RESULT
Enhancing REServoirs in Urban deveLopmenT: smart wells and reservoir development, Geothermica Project Number 200317

RESULT-D4.4:
Drill & Learn recommendations from all demo sites

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Management Summary

This short report serves as an overview of the research work performed by TNO during the RESULT project towards the application of state-of-the-art modelling and optimization methodologies for improving the understanding of the behavior of geothermal reservoirs and assessing the cost-effectiveness of different geothermal well designs.

It provides a brief description of the highlights from the various demo case studies and modelling techniques addressed throughout the project, including references to the technical RESULT deliverable reports presenting the work done in more details (available on the RESULT website[1]).

[1] https://www.result-geothermica.eu/home.html

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Table of Content

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List of figures

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1 Motivation and aim of RESULT

Confirmed heat demand at a certain surface location and a matching adjacent, prolific geothermal reservoir can result in successful geothermal projects. However, potentially poor reservoir quality at the location of existing heat demand may result in a poor business case. Advanced drilling solutions to improve the productivity of a geothermal system exist and have proven themselves in the oil & gas industry. The main scientific objective of the RESULT project is to investigate innovative approaches to guide the well concept selection and engineering design of geothermal wells.

In WP3 of the project, state-of-the-art modelling and optimization frameworks have been put in place by TNO for this purpose. This short report presents an overview of the scientific modelling efforts carried out with the computational methodologies and workflows presented by TNO. The first part of the report recaps the main case studies considered in the Netherlands (WP4), in Ireland (WP5) and Iceland (WP6) of the RESULT project. The second part gathers a short description of the key modelling and optimization techniques utilized throughout the project and summarizes the main findings and lessons learned of their application to the various case studies.

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2 Drill & Learn cases

The development of a geothermal site implies important investment decisions associated with the construction of surface facilities, and the drilling and operation of wells. The quality of such decisions rely on the degree of understanding of the available geothermal resources in the area of interest. The research work done in RESULT relates to the use of modern computational methodologies to help practitioners enhancing their understanding of their target subsurface reservoirs. In this context, the common challenge is the construction and use of models to mimic the subsurface and predict its dynamic behavior to evaluate the cost-effectiveness of the possible decision alternatives.

Depending on the stage of development of the site, the availability of information and the nature of the decisions of interest may differ. As a result, different modelling techniques and methodologies may be useful at different stages. In a green field area, optimization under uncertainty may guide experts in the search for the most robust placement of wells given the various model scenarios considered. In a site where drilling is taking place, it may be beneficial to anticipate the impact of drilling data on updating the drilling plan for subsequent wells. When the site is already operational for many years, data-driven approaches may assist in the calibration of models to best capture observed behavior and revise the understanding of the production response of the site.

In the RESULT project, TNO and partners have worked in a wide variety of case studies, representative of the various stages of the development and operation of a geothermal site. Advanced modelling and optimization techniques have been applied in a fit-for-purpose manner. The main highlights in terms of demo case studies are recapped in the following sections.

2.1 Sedimentary setting: Zwolle case study

In WP4, the focus was on studying the potential of the RESULT methodology for improving the business cases of marginal reservoirs. Activities aimed, in particular, at supporting the selection of the well concept for the doublet to be drilled in a candidate geothermal site in the municipality of Zwolle, targeting the Rotliegend reservoir formation.

A geological static model was generated by EBN using the Petrel software (Schlumberger) based on all the available knowledge of the geology of the area of interest. A number of scenarios have been considered concerning the reservoir cementation assumptions, and the best-guess scenario has been provided to TNO. The Petrel project provided by EBN contains an internal workflow to automate the generation of geostatistical model realizations for the best-guess scenario, which has been used to create an ensemble of 100 realizations of the spatially heterogenous model with different static properties (i.e., porosity and permeability fields) to reflect the inherent geological uncertainties. The model consists of a grid with 219 × 101 × 169 grid cells covering an area of approximately 45 km² (= 11 km × 4 km) at an average depth of 2,400 m and thickness ranging from 50-80 m, with a total of about 950,000 active cells (which varies slightly per model realization). Next, TNO prepared a dynamic reservoir simulation model by introducing typical thermodynamic properties for the fluids present in the reservoir, along with rock-fluid interaction and rock compressibility and thermal properties, and initialization of reservoir pressure (240-250 bar) and temperature conditions (85-90°C). In addition, a geothermal doublet was inserted by placing a production well and an injection well (both vertical) in one of the central sectors of the model – these serve as starting point for the optimization exercises described next. The producer is operated at a prescribed target flow rate of 7,000 m³/day (~300 m³/h) with a minimum bottom-hole pressure limit of 190 bar. The injector is assumed to operate in voidage replacement mode, where all produced volume is re-injected, with a maximum allowed bottom-hole injection pressure of 300 bar. The volumetric flow rate targets / limits were selected based on typical flow rates for existing geothermal doublets in the Netherlands and reflecting achievable limits with pumping technologies given typical well diameters. Figure 1 depicts the reservoir model of the candidate geothermal site in Zwolle.

