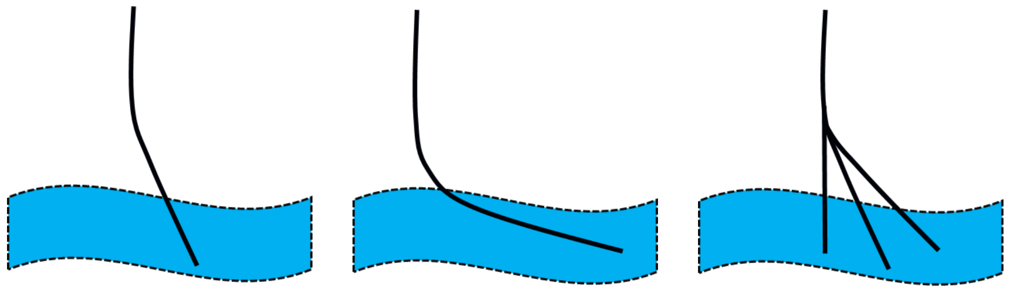
RESULT workshop – August 26th 2025

Demonstration of open-source tools for detailed techno-economic evaluation of geothermal well designs

Workshop agenda:

- 13.00 Welcome and opening remarks
- **Part 1**: Technical presentation on **well concept selection with optimization** (RESULT project)
  Eduardo Barros, Senior Reservoir Engineering Scientist (TNO)
- **Part 2**: Demonstration of **PyThermoNomics**, an open-source Python-based module to calculate economics of geothermal energy projects
  Stephan de Hoop, Reservoir Engineer / Software Developer, and Slawomir Szklarz, Optimization Expert (TNO)
- Ca. 14.45 – 15.00 Coffee break
- **Part 3**: Demonstration of **PyFastWell**, an open-source Python-based fast semi-analytical model for geothermal reservoirs
  Jan-Diederik van Wees, Principal Scientist Geothermal Energy (TNO)
- Joint discussion and conclusions
- Ca. 16.30 Networking drinks (borrel)



Optimization of well locations and trajectories:

comparing well concepts for marginal geothermal reservoir in NL

Eduardo Barros, Sławomir Szklarz, Negar Khoshnevis Gargar,
Jan-Diederik van Wees, Jens Wollenweber

Content

Content

1. Short introduction to RESULT project
2. EVEREST™ optimization technology
3. Well trajectory optimization for well concept selection
4. Conclusions

RESULT project

- Confirmed heat demand + matching adjacent, prolific geothermal reservoir = **successful geothermal projects**
  - However, potential poor reservoir quality at locations of existing heat demand may result in poor business case
  - Advanced drilling solutions to improve the productivity of geothermal system do exist

- **Main objective**: investigate innovative approaches to guide well concept selection and engineering design of geothermal wells
  - Use of state-of-the-art modelling and optimization frameworks
  - Demonstration of scientific methodology in various case studies (Netherlands, Ireland, Iceland)
  - Practical drilling demonstration of innovative well designs

Enhancing **RES**ervoirs in **U**rban deve**L**opmen**T**: smart wells and reservoir development
Geothermica Project Number 200317

https://www.result-geothermica.eu/home.html

RESULT project – solutions

- Enhanced well architectures can provide enhanced flow performance especially for “marginal” reservoirs
- Well concepts and cost-engineering
- Techno-economic evaluation
- Robust optimization using EVEREST /3D detailed reservoir models – Zwolle
- Fast models for homogeneous reservoirs

Content

EVEREST™ optimization technology

- Landing page: https://everest.tools/
- Github repository: https://github.com/equinor/ert
- Documentation: https://everest.readthedocs.io/en/latest/
- EVEREST overview paper with example applications (also shared as attached PDF): https://doi.org/10.2118/223850-MS

