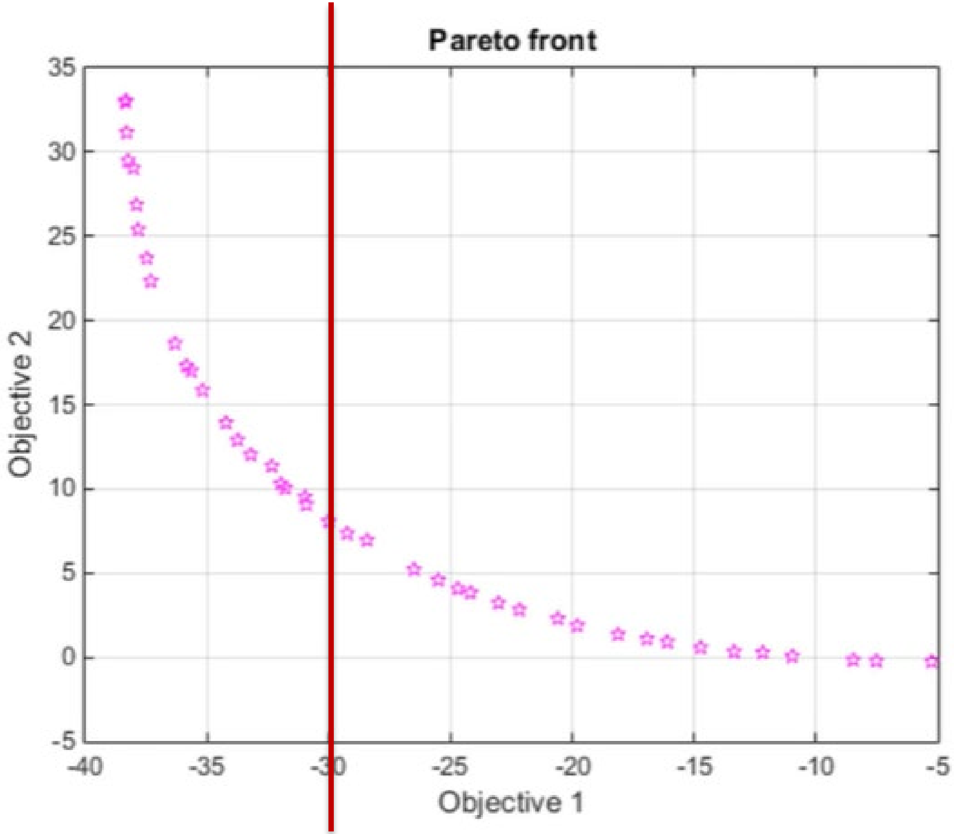
$$f(x) = \mathrm{w} \cdot f_1\ (x) + (1 - w) \cdot f_2\ \ (x)$$



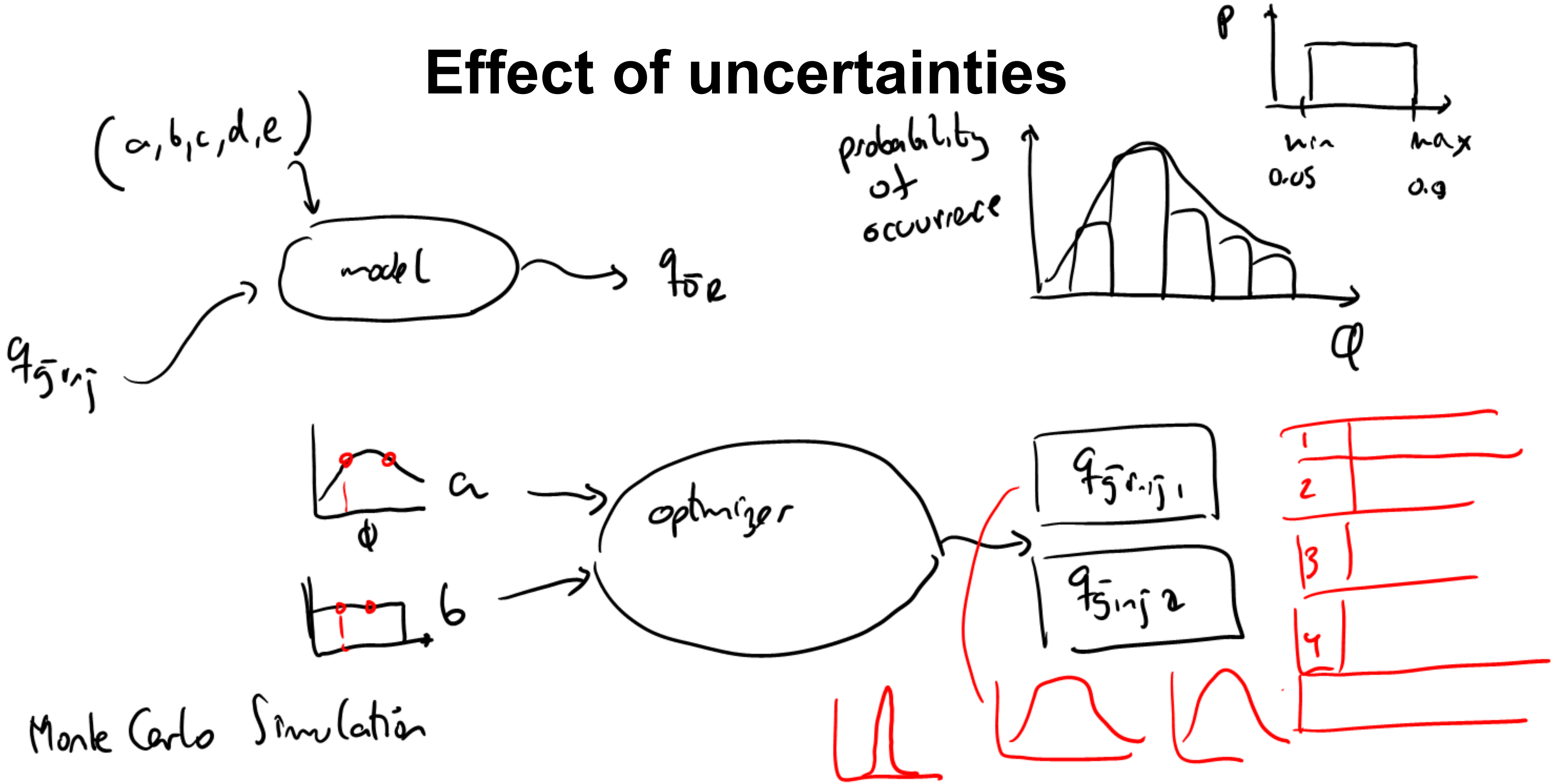
PARETO FRONT

max

$$f(x) = \mathrm{w} \cdot f_1\ (x) + (1 - w) \cdot f_2\ \ (x)$$



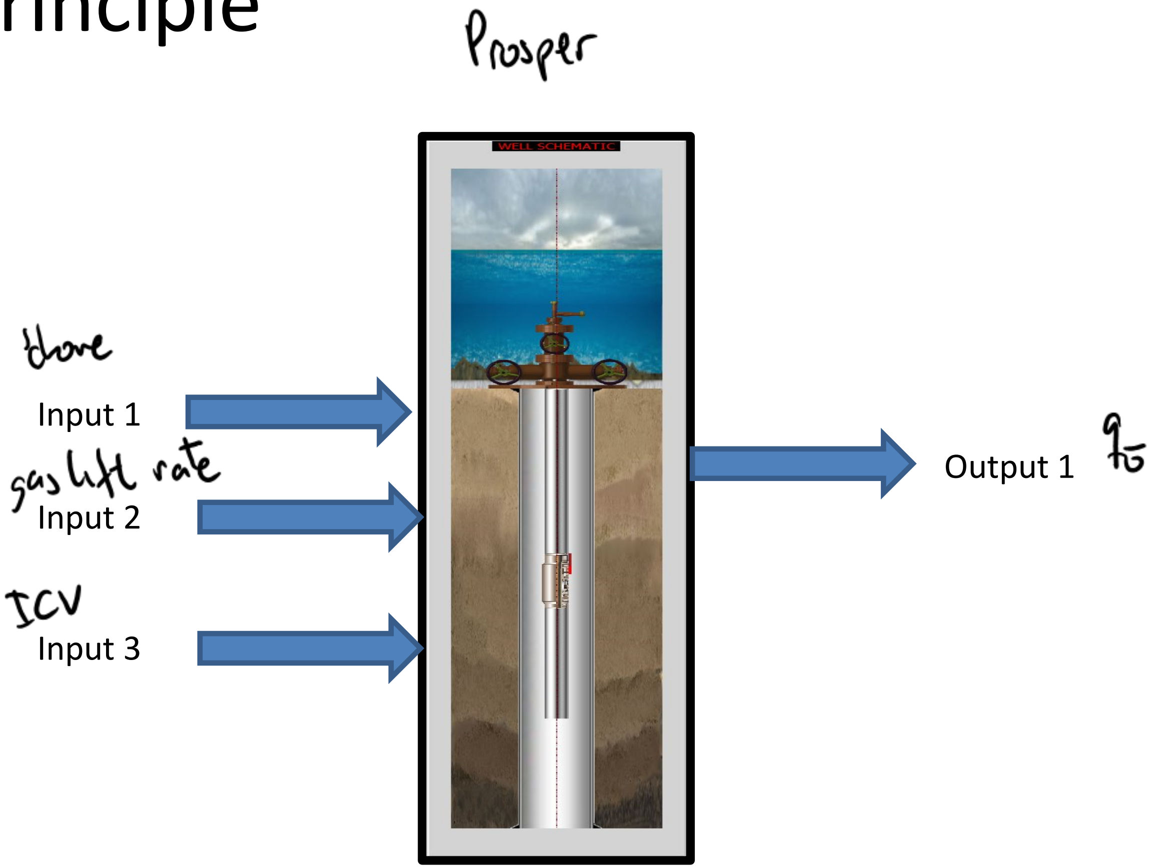
Effect of uncertainties



Proxy modeling

Proxy models
Interpolation on tables

Principle



MODEL

Principle

0-100

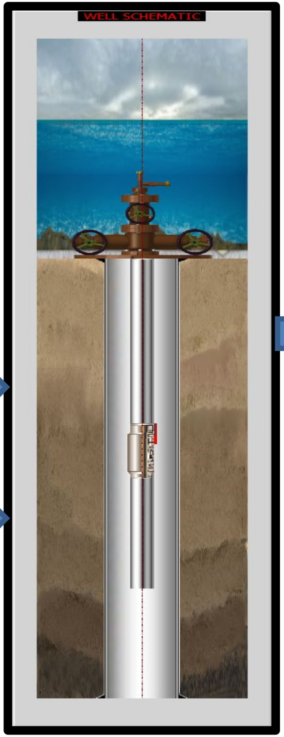
5 Input 1

5 min max

Input 2

5 0-100

Input 3



MODEL

Output 1

1	1	100	89	11	0.0623	2959.83	200	41.7848	41.7848	0.076605	2759.75	0.48442	133.296	1.45366	0.0031515

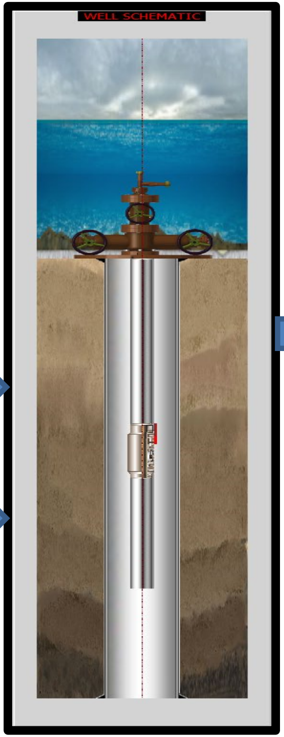
2

.