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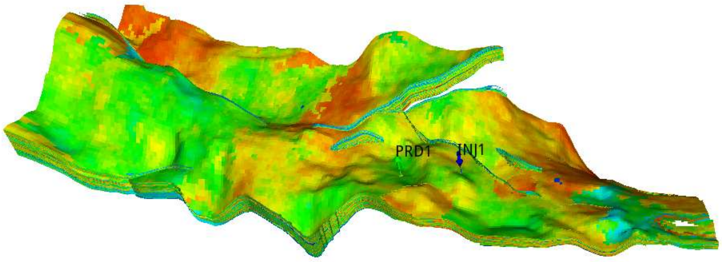

Figure 1: Zwolle reservoir model: 3D view of the model with heterogeneous porosity distribution and initial doublet placement.

Three well concepts (i.e., sub-vertical, sub-horizontal and multi-lateral) have been compared for Zwolle 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 in an improvement of economic performance. Optimization results showed that both sub-horizontal and multi-lateral well concepts are good candidates outperforming the sub-vertical choice (Figure 2).

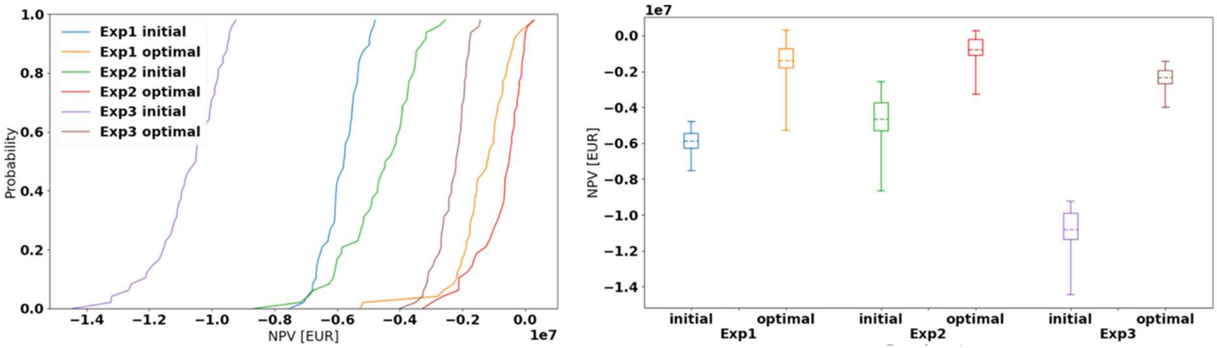

Figure 2: Cumulative density functions (CDFs) of NPV for the initial guess and optimal well locations/trajectories of the three optimization experiments: sub-vertical (exp1), sub-horizontal (exp2) and multi-lateral wells (exp3).

In addition, two Drill & Learn experiments for the sub-vertical well concept have been performed by varying which well is to be drilled first (producer or injector). The analysis of the results revealed also some interesting non-trivial insights into the order in which the wells should be drilled (injector first, then producer) in order to maximize the benefits of the learning from well-logs to further improve the optimized well trajectories.

For more information on this case study, we refer to RESULT-D4.1 and RESULT-D4.2 reports, the latter is available on the project website[2].

2.2 Carbonate setting: Dublin case study

In WP5, the research work addressed the choice of the most suitable well design in the context of carbonate reservoirs in the Dublin area, which are particular in terms of flow properties affecting the productivity of wells. Since this is a new frontier for geothermal developments, there are not many wells and analog projects available in the area. Therefore, the Dublin case study was used to guide and demonstrate the investigation in the context of green field development.