EVEREST

transforming uncertainty into opportunity

https://www.everest.tools/

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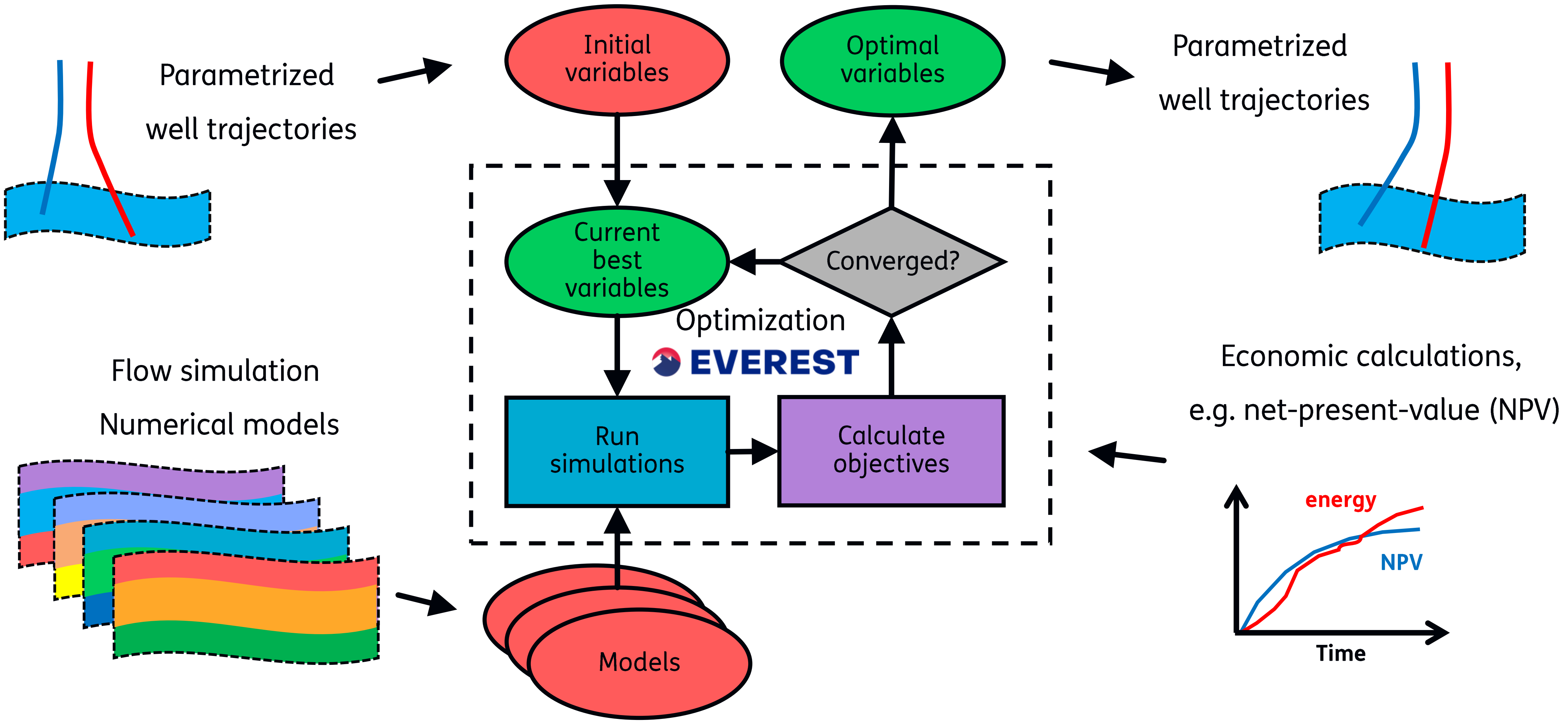
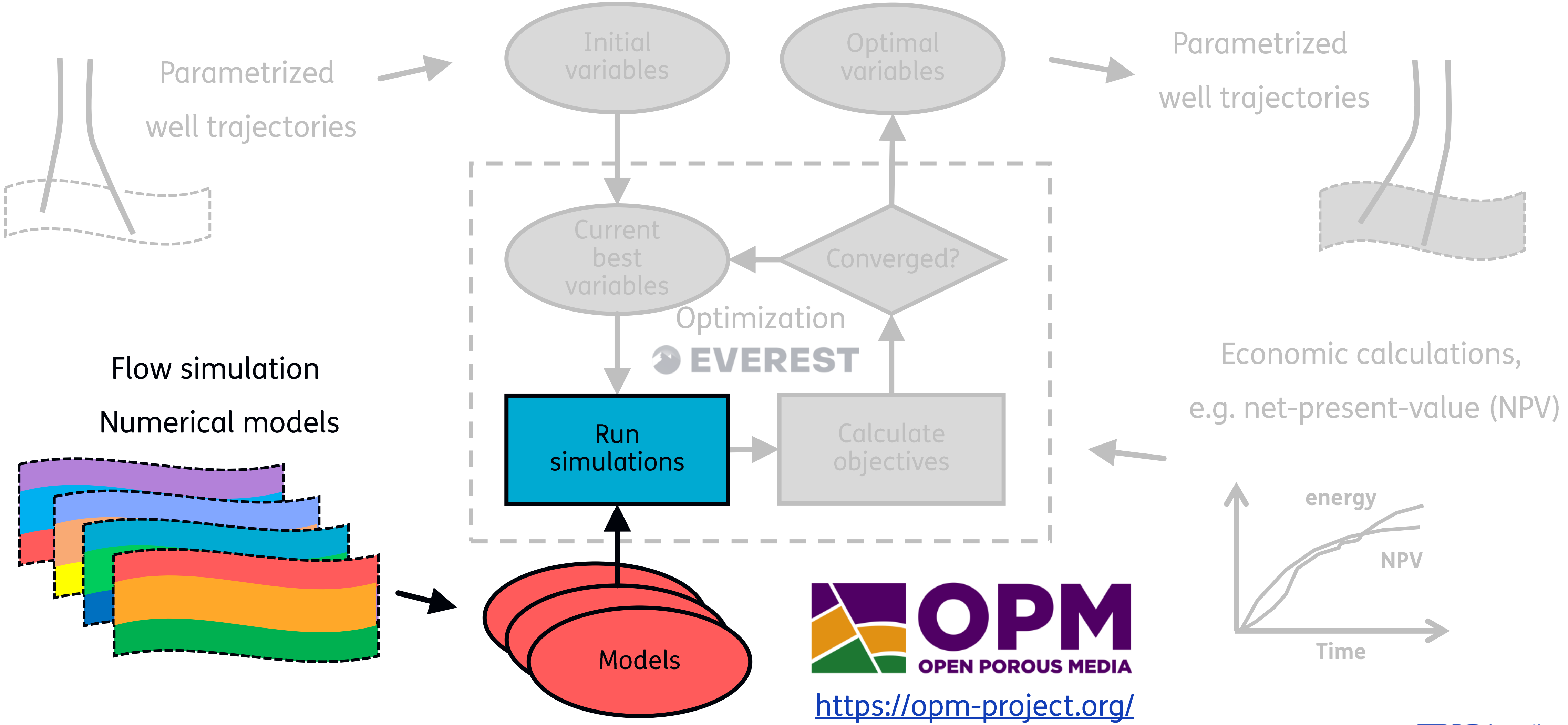
Context

- Numerical optimization approach is used to support the selection of the well concept for the Zwolle site by enabling the comparison of the three well concepts considered:
  - Quasi-vertical
  - Sub-horizontal
  - Multi-lateral
- **Well trajectory optimization** workflow investigated in the RESULT project for the Zwolle case
- Key points:
  - **Robust optimization** under prior uncertainty
  - **Efficient optimization** with EVEREST– for computationally expensive simulations of subsurface models
  - **Parametrization** of grid independent well trajectories
  - **Economic model** that takes into account different well concepts