.

125

Principle



Input 1

Input 2

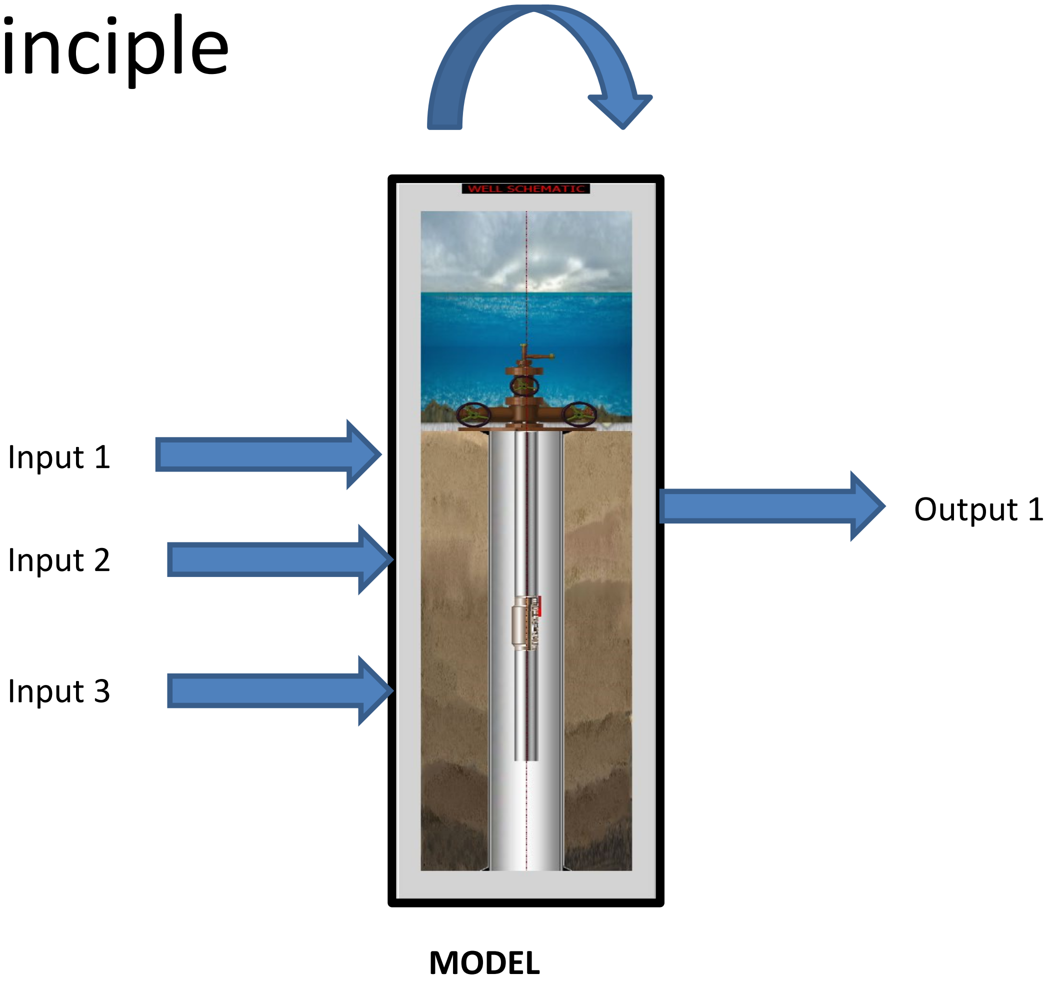
Input 3

Output 1

MODEL

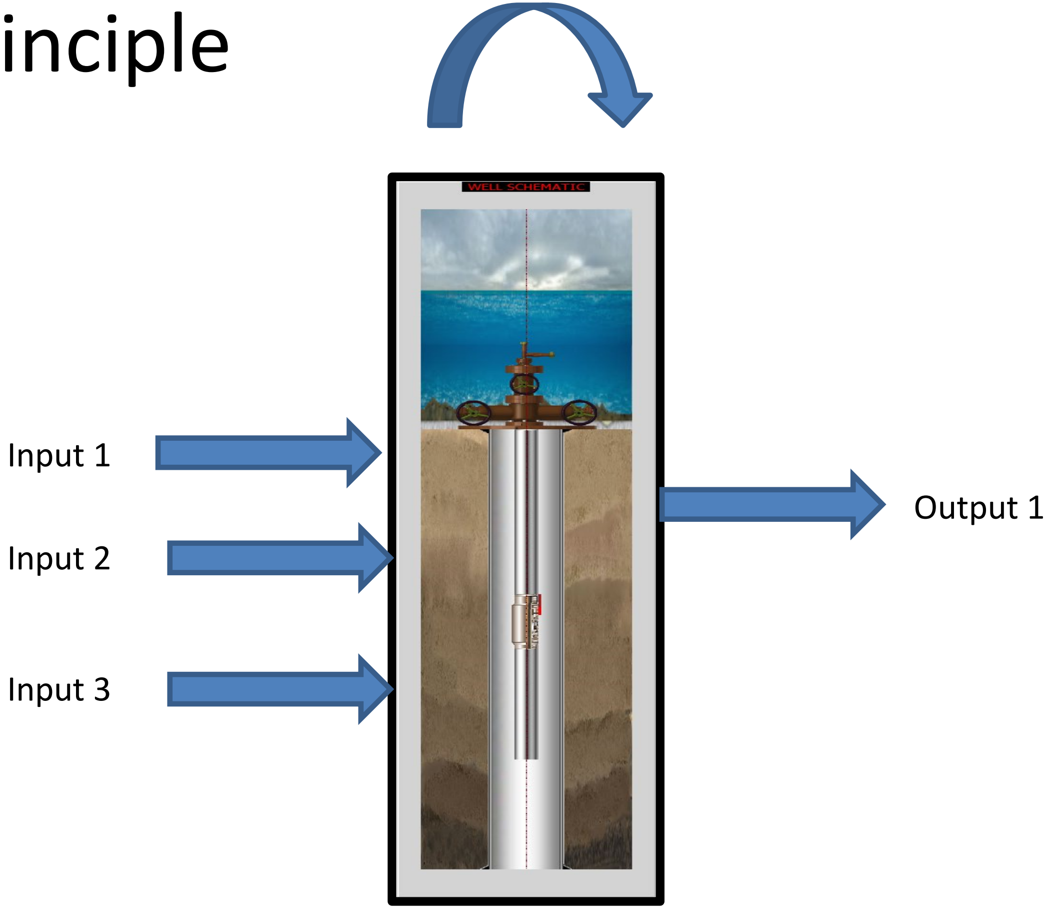
1	100	89	11	0.0623	2959.83	200	41.7848	41.7848	0.076605	2759.75	0.48442	133.296	1.45366	0.0031515
2	130.176	115.857	14.3194	0.0811	2813.43	200	42.3244	42.3244	0.12223	2613.31	0.6657	136.956	1.94428	0.0037617

Principle



1	100	89	11	0.0623	2959.83	200	41.7848	41.7848	0.076605	2759.75	0.48442	133.296	1.45366	0.0031515
2	130.176	115.857	14.3194	0.0811	2813.43	200	42.3244	42.3244	0.12223	2613.31	0.6657	136.956	1.94428	0.0037617
3	169.458	150.818	18.6404	0.10557	2598.22	200	43.0246	43.0246	0.21882	2398	0.87479	137.603	2.54295	0.0046161

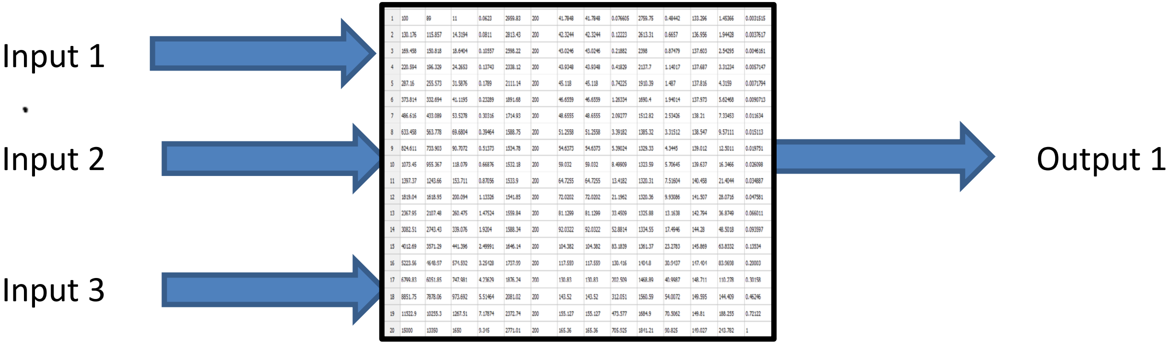
Principle



MODEL

1	100	89	11	0.0623	2959.83	200	41.7848	41.7848	0.076605	2759.75	0.48442	133.296	1.45366	0.0031515
2	130.176	115.857	14.3194	0.0811	2813.43	200	42.3244	42.3244	0.12223	2613.31	0.6657	136.956	1.94428	0.0037617
3	169.458	150.818	18.6404	0.10557	2598.22	200	43.0246	43.0246	0.21882	2398	0.87479	137.603	2.54295	0.0046161
4	220.594	196.329	24.2653	0.13743	2338.12	200	43.9348	43.9348	0.41829	2137.7	1.14017	137.687	3.31234	0.0057147
5	287.16	255.573	31.5876	0.1789	2111.14	200	45.118	45.118	0.74225	1910.39	1.487	137.816	4.3159	0.0071794
6	373.814	332.694	41.1195	0.23289	1891.68	200	46.6559	46.6559	1.26334	1690.4	1.94014	137.973	5.62468	0.0090713
7	486.616	433.089	53.5278	0.30316	1714.93	200	48.6555	48.6555	2.09277	1512.82	2.53426	138.21	7.33453	0.011634
8	633.458	563.778	69.6804	0.39464	1588.75	200	51.2558	51.2558	3.39182	1385.32	3.31512	138.547	9.57111	0.015113
9	824.611	733.903	90.7072	0.51373	1534.78	200	54.6373	54.6373	5.39024	1329.33	4.3445	139.012	12.5011	0.019751
10	1073.45	955.367	118.079	0.66876	1532.18	200	59.032	59.032	8.49909	1323.59	5.70645	139.637	16.3466	0.026098
11	1397.37	1243.66	153.711	0.87056	1533.9	200	64.7255	64.7255	13.4182	1320.31	7.51604	140.458	21.4044	0.034887
12	1819.04	1618.95	200.094	1.13326	1541.85	200	72.0202	72.0202	21.1962	1320.36	9.93086	141.507	28.0716	0.047581
13	2367.95	2107.48	260.475	1.47524	1559.84	200	81.1299	81.1299	33.4509	1325.88	13.1638	142.794	36.8749	0.066011
14	3082.51	2743.43	339.076	1.9204	1588.34	200	92.0322	92.0322	52.8814	1334.55	17.4946	144.28	48.5018	0.093597
15	4012.69	3571.29	441.396	2.49991	1646.14	200	104.382	104.382	83.1839	1361.37	23.2783	145.869	63.8332	0.13534
16	5223.56	4648.97	574.592	3.25428	1737.99	200	117.559	117.559	130.416	1404.8	30.9437	147.404	83.9698	0.20003
17	6799.83	6051.85	747.981	4.23629	1876.24	200	130.83	130.83	202.509	1468.89	40.9987	148.711	110.278	0.30158
18	8851.75	7878.06	973.692	5.51464	2081.02	200	143.52	143.52	312.051	1560.59	54.0072	149.595	144.409	0.46246
19	11522.9	10255.3	1267.51	7.17874	2372.74	200	155.127	155.127	473.577	1684.9	70.5062	149.81	188.255	0.72122
20	15000	13350	1650	9.345	2771.01	200	165.36	165.36	705.925	1841.21	90.825	149.027	243.782	1