[2] https://www.result-geothermica.eu/home.html

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The Waulsortian and Ballysteen limestone formations have been chosen as target aquifer strata at the study area. A static model was built on the basis of a Petrel project including updated fault location data. The main one is the Howth Fault. It was mapped in Dublin Bay, towards Sandymount, with uncertainty on its continuity under Dublin towards the south-west. It is considered an exploration target. The other two faults are located near the southern border of the area. Figure 3 shows the geological area of interest, with these main mapped faults.

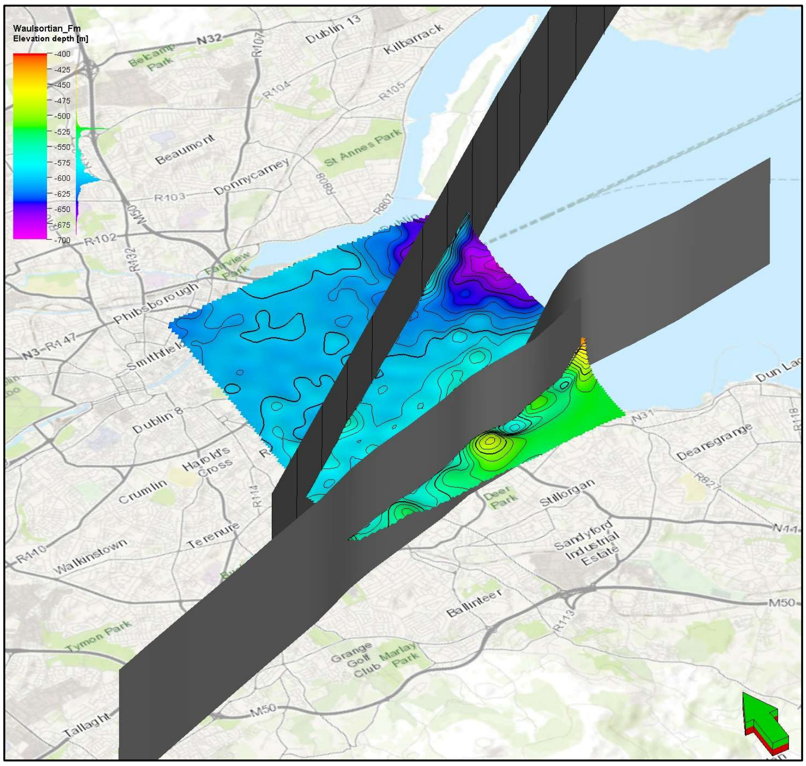

Figure 3: Geological area of interest and subsurface uncertainty assumptions. Main Howth Fault coming in from the North-East.

Based on the current state of subsurface characterization, the width of the Howth fault zone or the fault zone permeability are unknown. However, high flow rates have been encountered in the analog onshore boreholes (near the Dublin port – northeast of the study area), which are likely to be associated with the Howth fault extending down southwest. Dolomitization is pervasive in each borehole, with the intensity of fracturing increasing towards the west. This suggests the presence of a substantial faulting in the area, possibly related to the continuation of the Howth Fault to the southwest. Exact porosity values for the formations are not available. For the model it was decided to rely on porosity values of analogous formations based on literature. When the rocks are not faulted or karstified, a porosity of about 5% and a permeability of about 2 mD is reasonable, although higher permeability values may exist for deeper strata owing to fractures and dilation zones.

Based on the available information about the geological setting at the Dublin location, an ensemble of (dynamic) reservoir flow models was generated to represent the underlying geological uncertainty associated with the characterization of the properties of the target reservoir formation, including uncertainty on the position and properties of high-permeability fault zones. Geostatistical model realizations have been generated using the Petrel project created by TNO. An ensemble of 10 structural realizations of different fault location and width model has been created; each having 10 different static properties (i.e., porosity, NTG and permeability fields) to reflect the inherent geological uncertainties. Figure 4 shows several of model realizations randomly selected from the ensemble of 100 realizations.