Optimization workflow

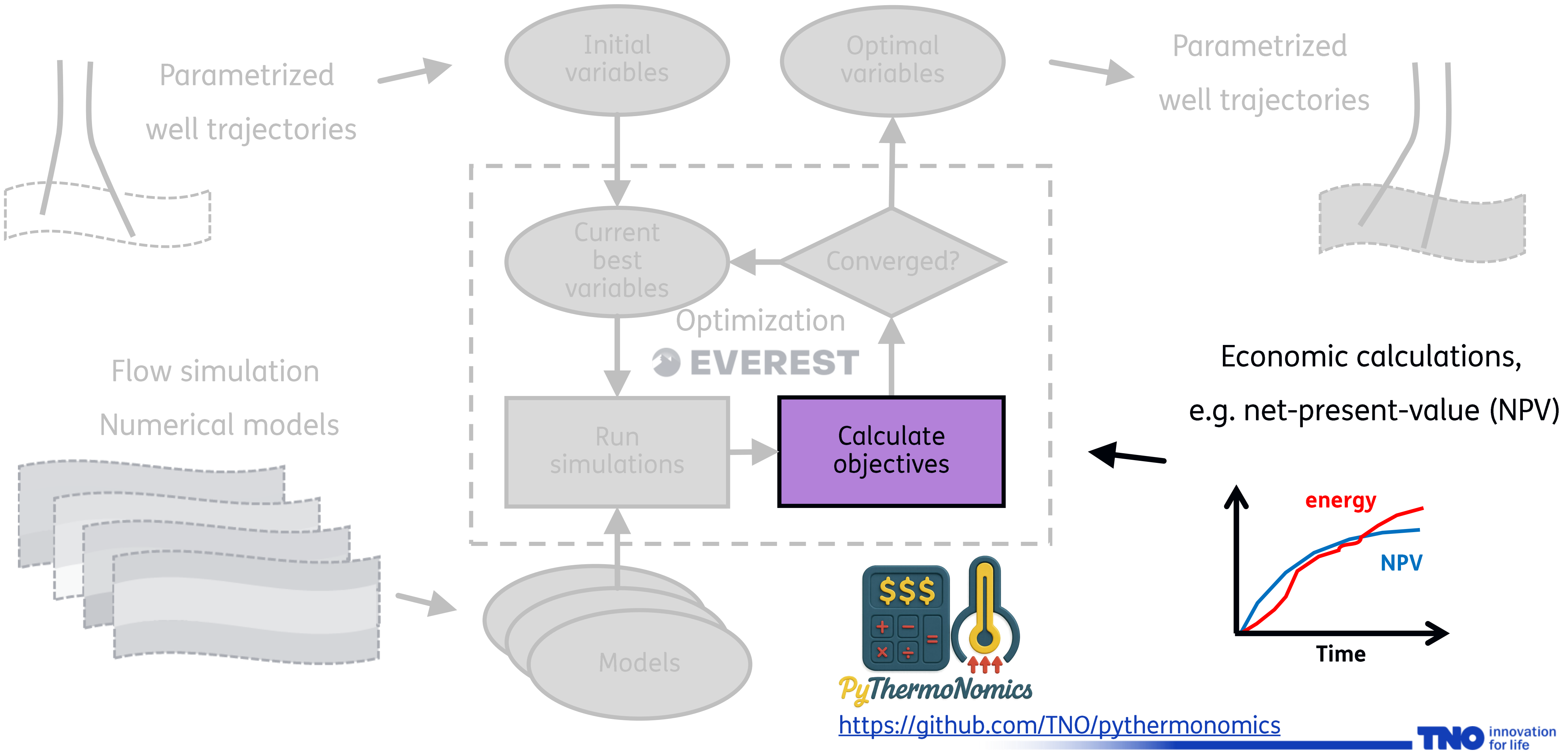


Optimization workflow



https://opm-project.org/

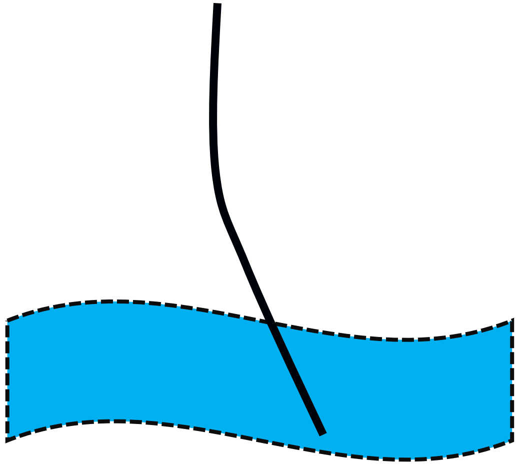
Optimization workflow



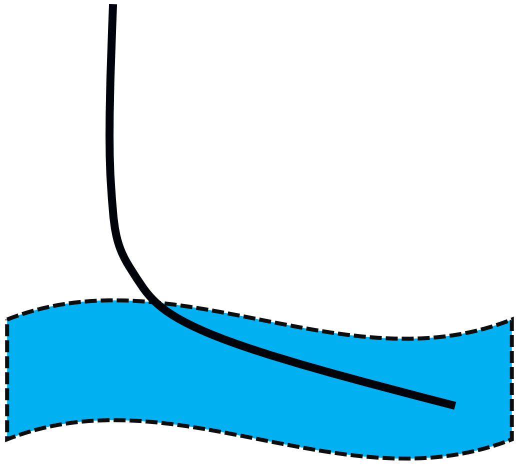
Different well concepts

- Well trajectory optimization functionality from EVEReST allows for simultaneous optimization of well locations and well shapes
- 3 optimization experiments have been performed with different initial assumptions regarding the shape of the wells, namely:

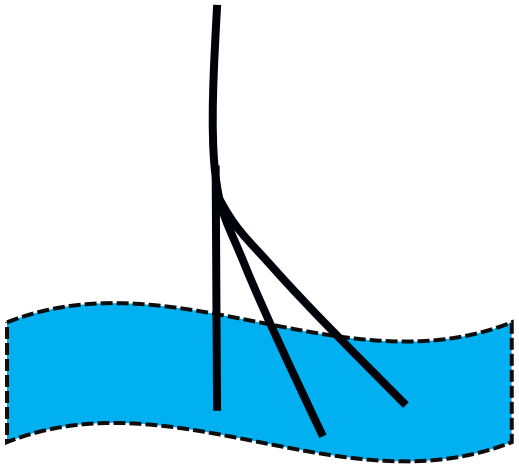
1. Slightly deviated wells (quasi-vertical)