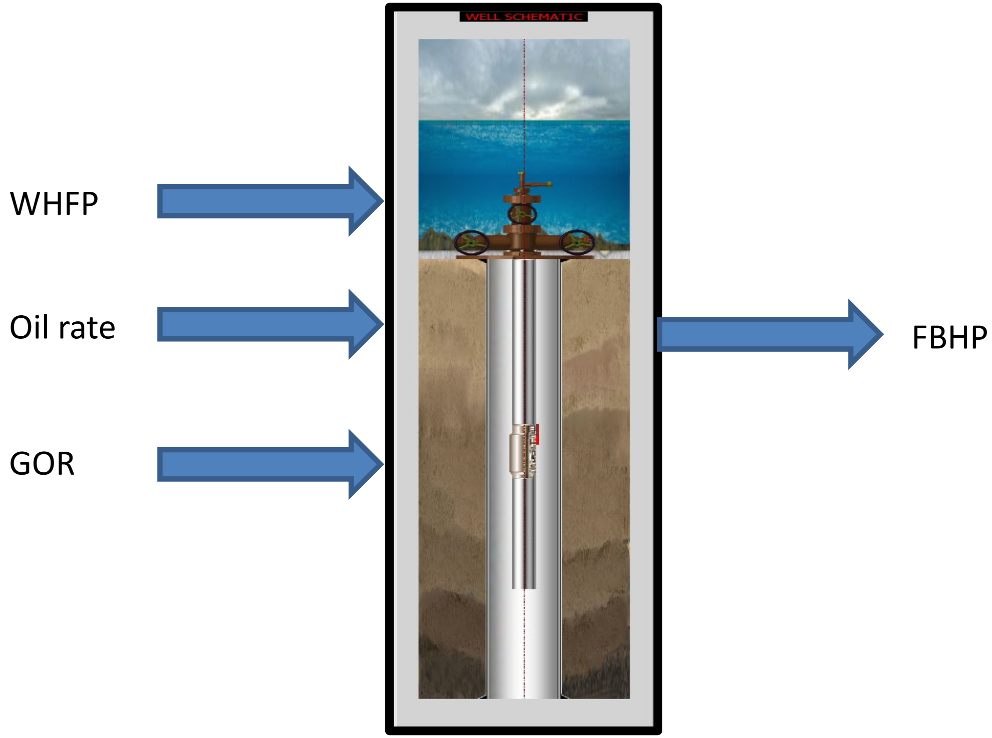
Principle



1	100	89	11	0.0623	2959.83	200	41.7848	41.7848	0.076605	2759.75	0.48442	133.296	1.45366	0.0031515
2	130.176	115.857	14.3194	0.0811	2813.43	200	42.3244	42.3244	0.12223	2613.31	0.6657	136.956	1.94428	0.0037617
3	169.458	150.818	18.6404	0.10557	2598.22	200	43.0246	43.0246	0.21882	2398	0.87479	137.603	2.54295	0.0046161
4	220.594	196.329	24.2653	0.13743	2338.12	200	43.9348	43.9348	0.41829	2137.7	1.14017	137.687	3.31234	0.0057147
5	287.16	255.573	31.5876	0.1789	2111.14	200	45.118	45.118	0.74225	1910.39	1.487	137.816	4.3159	0.0071794
6	373.814	332.694	41.1195	0.23289	1891.68	200	46.6559	46.6559	1.26334	1690.4	1.94014	137.973	5.62468	0.0090713
7	486.616	433.089	53.5278	0.30316	1714.93	200	48.6555	48.6555	2.09277	1512.82	2.53426	138.21	7.33453	0.011634
8	633.458	563.778	69.6804	0.39464	1588.75	200	51.2558	51.2558	3.39182	1385.32	3.31512	138.547	9.57111	0.015113
9	824.611	733.903	90.7072	0.51373	1534.78	200	54.6373	54.6373	5.39024	1329.33	4.3445	139.012	12.5011	0.019751
10	1073.45	955.367	118.079	0.66876	1532.18	200	59.032	59.032	8.49909	1323.59	5.70645	139.637	16.3466	0.026098
11	1397.37	1243.66	153.711	0.87056	1533.9	200	64.7255	64.7255	13.4182	1320.31	7.51604	140.458	21.4044	0.034887
12	1819.04	1618.95	200.094	1.13326	1541.85	200	72.0202	72.0202	21.1962	1320.36	9.93086	141.507	28.0716	0.047581
13	2367.95	2107.48	260.475	1.47524	1559.84	200	81.1299	81.1299	33.4509	1325.88	13.1638	142.794	36.8749	0.066011
14	3082.51	2743.43	339.076	1.9204	1588.34	200	92.0322	92.0322	52.8814	1334.55	17.4946	144.28	48.5018	0.093597
15	4012.69	3571.29	441.396	2.49991	1646.14	200	104.382	104.382	83.1839	1361.37	23.2783	145.869	63.8332	0.13534
16	5223.56	4648.97	574.592	3.25428	1737.99	200	117.559	117.559	130.416	1401.8	30.9437	147.401	83.9698	0.20003
17	6799.83	6051.85	747.981	4.23629	1876.24	200	130.83	130.83	202.509	1468.89	40.9987	148.711	110.278	0.30158
18	8851.75	7878.06	973.692	5.51464	2081.02	200	143.52	143.52	312.051	1560.59	54.0072	149.595	144.409	0.46246
19	11522.9	10255.3	1267.51	7.17874	2372.74	200	155.127	155.127	473.577	1684.9	70.5062	149.81	188.255	0.72122
20	15000	13350	1650	9.345	2771.01	200	165.36	165.36	705.925	1841.21	90.825	149.027	243.782	1

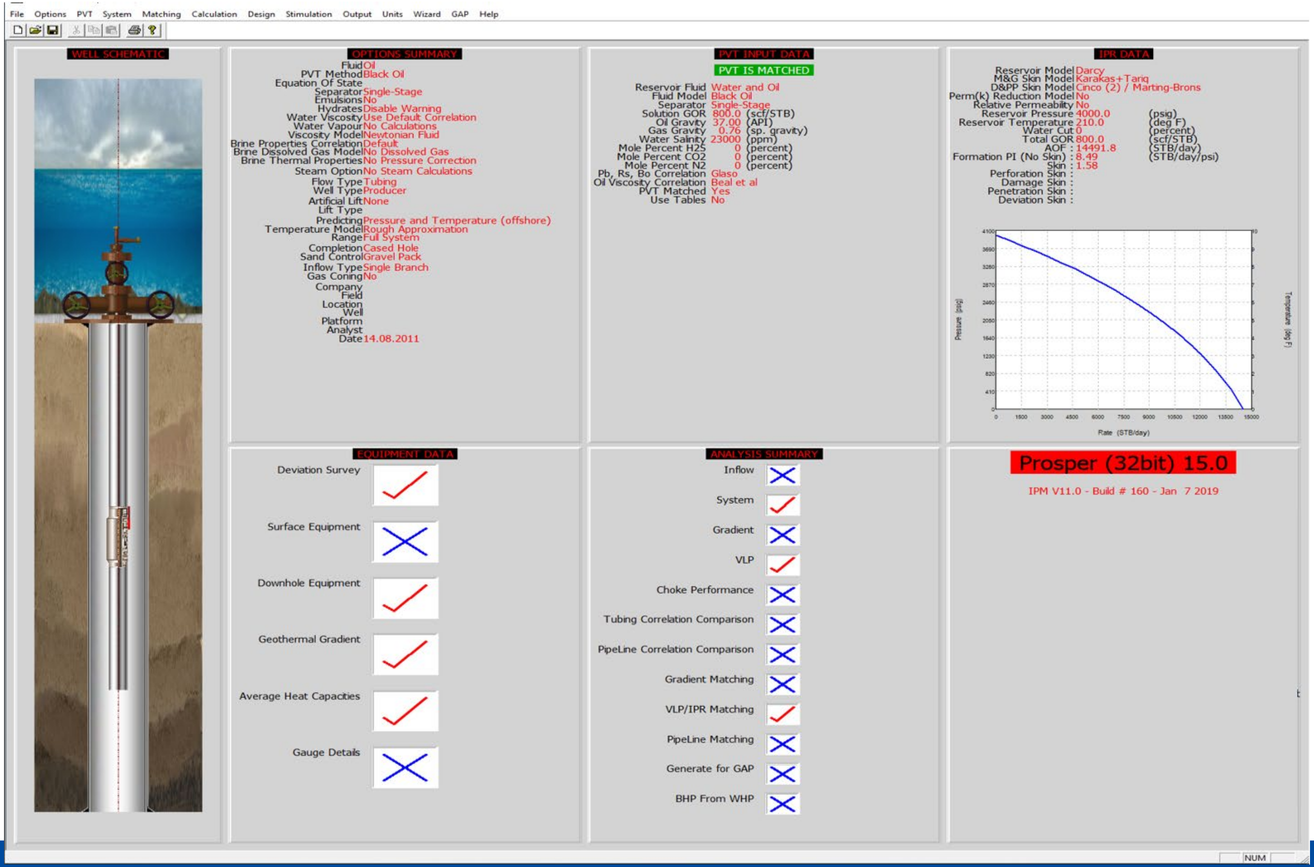
«PROXY» MODEL

Example: Well tubing tables from PROSPER



PROSPER MODEL

Example: Well tubing tables from PROSPER



Example: Well tubing tables from PROSPER

VLP (TUBING CURVE) CALCULATIONS (Well1A.out) (Matched PVT)

Done | Cancel | Cages | Calculate | Plot | Export Lift Curve | Export | Help | Generate | Save Results | Transfer Data | GAP

Top Node Pressure		psig
Water Cut	0	percent
Total GOR	800	scf/STB
Surface Equipment Correlation	Beggs and Brill	
Vertical Lift Correlation	Petroleum Experts 2 1.03 1.01	
Rate Method	User Selected	
Rate Type	Liquid Rate	
First Node	1 Xmas Tree 600 (feet)	
Last Node	8 Casing 9275 (feet)	
Include Sand Control Pressur…	No	
PE5 Stability Flag	No	