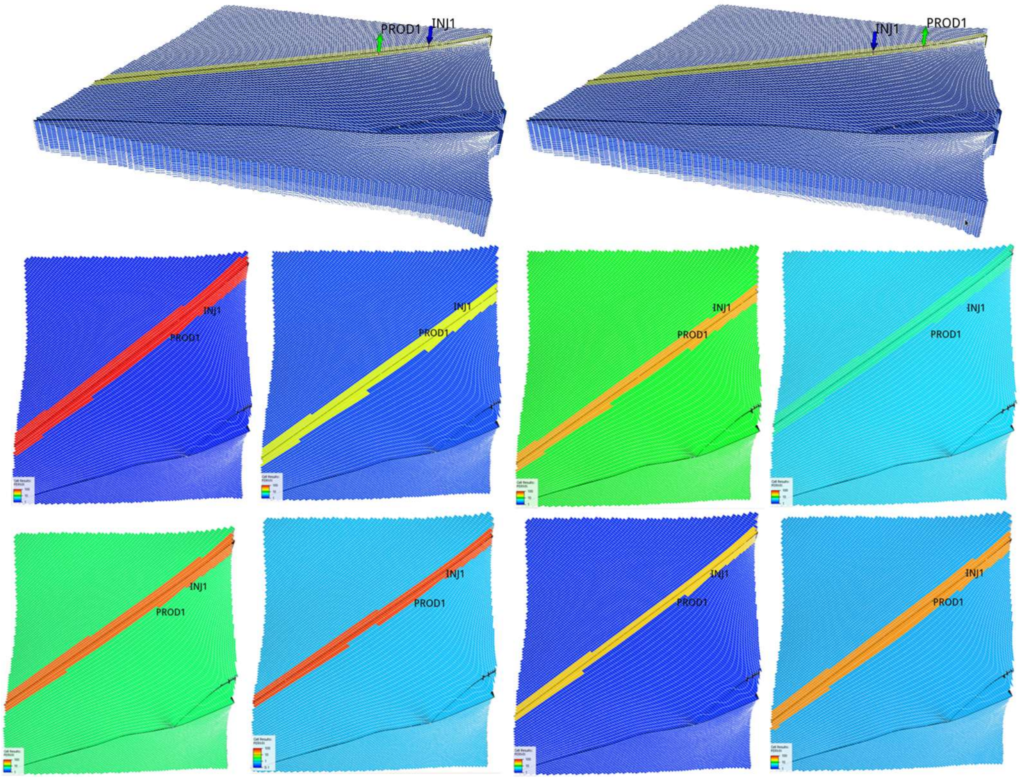

Figure 4: Dublin reservoir model with two different well type configurations (top figure) and different grid structure (fault positions) and permeability fields for eight model realizations (bottom figure).

Optimization experiments were performed to search for the best location and shape of wells in a doublet configuration in terms of techno-economic performance. Two distinct optimization experiments, each considering different initial well placement for the producer and injector along the fault zone: producer at west of injector (exp1) and producer at east of injector (exp2). In both optimization experiments, the optimized solutions resulted in higher NPV than in the respective initial guesses (only well type differed between initial guesses). Experiment 2 resulted in significantly higher NPV on average than Experiment 1. The gain is primarily driven by the noticeable increase in production rates achieved with the optimized well placement (i.e., production rates almost doubled with respect to initial solution), which positively influences the NPV. The relative poor reservoir properties and low formation temperatures leads to a negative business case under considered economic assumptions, indicating low potential for geothermal developments even after optimization (Figure 5). Most room for improvement in optimization seems to be associated with best performing model realizations, with some of them achieving a positive business case. The gains in NPV on average are more modest due to the many poorly performing realizations.

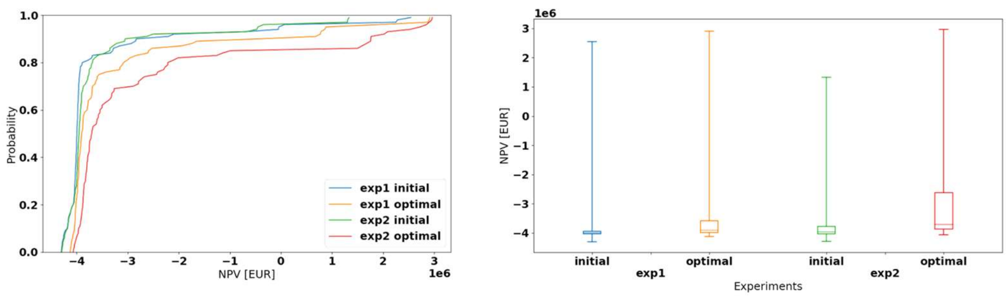

Figure 5: Cumulative density functions (CDFs) of the objective function (NPV) for initial guess and optimal strategies for both experiments in the Dublin case study.