2. Strongly deviated (i.e. horizontal) wells

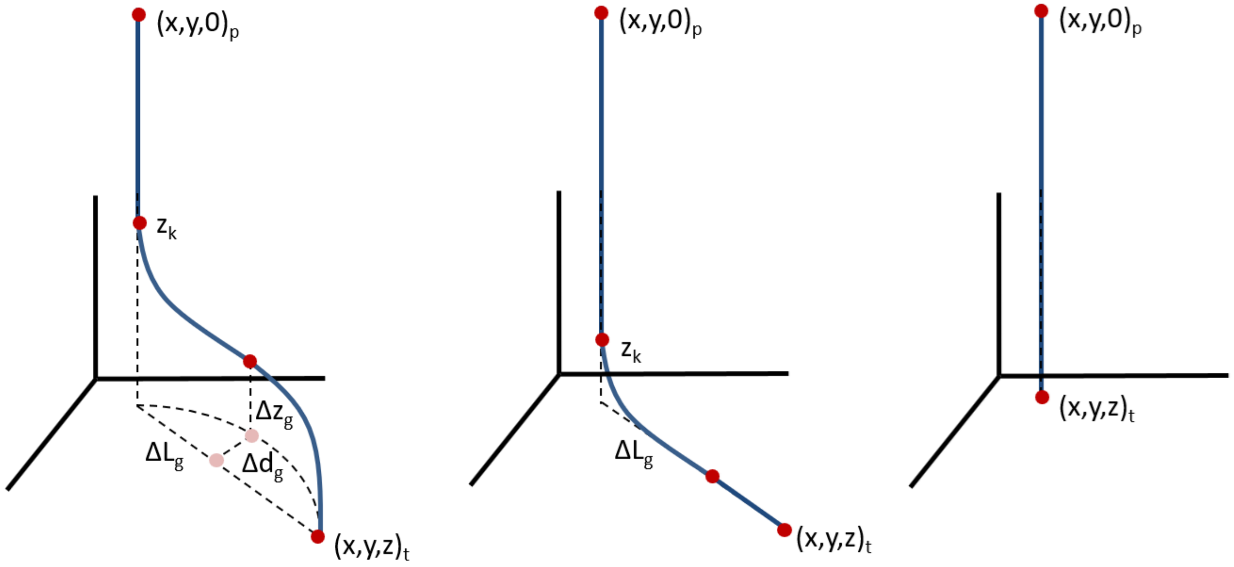


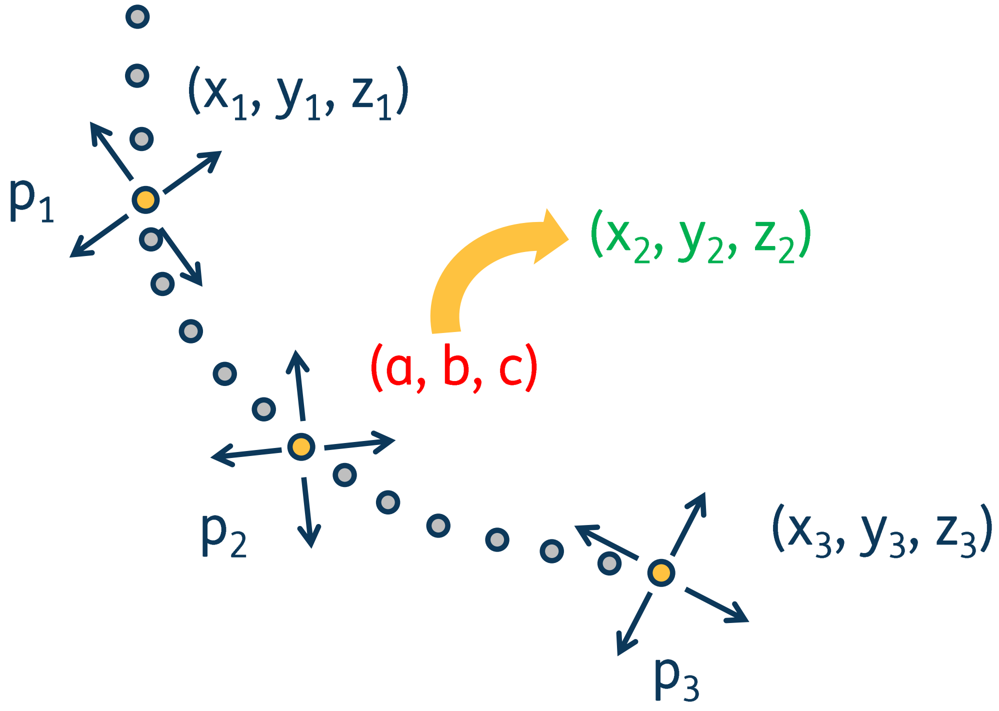
3. Multi-lateral wells (3 quasi-vertical branches)



Well trajectory and location parametrization (1/2)

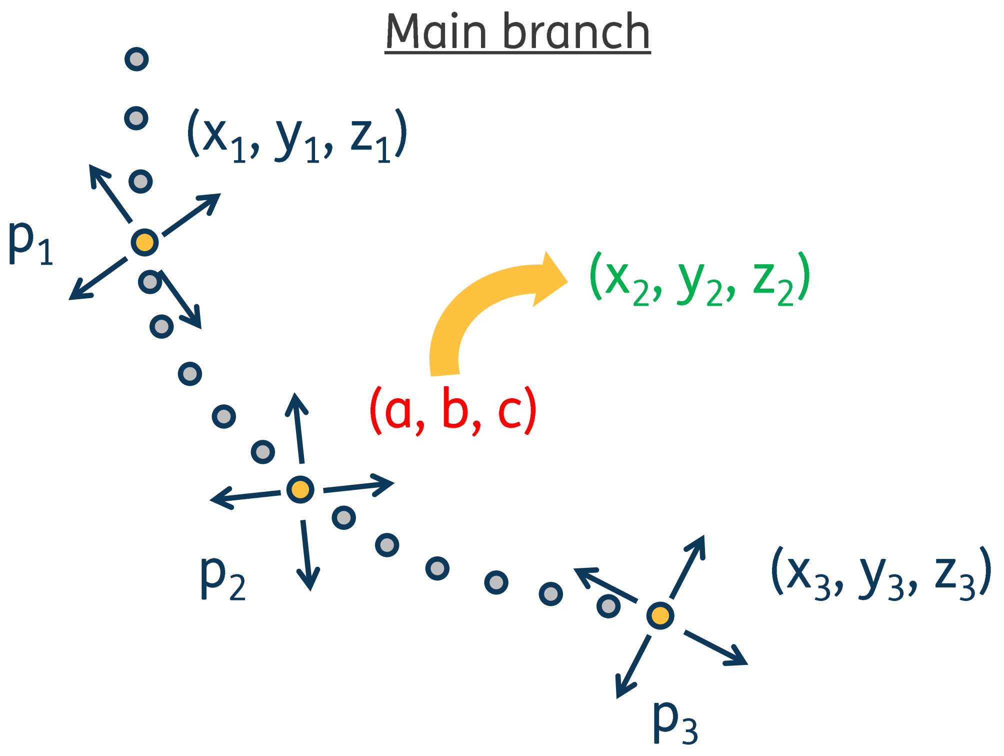
- Special parametrization defines complex well geometries with as little variables as possible
- Also constrains “target points” to move in coordinated manner: avoids un-drillable wells
- Below example of parametrization but other parametrizations possible (flexible)