Enter Rates

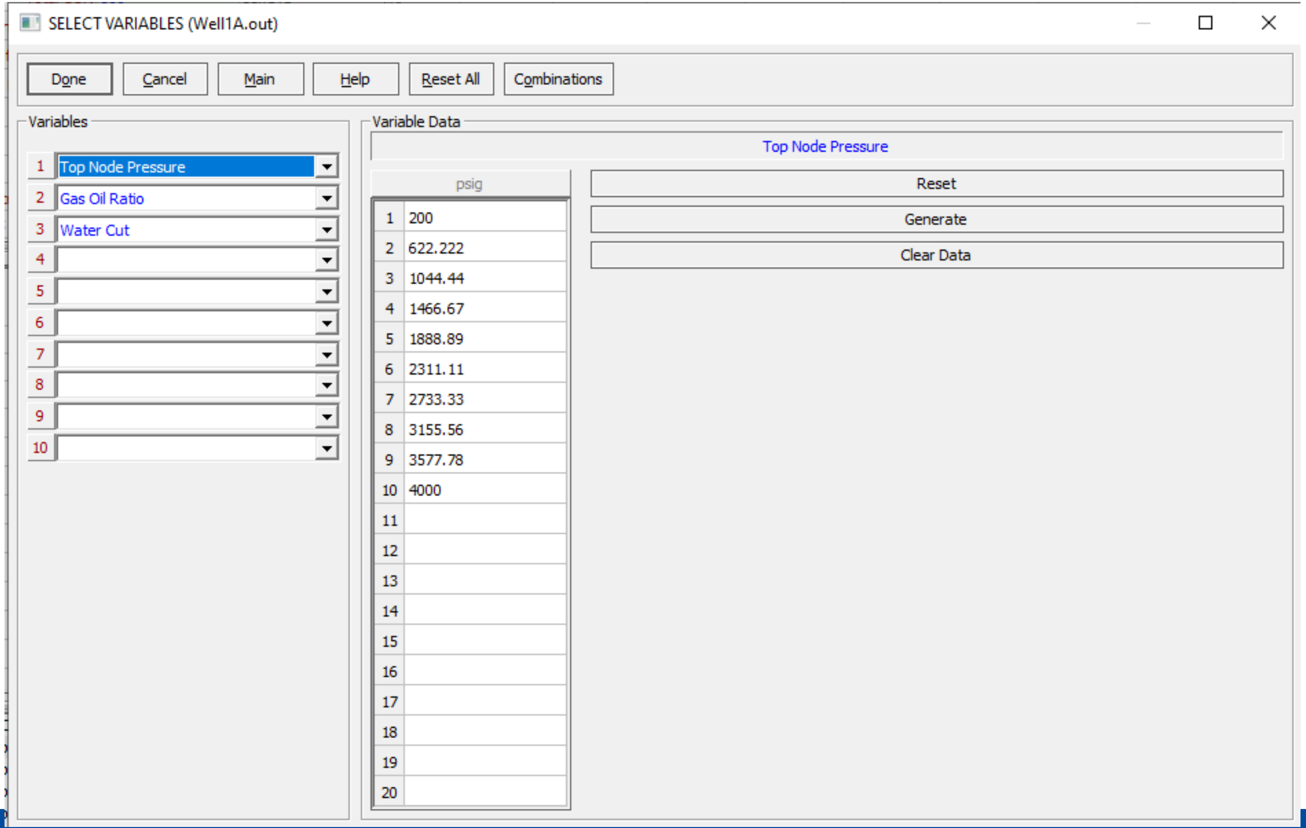
Point	Liquid Rate (STB/day)
1	100
2	130.176
3	169.458
4	220.594
5	287.16
6	373.814
7	486.616
8	633.458
9	824.611
10	1073.45
11	1397.37
12	1819.04
13	2367.95

Sensitivity Cases (10 x 10 x 10 = 1000 cases)
- 1 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cu
- 2 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cu
- 3 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cu
- 4 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cu
- 5 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cu
- 6 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cu

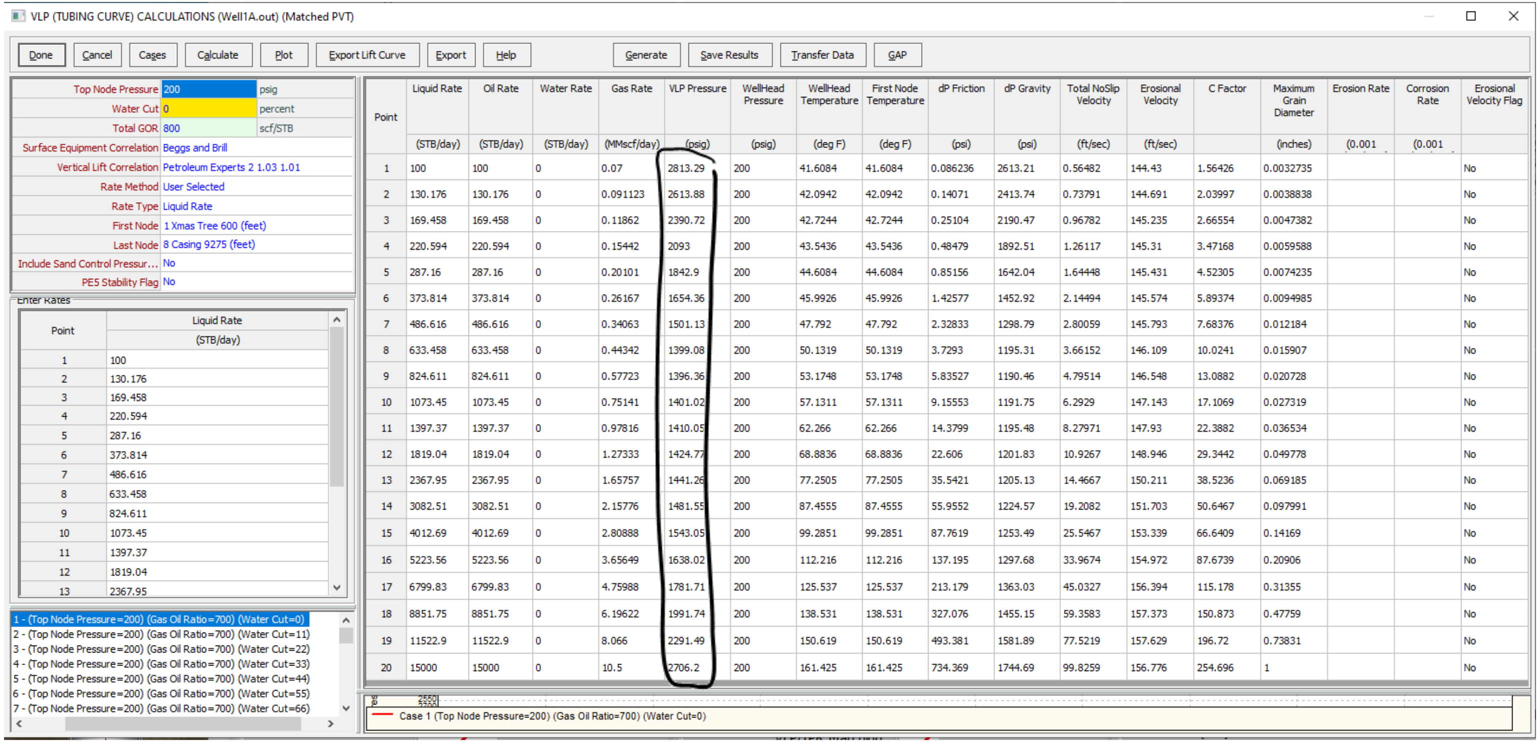
Point	Liquid Rate (STB/day)	Oil Rate (STB/day)	Water Rate (STB/day)	Gas Rate (MMscf/day)	VLP Pressure (psig)	WellHead Pressure (psig)	WellHead Temperature (deg F)	First Node Temperature (deg F)	dP Friction (psi)	dP Gravity (psi)	Total NoSlip Velocity (ft/sec)	Erosional Velocity (ft/sec)	C Factor	Maximum Grain Diameter (inches)	Erosion Rate (0.001	Corrosion Rate (0.001	Erosional Velocity Flag
1	100	100	0	0.07	2813.29	200	41.6084	41.6084	0.086236	2613.21	0.56482	144.43	1.56426	0.0032735			No
2	130.176	130.176	0	0.091123	2613.88	200	42.0942	42.0942	0.14071	2413.74	0.73791	144.691	2.03997	0.0038838			No
3	169.458	169.458	0	0.11862	2390.72	200	42.7244	42.7244	0.25104	2190.47	0.96782	145.235	2.66554	0.0047382			No
4	220.594	220.594	0	0.15442	2093	200	43.5436	43.5436	0.48479	1892.51	1.26117	145.31	3.47168	0.0059588			No
5	287.16	287.16	0	0.20101	1842.9	200	44.6084	44.6084	0.85156	1642.04	1.64448	145.431	4.52305	0.0074235			No
6	373.814	373.814	0	0.26167	1654.36	200	45.9926	45.9926	1.42577	1452.92	2.14494	145.574	5.89374	0.0094985			No
7	486.616	486.616	0	0.34063	1501.13	200	47.792	47.792	2.32833	1298.79	2.80059	145.793	7.68376	0.012184			No
8	633.458	633.458	0	0.44342	1399.08	200	50.1319	50.1319	3.7293	1195.31	3.66152	146.109	10.0241	0.015907			No
9	824.611	824.611	0	0.57723	1396.36	200	53.1748	53.1748	5.83527	1190.46	4.79514	146.548	13.0882	0.020728			No
10	1073.45	1073.45	0	0.75141	1401.02	200	57.1311	57.1311	9.15553	1191.75	6.2929	147.143	17.1069	0.027319			No
11	1397.37	1397.37	0	0.97816	1410.05	200	62.266	62.266	14.3799	1195.48	8.27971	147.93	22.3882	0.036534			No
12	1819.04	1819.04	0	1.27333	1424.77	200	68.8836	68.8836	22.606	1201.83	10.9267	148.946	29.3442	0.049778			No
13	2367.95	2367.95	0	1.65757	1441.26	200	77.2505	77.2505	35.5421	1205.13	14.4667	150.211	38.5236	0.069185			No
14	3082.51	3082.51	0	2.15776	1481.55	200	87.4555	87.4555	55.9552	1224.57	19.2082	151.703	50.6467	0.097991			No
15	4012.69	4012.69	0	2.80888	1543.05	200	99.2851	99.2851	87.7619	1253.49	25.5467	153.339	66.6409	0.14169			No
16	5223.56	5223.56	0	3.65649	1638.02	200	112.216	112.216	137.195	1297.68	33.9674	154.972	87.6739	0.20906			No
17	6799.83	6799.83	0	4.75988	1781.71	200	125.537	125.537	213.179	1363.03	45.0327	156.394	115.178	0.31355			No
18	8851.75	8851.75	0	6.19622	1991.74	200	138.531	138.531	327.076	1455.15	59.3583	157.373	150.873	0.47759			No
19	11522.9	11522.9	0	8.066	2291.49	200	150.619	150.619	493.381	1581.89	77.5219	157.629	196.72	0.73831			No
20	15000	15000	0	10.5	2706.2	200	161.425	161.425	734.369	1744.69	99.8259	156.776	254.696	1			No

Case 1 (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cut=0)

Example: Well tubing tables from PROSPER



Example: Well tubing tables from PROSPER



VLP (TUBING CURVE) CALCULATIONS (Well1A.out) (Matched PVT)

Done | Cancel | Cases | Calculate | Plot | Export Lift Curve | Export | Help | Generate | Save Results | Transfer Data | GAP

Top Node Pressure	200	psig
Water Cut	0	percent
Total GOR	800	scf/STB
Surface Equipment Correlation	Beggs and Brill	
Vertical Lift Correlation	Petroleum Experts 2 1.03 1.01	
Rate Method	User Selected	
Rate Type	Liquid Rate	
First Node	1 Xmas Tree 600 (feet)	
Last Node	8 Casing 9275 (feet)	
Include Sand Control Pressur...	No	
PE5 Stability Flag	No	

Enter Rates

Point	Liquid Rate (STB/day)
1	100
2	130.176
3	169.458
4	220.594
5	287.16
6	373.814
7	486.616
8	633.458
9	824.611
10	1073.45
11	1397.37
12	1819.04
13	2367.95

1 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cut=0)
2 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cut=11)
3 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cut=22)
4 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cut=33)
5 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cut=44)
6 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cut=55)
7 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cut=66)

Point	Liquid Rate (STB/day)	Oil Rate (STB/day)	Water Rate (STB/day)	Gas Rate (MMscf/day)	VLP Pressure (psig)	WellHead Pressure (psig)	WellHead Temperature (deg F)	First Node Temperature (deg F)	dP Friction (psi)	dP Gravity (psi)	Total NoSlip Velocity (ft/sec)	Erosional Velocity (ft/sec)	C Factor	Maximum Grain Diameter (inches)	Erosion Rate (0.001	Corrosion Rate (0.001	Erosional Velocity Flag
1	100	100	0	0.07	2813.29	200	41.6084	41.6084	0.086236	2613.21	0.56482	144.43	1.56426	0.0032735			No
2	130.176	130.176	0	0.091123	2613.88	200	42.0942	42.0942	0.14071	2413.74	0.73791	144.691	2.03997	0.0038838			No
3	169.458	169.458	0	0.11862	2390.72	200	42.7244	42.7244	0.25104	2190.47	0.96782	145.235	2.66554	0.0047382			No
4	220.594	220.594	0	0.15442	2093	200	43.5436	43.5436	0.48479	1892.51	1.26117	145.31	3.47168	0.0059588			No
5	287.16	287.16	0	0.20101	1842.9	200	44.6084	44.6084	0.85156	1642.04	1.64448	145.431	4.52305	0.0074235			No
6	373.814	373.814	0	0.26167	1654.36	200	45.9926	45.9926	1.42577	1452.92	2.14494	145.574	5.89374	0.0094985			No
7	486.616	486.616	0	0.34063	1501.13	200	47.792	47.792	2.32833	1298.79	2.80059	145.793	7.68376	0.012184			No
8	633.458	633.458	0	0.44342	1399.08	200	50.1319	50.1319	3.7293	1195.31	3.66152	146.109	10.0241	0.015907			No
9	824.611	824.611	0	0.57723	1396.36	200	53.1748	53.1748	5.83527	1190.46	4.79514	146.548	13.0882	0.020728			No
10	1073.45	1073.45	0	0.75141	1401.02	200	57.1311	57.1311	9.15553	1191.75	6.2929	147.143	17.1069	0.027319			No
11	1397.37	1397.37	0	0.97816	1410.05	200	62.266	62.266	14.3799	1195.48	8.27971	147.93	22.3882	0.036534			No
12	1819.04	1819.04	0	1.27333	1424.77	200	68.8836	68.8836	22.606	1201.83	10.9267	148.946	29.3442	0.049778			No
13	2367.95	2367.95	0	1.65757	1441.26	200	77.2505	77.2505	35.5421	1205.13	14.4667	150.211	38.5236	0.069185			No
14	3082.51	3082.51	0	2.15776	1481.55	200	87.4555	87.4555	55.9552	1224.57	19.2082	151.703	50.6467	0.097991			No
15	4012.69	4012.69	0	2.80888	1543.05	200	99.2851	99.2851	87.7619	1253.49	25.5467	153.339	66.6409	0.14169			No
16	5223.56	5223.56	0	3.65649	1638.02	200	112.216	112.216	137.195	1297.68	33.9674	154.972	87.6739	0.20906			No
17	6799.83	6799.83	0	4.75988	1781.71	200	125.537	125.537	213.179	1363.03	45.0327	156.394	115.178	0.31355			No
18	8851.75	8851.75	0	6.19622	1991.74	200	138.531	138.531	327.076	1455.15	59.3583	157.373	150.873	0.47759			No
19	11522.9	11522.9	0	8.066	2291.49	200	150.619	150.619	493.381	1581.89	77.5219	157.629	196.72	0.73831			No
20	15000	15000	0	10.5	2706.2	200	161.425	161.425	734.369	1744.69	99.8259	156.776	254.696	1			No

Case 1 (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cut=0)

Example: Well tubing tables from PROSPER

VLP (TUBING CURVE) CALCULATIONS (Well1A.out) (Matched PVT)

Done | Cancel | Cases | Calculate | Plot | Export Lift Curve | Export | Help | Generate | Save Results | Transfer Data | GAP

Top Node Pressure		psig
Water Cut	0	percent
Total GOR	800	scf/STB
Surface Equipment Correlation	Beggs and Brill	
Vertical Lift Correlation	Petroleum Experts 2 1.03 1.01	
Rate Method	User Selected	
Rate Type	Liquid Rate	
First Node	1 Xmas Tree 600 (feet)	
Last Node	8 Casing 9275 (feet)	
Include Sand Control Pressur…	No	
PE5 Stability Flag	No	

Enter Rates

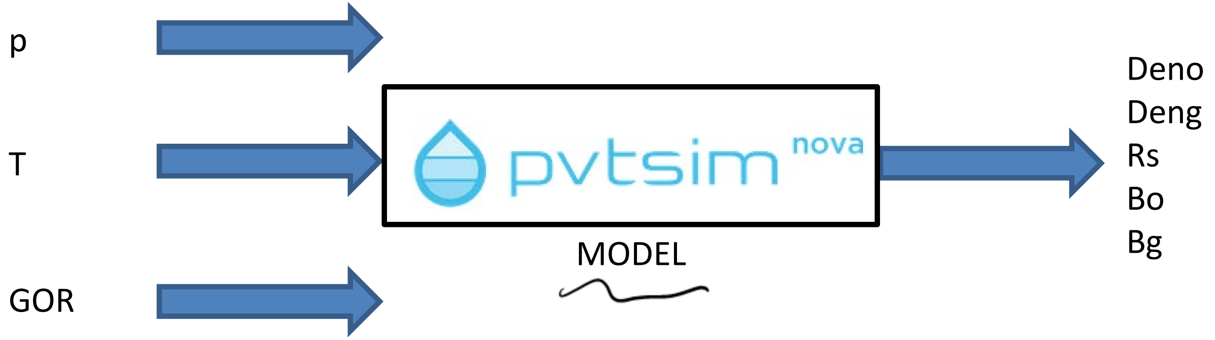
Point	Liquid Rate (STB/day)
1	100
2	130.176
3	169.458
4	220.594
5	287.16
6	373.814
7	486.616
8	633.458
9	824.611
10	1073.45
11	1397.37
12	1819.04
13	2367.95

Sensitivity Cases (10 x 10 x 10 = 1000 cases)
- 1 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cu
- 2 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cu
- 3 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cu
- 4 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cu
- 5 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cu
- 6 - (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cu

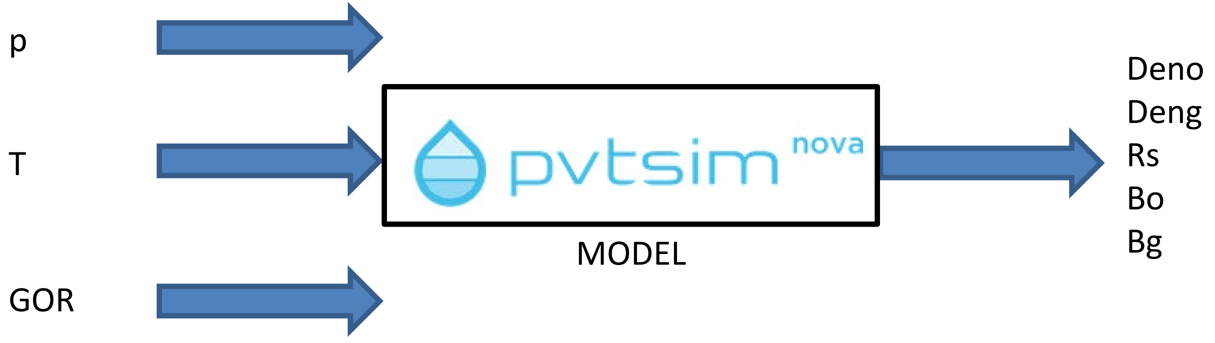
Point	Liquid Rate (STB/day)	Oil Rate (STB/day)	Water Rate (STB/day)	Gas Rate (MMscf/day)	VLP Pressure (psig)	WellHead Pressure (psig)	WellHead Temperature (deg F)	First Node Temperature (deg F)	dP Friction (psi)	dP Gravity (psi)	Total NoSlip Velocity (ft/sec)	Erosional Velocity (ft/sec)	C Factor	Maximum Grain Diameter (inches)	Erosion Rate (0.001	Corrosion Rate (0.001	Erosional Velocity Flag
1	100	89	11	0.0623	2959.83	200	41.7848	41.7848	0.076605	2759.75	0.48442	133.296	1.45366	0.0031515			No
2	130.176	115.857	14.3194	0.0811	2813.43	200	42.3244	42.3244	0.12223	2613.31	0.6657	136.956	1.94428	0.0037617			No
3	169.458	150.818	18.6404	0.10557	2598.22	200	43.0246	43.0246	0.21882	2398	0.87479	137.603	2.54295	0.0046161			No
4	220.594	196.329	24.2653	0.13743	2338.12	200	43.9348	43.9348	0.41829	2137.7	1.14017	137.687	3.31234	0.0057147			No
5	287.16	255.573	31.5876	0.1789	2111.14	200	45.118	45.118	0.74225	1910.39	1.487	137.816	4.3159	0.0071794			No
6	373.814	332.694	41.1195	0.23289	1891.68	200	46.6559	46.6559	1.26334	1690.4	1.94014	137.973	5.62468	0.0090713			No
7	486.616	433.089	53.5278	0.30316	1714.93	200	48.6555	48.6555	2.09277	1512.82	2.53426	138.21	7.33453	0.011634			No
8	633.458	563.778	69.6804	0.39464	1588.75	200	51.2558	51.2558	3.39182	1385.32	3.31512	138.547	9.57111	0.015113			No
9	824.611	733.903	90.7072	0.51373	1534.78	200	54.6373	54.6373	5.39024	1329.33	4.3445	139.012	12.5011	0.019751			No
10	1073.45	955.367	118.079	0.66876	1532.18	200	59.032	59.032	8.49909	1323.59	5.70645	139.637	16.3466	0.026098			No
11	1397.37	1243.66	153.711	0.87056	1533.9	200	64.7255	64.7255	13.4182	1320.31	7.51604	140.458	21.4044	0.034887			No
12	1819.04	1618.95	200.094	1.13326	1541.85	200	72.0202	72.0202	21.1962	1320.36	9.93086	141.507	28.0716	0.047581			No
13	2367.95	2107.48	260.475	1.47524	1559.84	200	81.1299	81.1299	33.4509	1325.88	13.1638	142.794	36.8749	0.066011			No
14	3082.51	2743.43	339.076	1.9204	1588.34	200	92.0322	92.0322	52.8814	1334.55	17.4946	144.28	48.5018	0.093597			No
15	4012.69	3571.29	441.396	2.49991	1646.14	200	104.382	104.382	83.1839	1361.37	23.2783	145.869	63.8332	0.13534			No
16	5223.56	4648.97	574.592	3.25428	1737.99	200	117.559	117.559	130.416	1404.8	30.9437	147.404	83.9698	0.20003			No
17	6799.83	6051.85	747.981	4.23629	1876.24	200	130.83	130.83	202.509	1468.89	40.9987	148.711	110.278	0.30158			No
18	8851.75	7878.06	973.692	5.51464	2081.02	200	143.52	143.52	312.051	1560.59	54.0072	149.595	144.409	0.46246			No
19	11522.9	10255.3	1267.51	7.17874	2372.74	200	155.127	155.127	473.577	1684.9	70.5062	149.81	188.255	0.72122			No
20	15000	13350	1650	9.345	2771.01	200	165.36	165.36	705.925	1841.21	90.825	149.027	243.782	1			No