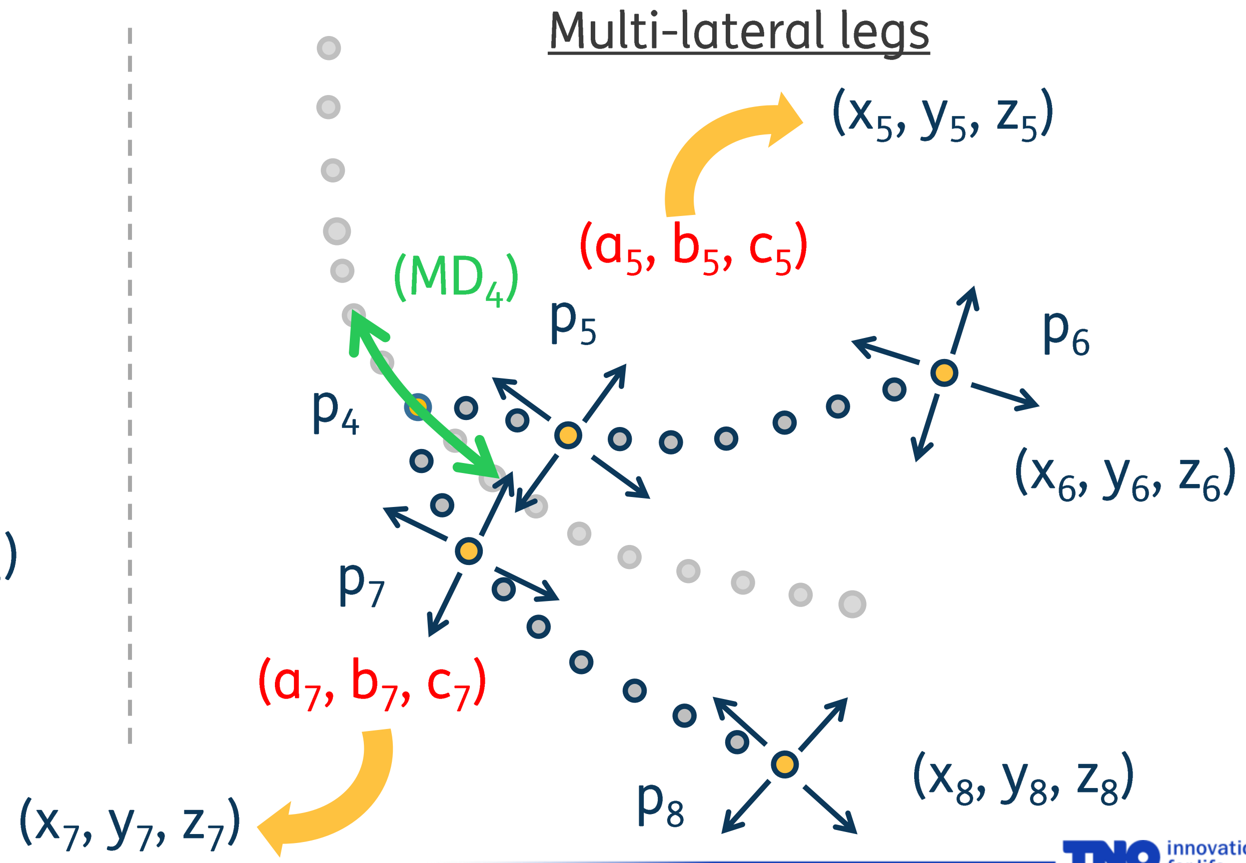




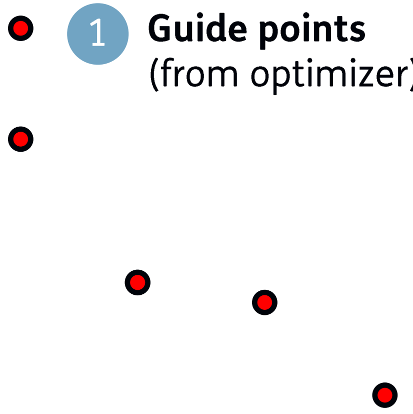
Well trajectory and location parametrization (2/2)

- Multi-lateral wells with 3 branches have been considered (1 main branch + 2 legs)
- Parametrization of main branch remains the same, and additional parameters are introduced to describe the multi-lateral legs

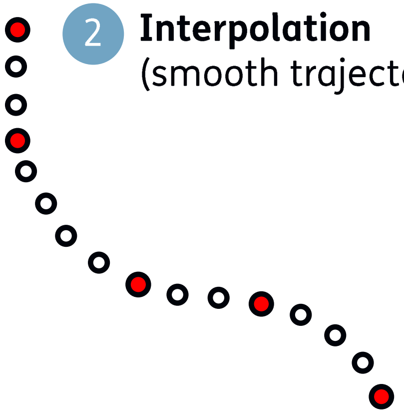




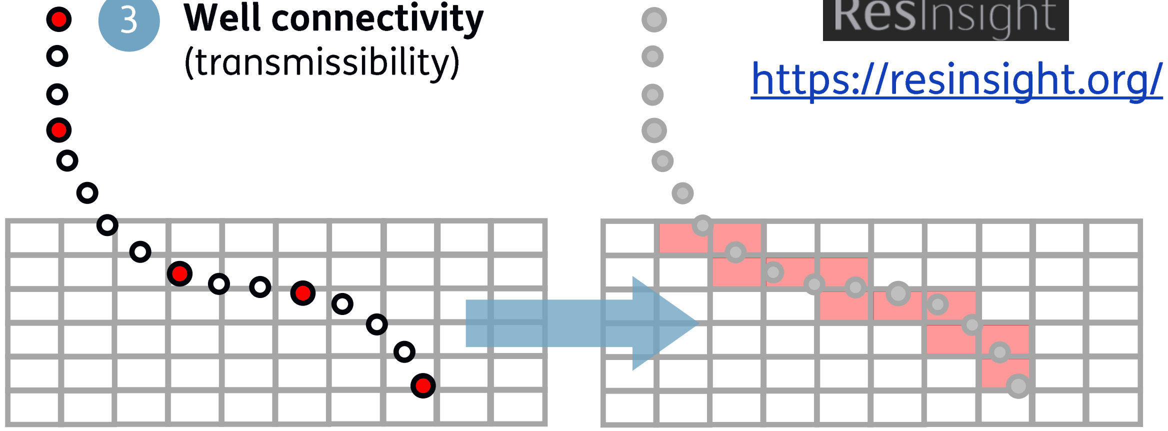
Well trajectory workflow



1 **Guide points**
(from optimizer)



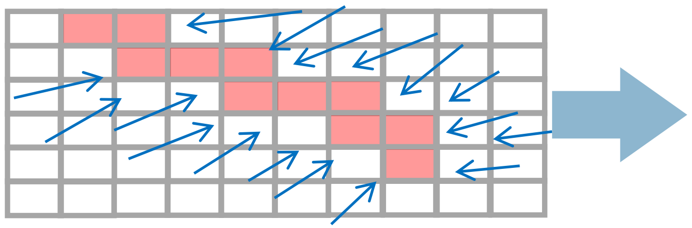
2 **Interpolation**
(smooth trajectory)



3 **Well connectivity**
(transmissibility)

https://resinsight.org/

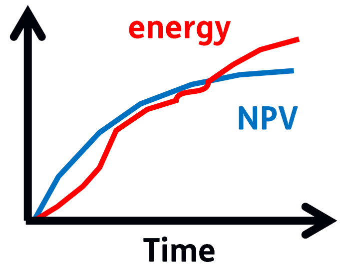
4 **Production forecast**
(from reservoir simulator)



OPEN POROUS MEDIA

https://opm-project.org/

5 **Objectives**
(energy, economics)