Case 2 (Top Node Pressure=200) (Gas Oil Ratio=700) (Water Cut=11)

Example: PVT tables from PVTsim



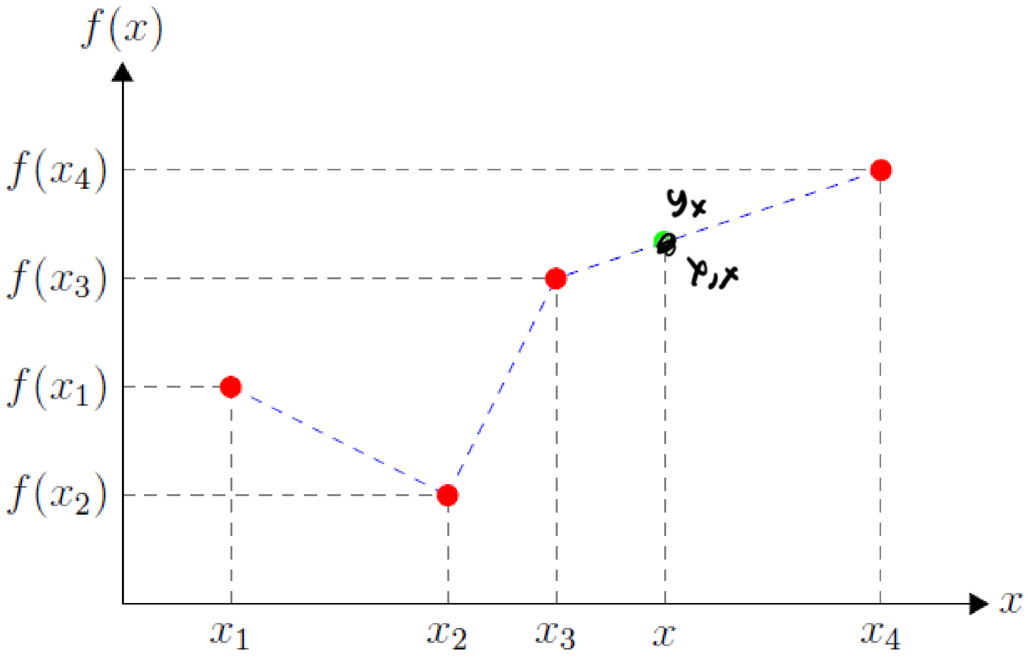
Example: PVT tables from PVTsim



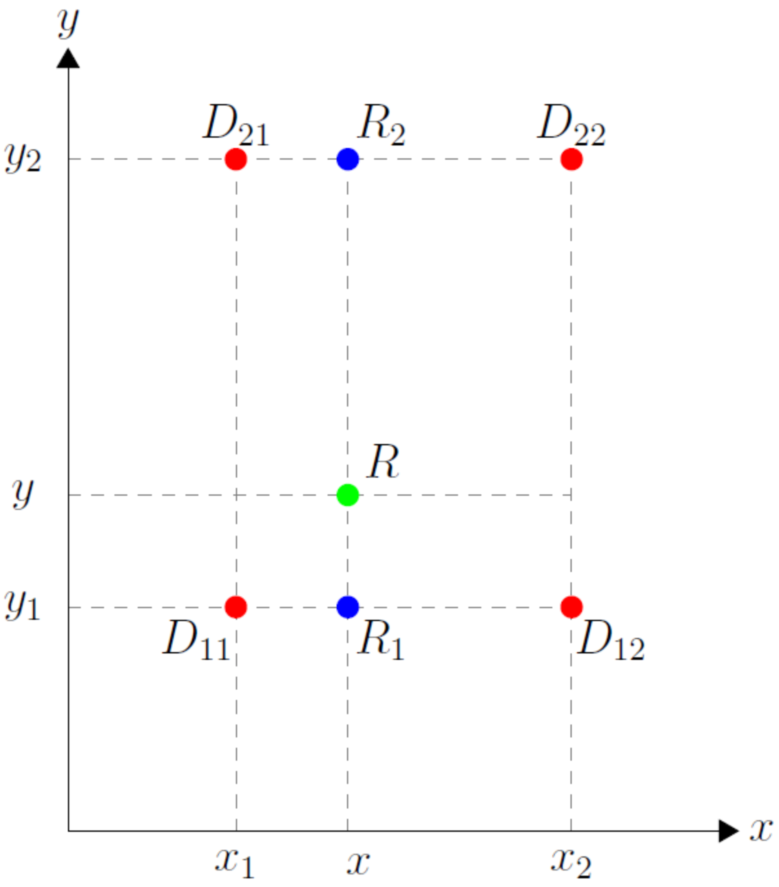

```
'WATER-OPTION ENTROPY 'GAS-WELL US GAS WITH H2O DRY US GAS - W
    50   50    .101355E-01
     .209093E+06    .226757E+01
     .965263E+05   -.177778E+02
     .100000E+10    .100000E+10    .100000E+10    .100000E+10    .100000E+10
     .100000E+10    .100000E+10    .100000E+10    .100000E+10    .100000E+10
     .100000E+10    .100000E+10    .100000E+10    .100000E+10    .100000E+10
     .100000E+10    .100000E+10    .100000E+10    .100000E+10    .100000E+10
     .100000E+10    .100000E+10    .100000E+10    .100000E+10    .100000E+10
     .100000E+10    .100000E+10    .100000E+10    .100000E+10    .100000E+10
     .100000E+10    .100000E+10    .100000E+10    .100000E+10    .100000E+10
     .100000E+10    .100000E+10    .100000E+10    .100000E+10    .100000E+10
     .100000E+10    .100000E+10    .100000E+10    .100000E+10    .100000E+10
     .100000E+10    .100000E+10    .100000E+10    .100000E+10    .100000E+10
     .000000E+00    .000000E+00    .000000E+00    .000000E+00    .000000E+00
     .000000E+00    .000000E+00    .000000E+00    .000000E+00    .000000E+00
     .000000E+00    .000000E+00    .000000E+00    .000000E+00    .000000E+00
     .000000E+00    .000000E+00    .000000E+00    .000000E+00    .000000E+00
     .000000E+00    .000000E+00    .000000E+00    .000000E+00    .000000E+00
     .000000E+00    .000000E+00    .000000E+00    .000000E+00    .000000E+00
     .000000E+00    .000000E+00    .000000E+00    .000000E+00    .000000E+00
     .000000E+00    .000000E+00    .000000E+00    .000000E+00    .000000E+00
     .000000E+00    .000000E+00    .000000E+00    .000000E+00    .000000E+00
     .000000E+00    .000000E+00    .000000E+00    .000000E+00    .000000E+00
 GAS DENSITY (KG/M3)
     .802592E+00    .795453E+00    .788442E+00    .781555E+00    .774790E+00
     .768144E+00    .761613E+00    .755196E+00    .748889E+00    .742689E+00
     .736596E+00    .730605E+00    .724716E+00    .718923E+00    .713197E+00
     .707562E+00    .702016E+00    .696556E+00    .691182E+00    .685890E+00
     .680679E+00    .675547E+00    .670493E+00    .665514E+00    .660609E+00
     .655776E+00    .651014E+00    .646321E+00    .641695E+00    .637136E+00
     .632641E+00    .628209E+00    .623840E+00    .619531E+00    .615281E+00
     .611090E+00    .606956E+00    .602877E+00    .598854E+00    .594884E+00
     .590966E+00    .587100E+00    .583284E+00    .579518E+00    .575801E+00
     .572131E+00    .568507E+00    .564930E+00    .561397E+00    .557909E+00
     .256073E+01    .253737E+01    .251446E+01    .249196E+01    .246988E+01
     .244820E+01    .242690E+01    .240599E+01    .238544E+01    .236525E+01
     .234542E+01    .232592E+01    .230676E+01    .228792E+01    .226940E+01
     .225120E+01    .223329E+01    .221568E+01    .219836E+01    .218133E+01
     .216458E+01    .214804E+01    .213172E+01    .211565E+01    .209982E+01
     .208423E+01    .206888E+01    .205375E+01    .203885E+01    .202417E+01
     .200969E+01    .199543E+01    .198138E+01    .196752E+01    .195386E+01
     .194039E+01    .192710E+01    .191400E+01    .190108E+01    .188834E+01
     .187577E+01    .186337E+01    .185113E+01    .183905E+01    .182713E+01
     .181537E+01    .180376E+01    .179230E+01    .178099E+01    .176982E+01
     .434634E+01    .430571E+01    .426587E+01    .422679E+01    .418846E+01
     .415084E+01    .411393E+01    .407770E+01    .404213E+01    .400721E+01
     .397291E+01    .393922E+01    .390612E+01    .387360E+01    .384165E+01
     .381024E+01    .377937E+01    .374903E+01    .371919E+01    .368985E+01
     .366100E+01    .363263E+01    .360472E+01    .357727E+01    .355027E+01
     .352357E+01    .349724E+01    .347131E+01    .344577E+01    .342062E+01
     .339584E+01    .337143E+01    .334738E+01    .332367E+01    .330031E+01
     .327729E+01    .325459E+01    .323221E+01    .321014E+01    .318838E+01
     .316693E+01    .314576E+01    .312488E+01    .310429E+01    .308397E+01
     .306392E+01    .304413E+01    .302461E+01    .300534E+01    .298632E+01
     .616023E+01    .610119E+01    .604334E+01    .598665E+01    .593108E+01
     .587660E+01    .582317E+01    .577076E+01    .571935E+01    .566890E+01
     .561938E+01    .557078E+01    .552305E+01    .547619E+01    .543017E+01
     .538496E+01    .534054E+01    .529690E+01    .525401E+01    .521185E+01
     .517041E+01    .512967E+01    .508961E+01    .505022E+01    .501149E+01
     .497339E+01    .493592E+01    .489903E+01    .486249E+01    .482652E+01
     .479109E+01    .475620E+01    .472184E+01    .468799E+01    .465463E+01
```

Linear interpolation – 1D

$$\frac{y_4 - y_3}{x_4 - x_3} = \frac{y_x - y_3}{x_x - x_3}$$



Linear interpolation – 2D

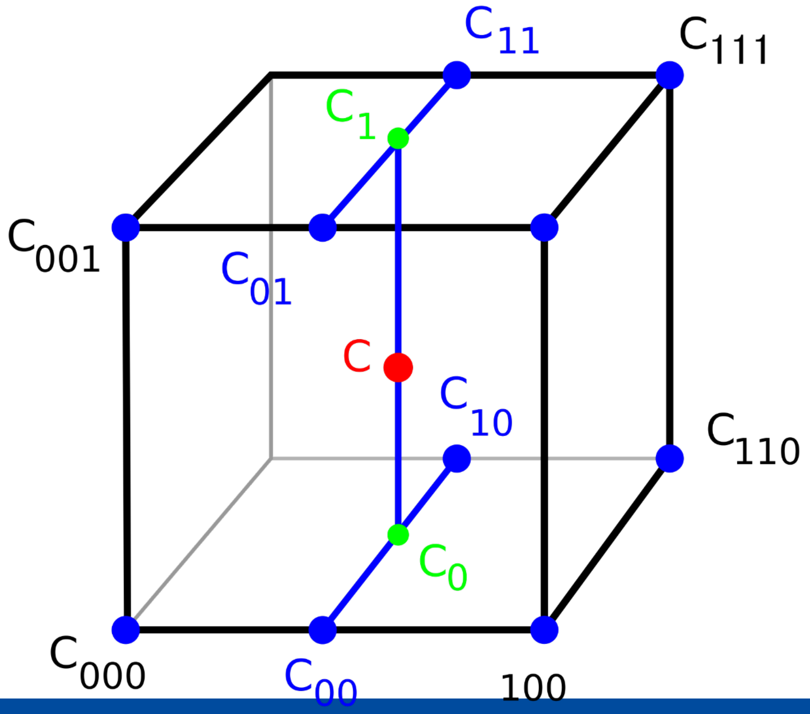


$$f(R) \approx \frac{y_2 - y}{y_2 - y_1} \cdot f(R_1) + \frac{y - y_1}{y_2 - y_1} \cdot f(R_2)$$

$$f(R_1) \approx \frac{x_2 - x}{x_2 - x_1} \cdot f(D_{11}) + \frac{x - x_1}{x_2 - x_1} \cdot f(D_{12})$$

$$f(R_2) \approx \frac{x_2 - x}{x_2 - x_1} \cdot f(D_{21}) + \frac{x - x_1}{x_2 - x_1} \cdot f(D_{22})$$

Linear interpolation – 3D



$$x_d = \frac{x - x_0}{x_1 - x_0}$$
$$y_d = \frac{y - y_0}{y_1 - y_0}$$
$$z_d = \frac{z - z_0}{z_1 - z_0}$$

$$c_{00} = c_{000}(1 - x_d) + c_{100} x_d$$
$$c_{01} = c_{001}(1 - x_d) + c_{101} x_d$$
$$c_{10} = c_{010}(1 - x_d) + c_{110} x_d$$
$$c_{11} = c_{011}(1 - x_d) + c_{111} x_d$$

$$c_0 = c_{00}(1 - y_d) + c_{10} y_d$$
$$c_1 = c_{01}(1 - y_d) + c_{11} y_d$$

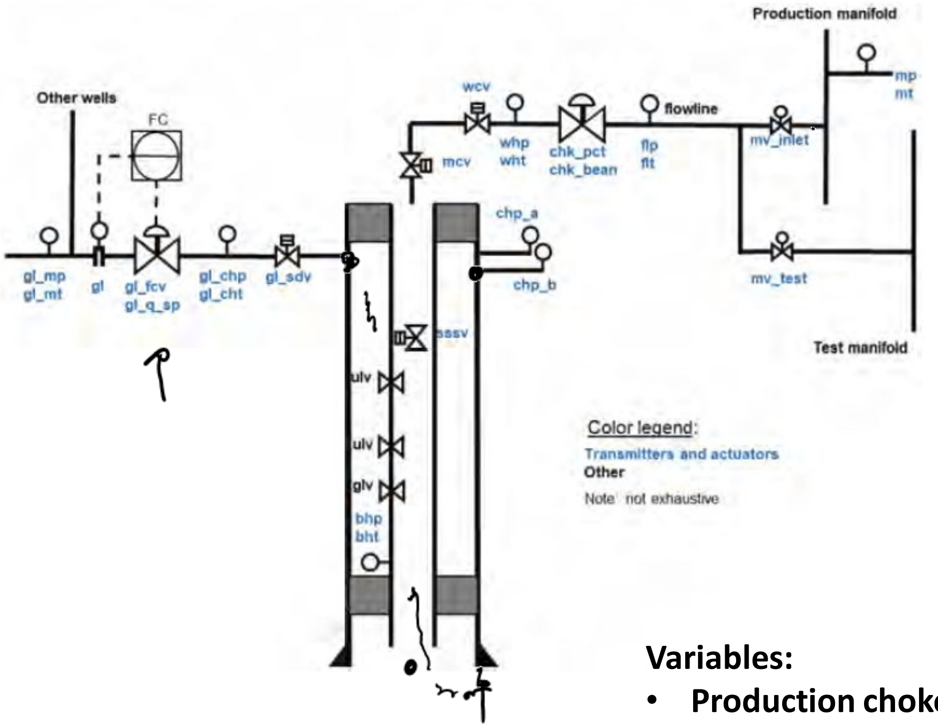
$$c = c_0(1 - z_d) + c_1 z_d$$

Advantages of using tables

- Faster than running the model
- Introduces no approximation errors (except interpolation)
- The O&G industry has extensive experience
- Easy to set up
- Can optimize software and license usage

Example: Gas-lifted well including several constraints and using a table

SPE-202840 (ADNOC, UAE)



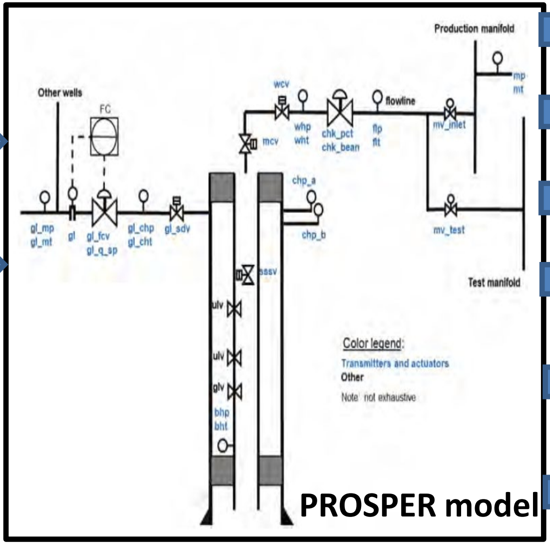
Variables:
- **Production choke**
- **Gas lift rate**

Constraints:

1. Dead (no flow)
2. Unstable flow (tubing heading)
3. Casing heading — Instability
4. Max CHP (1800 psig)
5. Min BHP (2750 psig)
6. Max oil (2080 bopd)
7. Hydrate formation in gas lift valve

Production choke opening

Gas lift rate



Oil rate

Casing head pressure (CHP)

BHP

Casing heading instability flag

Tubing heading instability flag

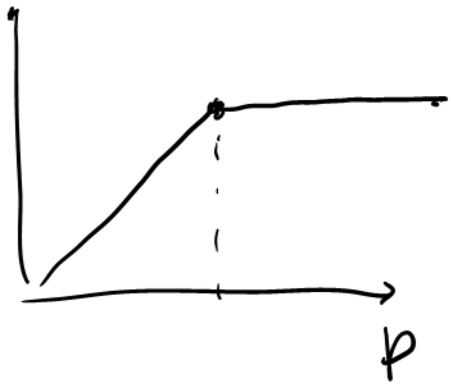
Hydrate presence indicator

Combinations (558 runs):
Production choke opening: 5, 10, …., 100%
Gas lift rate: 0, 0.1,…, 3 MMscfd

Excel file

Issues with interpolation

- If system changes points usually must be generated again
- (Usually) requires regular grid
- Can be expensive to create the table
- Complexity grows with number of variables
- Logic (IF) and looping (FOR) is required to find the bounding values in the interpolation
- Handling discontinuities
- Be careful with the limits
- Number of points required
- Point spacing



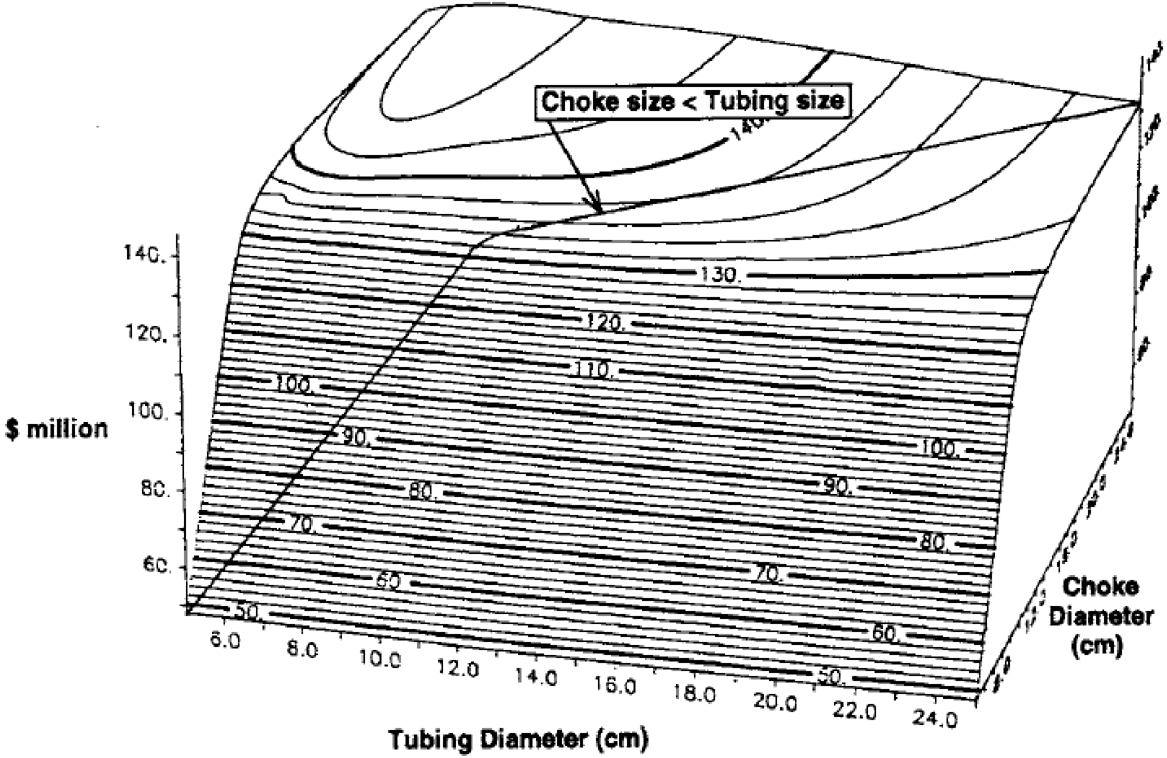
Production optimization: Limitations and pitfalls

Limitations and pitfalls

- Model fidelity
- Is it actually possible to change the decision settings?:
  - Is the equipment/actuator functional and available?
  - Am I allowed to operate the control element?
  - Actuator response time