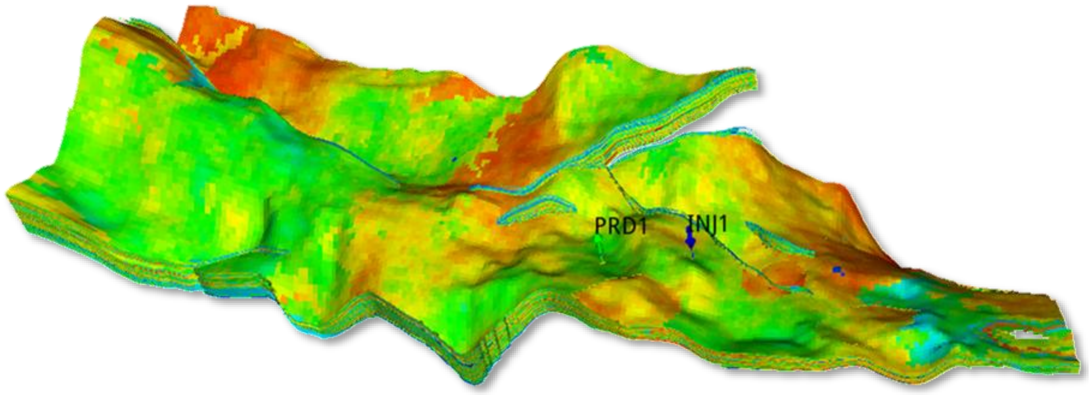


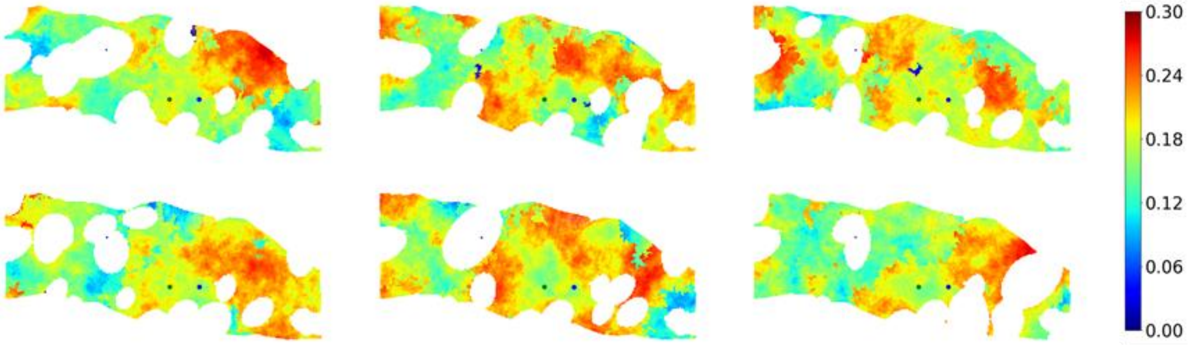
PyThermoNomics https://github.com/TNO/pythermonomics

Well trajectories are grid-independent and need to be translated into trajectories for reservoir simulator, i.e. into grid well cells indices and the connection transmissibility factors

Zwolle case study

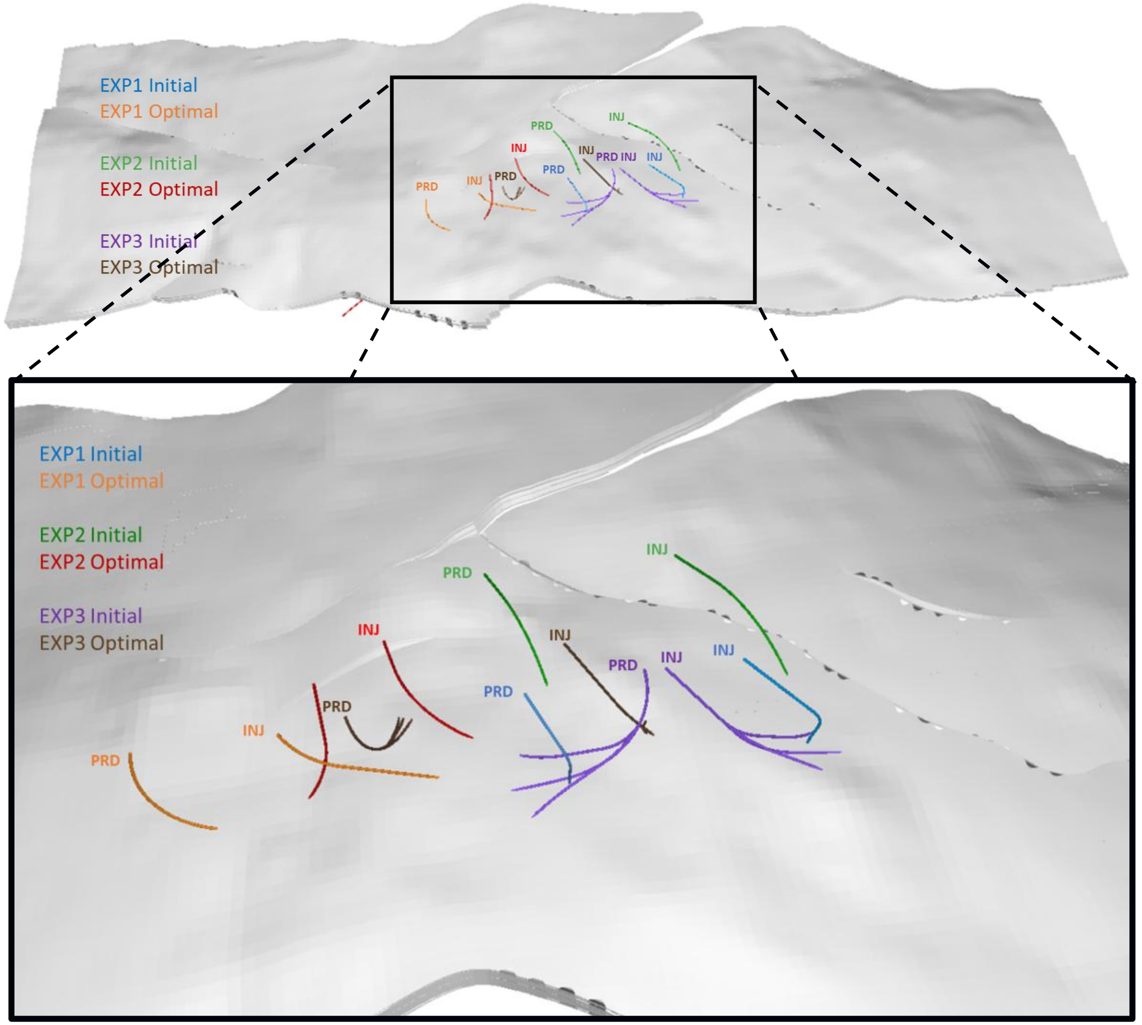
- The numerical model is a representation of reservoir at the Rotliegend formation
- The geological static model was generated by EBN based on geological knowledge
- Best-guess scenario concerning the cementation assumptions was used to create ensemble of 100 realizations
- Spatially heterogenous model with different static properties (i.e., porosity and permeability fields) to reflect the inherent geological uncertainties
- The model specifics:
    - Grid with 219 × 101 × 169 grid cells
    - Area of approximately 45 km² (= 11 km × 4 km)
    - Average depth: 2,400 m
    - Thickness from 50-80 m
- Total of about 950,000 active cells
(which varies slightly per model realization)