Limitations and pitfalls

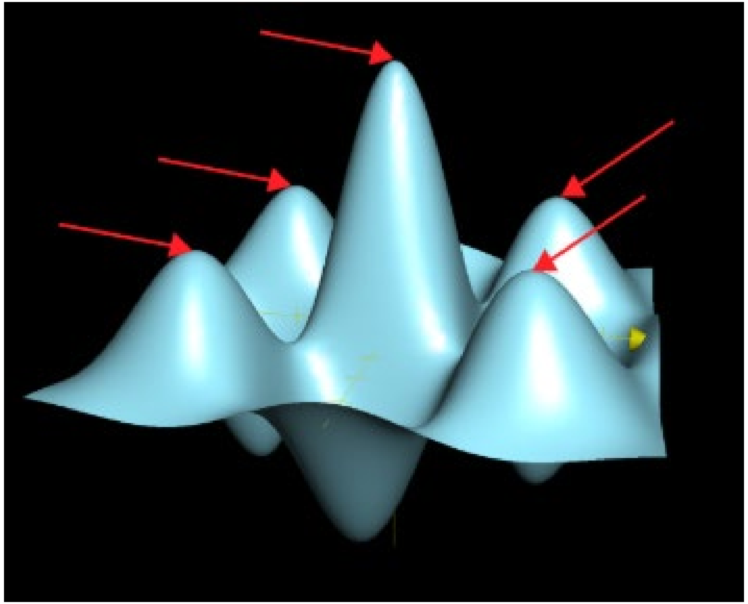
- Flat peak of optimum- more efforts give less results



SPE-166027-MS Multivariate optimization of production systems optimization Carroll and Horne

Limitations and pitfalls

- Local optima
- Starting point
- Running time
- Short term versus long term optimization



(Khan academy)

Limitations and pitfalls

- Short term versus long term optimization

Maximize NPV
By changing $q_o(t)$

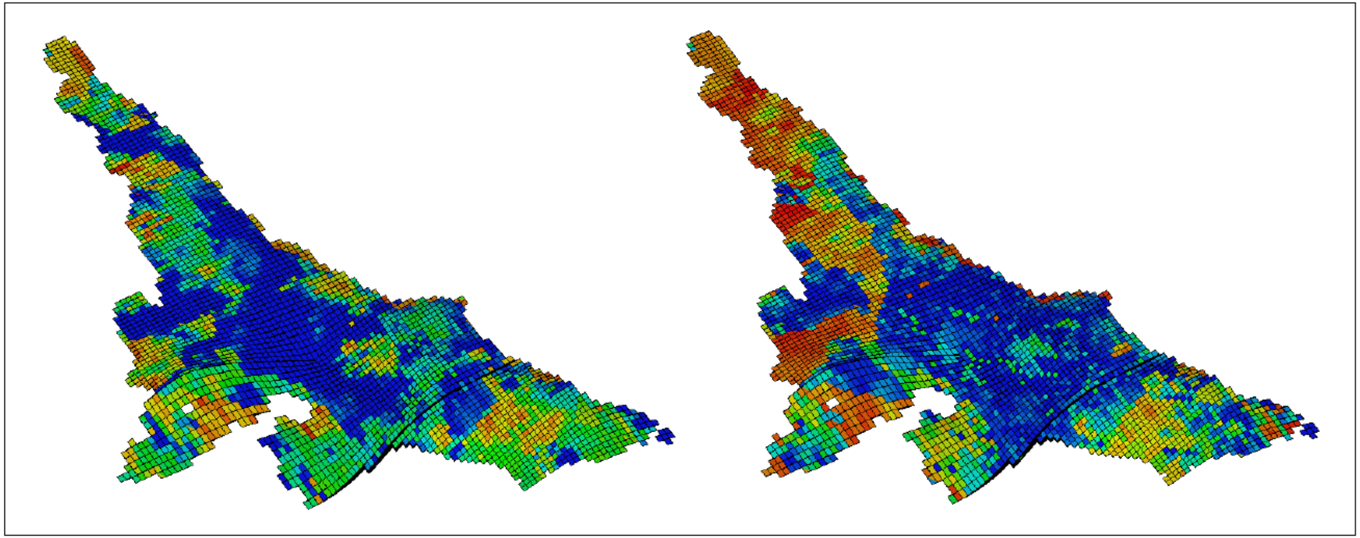


Figure 3: Permeability (left) and porosity (right) distributions of the south wing.

- Short term versus long term optimization

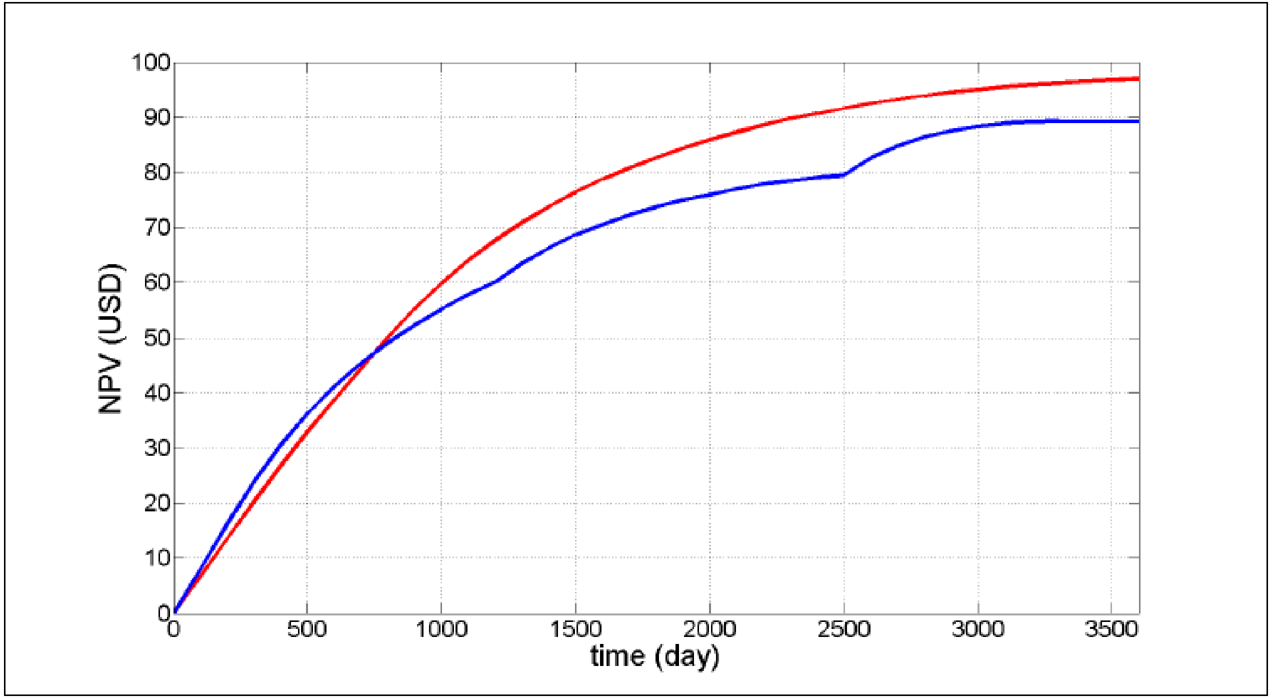


Figure 4: Normalized NPV of the long-term optimization (red) using adjoint-based optimization and short-term optimization (blue) using reactive control.

• Short term versus long term optimization

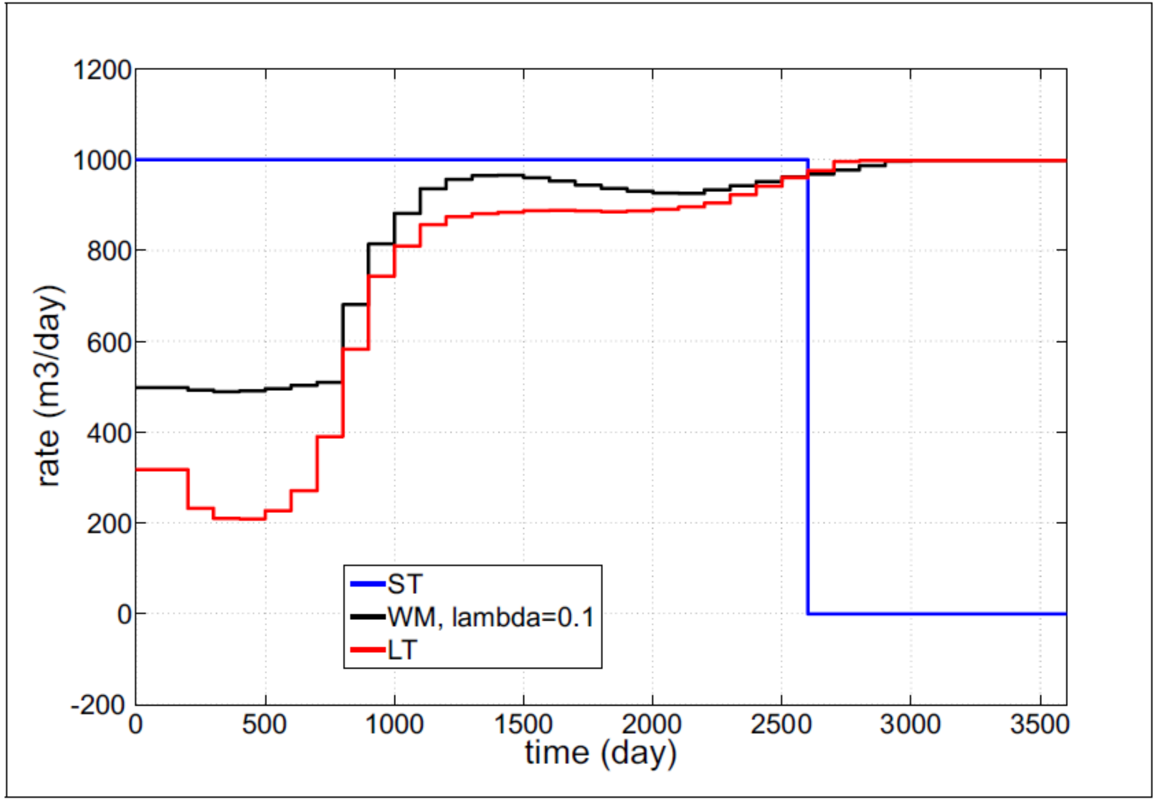


Figure 9: Oil rate from production well PROD3 using different strategies; reactive control (blue), adjoint-based optimization (red), and the weighted-sum method (black).

Take-aways when implementing prod optimization

- Look at the rest of the list first!
- Do we REALLY need to do optimization?
- Think carefully what is the main, most important, first order of magnitude problem

SLIDE 2

- Detect locations in the system with abnormally high-pressure loss and flow restrictions
- Verification of equipment design conditions vs actual operating conditions
- Identification and addressing fluid sources that have disadvantageous characteristics (e.g. high water cut, high H_2S content)
- Identify and correct system malfunctions and non-intended behavior
- Analyze and improve the logistics and planning of maintenance, replacement and installation of equipment or in the execution of field activities.
- Review the occurrence of failures and recognize patterns
- Calibration of instrumentation
- Identification of operational constraints (e.g. water handling capacity, power capacity)
- Observe and analyze the response of the system when changes are introduced
- Find control settings of equipment that give a production higher than current (or, preferably, that give maximum production possible)
- Identify Bottlenecks
- Identifying and monitoring Key Performance Indicators (KPIs)

Take-aways when implementing prod optimization

- Define objective, constraints and variables
- Determine relevance of constraints
- Is it realistic to modify optimization variables?
- Formulate your optimization in a smart way (choose the right variable)
- Study how your input affects your results

THE END

THANK YOU