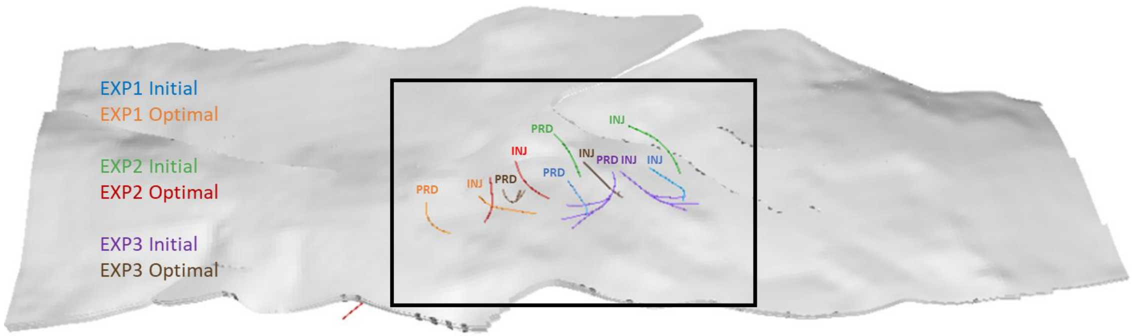
Optimization results: well locations

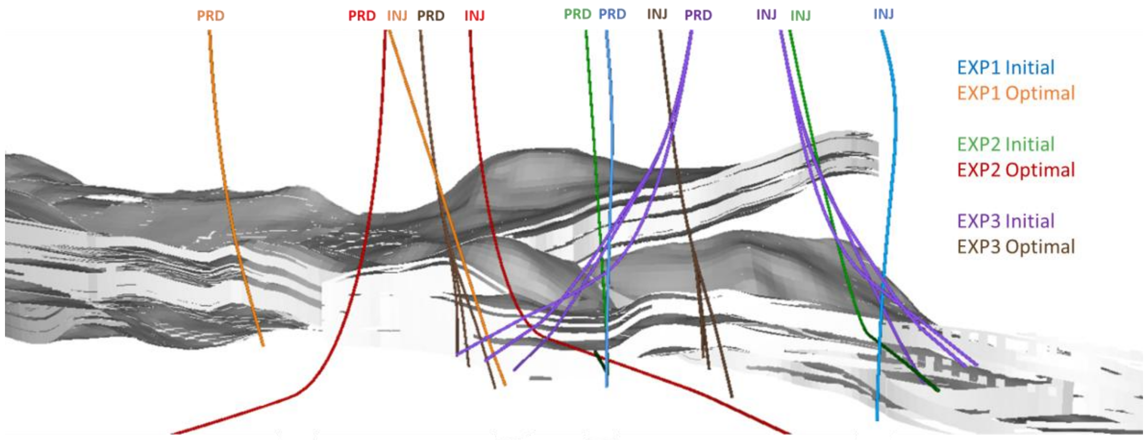
- Three well location/trajectory optimization experiments have been performed with different initial well concepts:
  - Experiment 1 starts with slightly deviated wells
  - Experiment 2 starts with strongly deviated wells
  - Experiment 3 considers multilateral wells with two additional leg
    - Constraint of search space by imposing a maximum allowed inclination of 60° for each branch
- Similar locations and the distance between the injector and producer in the reservoir for the initial guesses of all experiments, i.e. ~1000 meters
- Included cost per length of each well. For multilateral wells the total combined well length was considered



Optimization results: trajectories

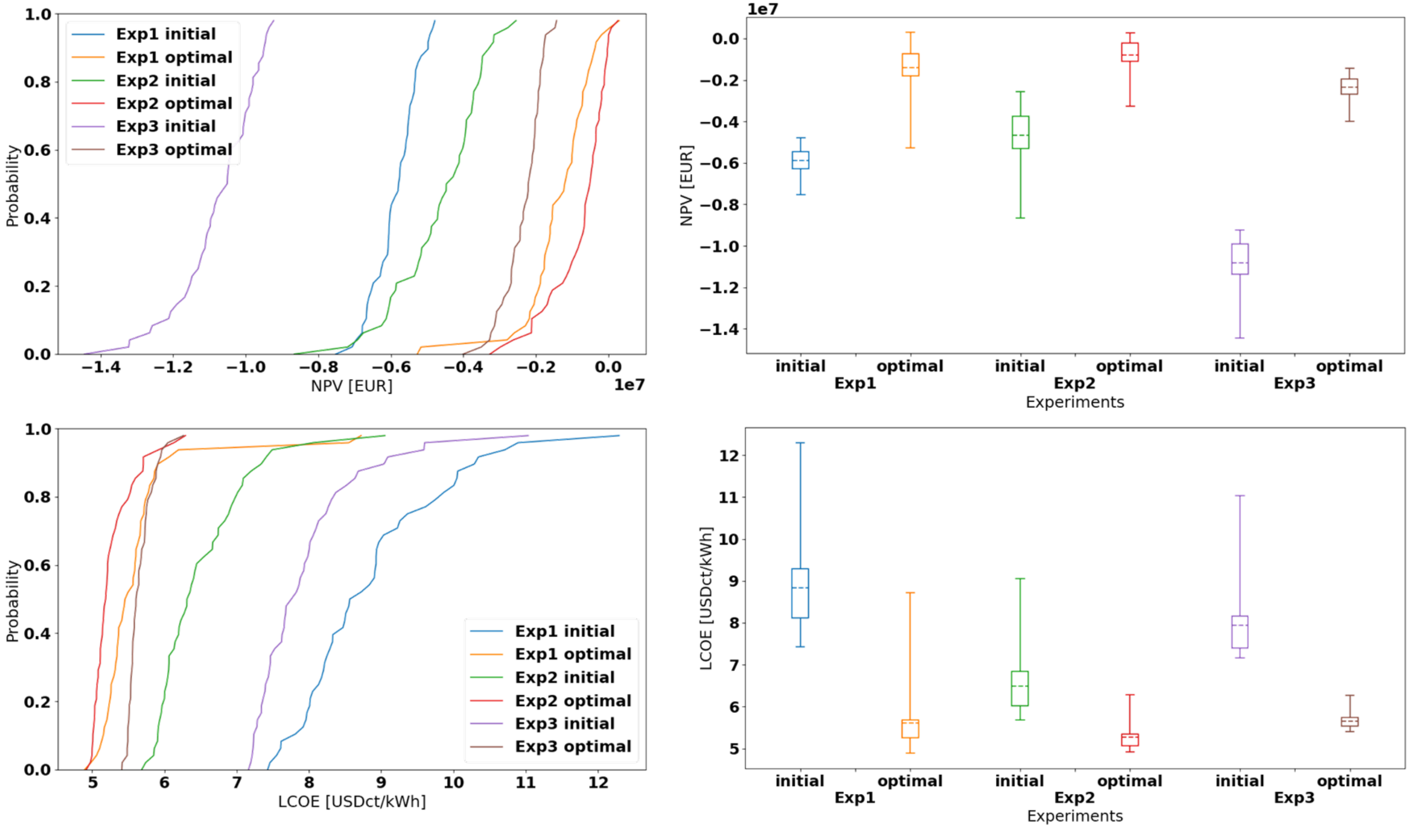
- We notice that optimal locations of the wells for all the three experiments follow some pattern by moving in the same (west) direction
- The shapes of the optimized well trajectories differ considerably across the experiments:
  - **Experiment 1**
    - Trajectories for both wells stay slightly deviated
  - **Experiment 2**
    - Producer's shape becomes slightly deviated
    - Injector's shape remains strongly deviated as in the initial guess in order to sustain high enough injection rate (affected by higher viscosity of cold water) to meet the production rate
  - **Experiment 3**
    - Optimal branches are closer to vertical shape and the tie-in is deeper due to constraint on maximum inclination for each leg





Optimization results: NPV and LCoE

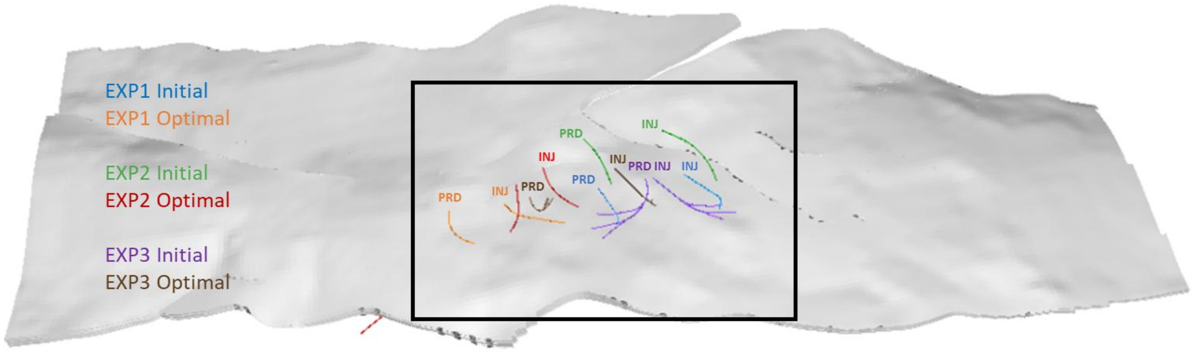
- Higher NPV (and lower average LCoE) on average when the optimal shape of the injector is strongly deviated (Experiment 2)
- Uncertainty (values spread) on both NPV and LCoE associated with the optimal solution for multilateral wells (Experiment 3) is the lowest, even though the optimization was not explicitly set up to reduce this spread
- Initial solutions with stronger deviated wells resulted in improvement
  - However, this improvement is significantly lower comparing to the improvement found by any of the optimization experiments

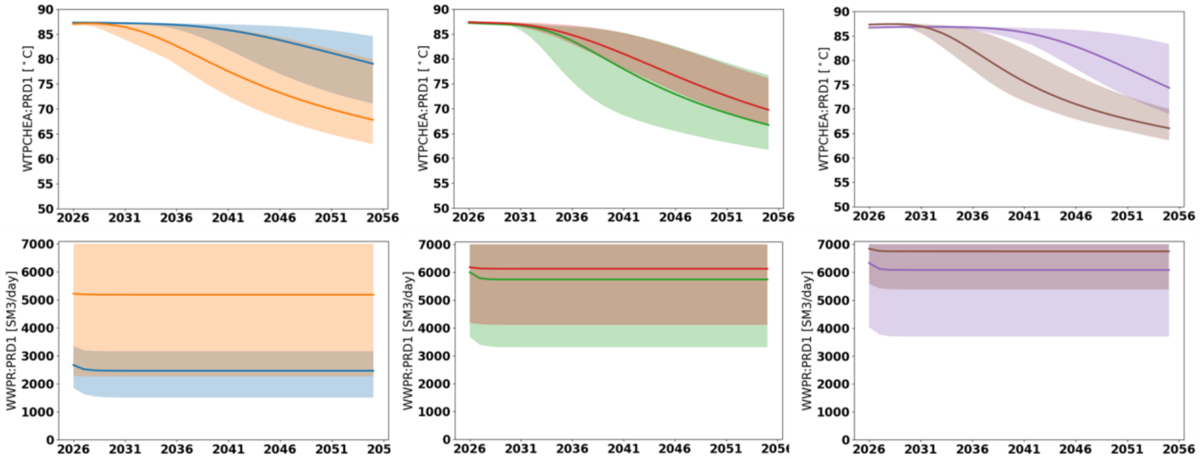


- Shape of wells is not the only factor, but the **combination of shape and location of wells** which determine the techno-economic performance.
- **For multi-lateral wells (Experiment 3) initial solution is the worst** in terms of economics which is due to higher drilling cost

Optimization results: production rates and temperatures

- **Experiment 1** (with slightly deviated wells) was able to **increase injectivity** mostly by finding better well locations
  - This, however, resulted in significantly earlier arrival of the cold water in the producer
- In Experiment 2, (initial guess with strongly deviated, longer wells):
  - We start with better injectivity
  - However, also with earlier cold-water breakthrough in the producer
- In Experiment 2, by simultaneously determining optimal well locations (including well distance) and adjusting well trajectory shapes optimization was able to improve upon both aspects:
  - Delaying the arrival of the cold water
  - Increasing injection/production well rates
- For Experiment 3 (multilateral wells):
  - Increasing injectivity comes at the cost of earlier cold-water breakthrough





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Conclusions and discussion

- The three well concepts (subvertical, sub-horizontal, and multi-lateral have been compared for Zwolle case study in the context of well location and trajectory optimization
- For each well concept, optimization was able to significantly improve techno-economic performance of the doublet system in Zwolle site by changing locations and trajectories of both wells
- Resulting improvement of economic performance from prior LCOE from 7-9 €cts/kWh to ca 5€cts/kWh
- Optimal well locations are significantly different than the initial guess and they reveal a trend in location of optimal development area. This suggests that it is not only the shape of wells, but the combination of shape and location of wells which determine the techno-economic performance of the doublet
- Sub-horizontal and multilateral well concepts are good candidates outperforming the sub-vertical choice
- Sub-horizontal scenario resulted in higher NPV on average across the geological realizations, however multilateral solution delivers lowest economic risk (reduced spread in NPV and LCOE)

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PyThermoNomics

- Github repository: https://github.com/TNO/pythermonomics
- Documentation: https://tno.github.io/pythermonomics/
- Jupyter notebook with demonstration examples (also shared as attached PDF): https://github.com/TNO/pythermonomics/blob/main/examples/main_example_notebook.ipynb

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PyFastWell

Take-home messages

- Optimization results are case-dependent: **general recommendation** is to **use EVEREST** to augment the capabilities of engineers to **find improved case-specific field development solutions**
- **EVEREST + all workflow components** used to obtain presented results from RESULT project are **open-source**
- Specialized geothermal economic model **PyThermoNomics** allows practitioners in the geothermal sector to **evaluate the techno-economic performance of field development strategies** for:
  - Well trajectory of any complex shapes
  - Any production rate and temperature profiles over time
  - With simple but representative economic parameters which can be set by the user

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OPM OPEN POROUS MEDIA
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PyThermoNomics
https://github.com/TNO/pythermonomics

Thank you! Questions?

This study has been performed as part of the RESULT project
(Enhancing REServoirs in Urban deveLopmenT: smart wells and reservoir development).
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