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For more information on this case study, we refer to RESULT-D5.2 report, available on the project website[3].

2.3 Volcanic setting: Elliðaárdalur case study

In WP6, the focus was on exploring the use of data-driven approaches to improve the understanding of the observed behavior of the existing wells in the aquifer of volcanic formation in the Elliðaárdalur site in Iceland (Figure 6), i.e. no new drilling was considered.

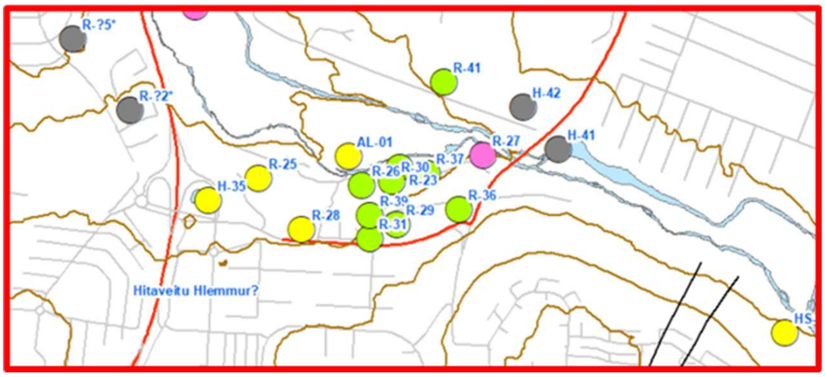

Figure 6: Geographical location of production wells of Elliðaárdalur site in Iceland subject to the performed data analysis studies: overview (top panel) and detailed zoom-in view (bottom panel).

The Elliðaárdalur system comprises three primary aquifer zones. The initial 15 layers characterize the uppermost zone (basalt) with initial temperatures ranging from 40-90°C. Subsequently, the following 30 layers depict the middle zone (hyaloclastite), featuring the highest temperatures. The final 75 layers represent the lower formation (another basalt sequence) with temperatures initially ranging from 70-115°C. A simplified dynamic simulation box model of the area described in RESULT-D6.2 report and illustrated in Figure 7, was constructed to represent three distinct layers corresponding to the static properties of the formation, namely porosity, NTG (net-to-gross ratio), and permeability fields. Pseudo-wells on the edge of the reservoir model have been introduced to model aquifer recharge boundary conditions.

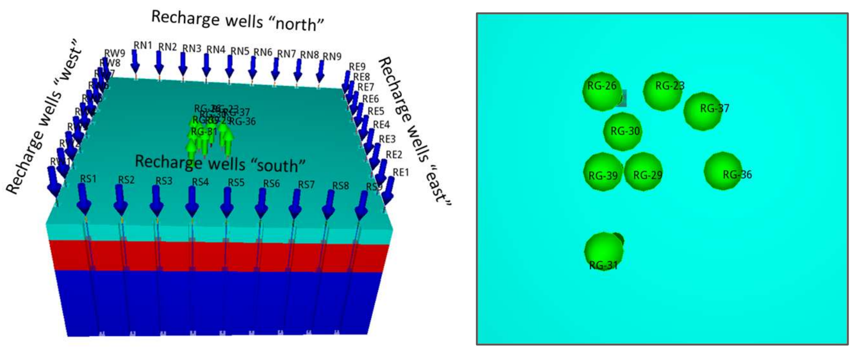

Figure 7: Simplified reservoir flow simulation model constructed for data assimilation study of the Elliðaárdalur site, with 8 production wells and pseudo-wells to mimic the effect of natural recharge of the reservoir.

Ensemble-based data assimilation techniques was applied to calibrate simplified reservoir flow models representing the Elliðaárdalur case based on historical measurement data and, thereby, gain insight on the key variables determining the observed behavior of the production wells. Historical

[3] https://www.result-geothermica.eu/home.html

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observations of production rates, temperatures, and water levels observations for each production well (over the period from 2014-2023) have been considered to calibrate the simplified conceptual reservoir model. Parameters like the rate of recharge of the reservoir from different directions (Figure 8) and initial aquifer pressure have been calibrated, allowing for a better match of historical observations to be achieved (Figure 9).

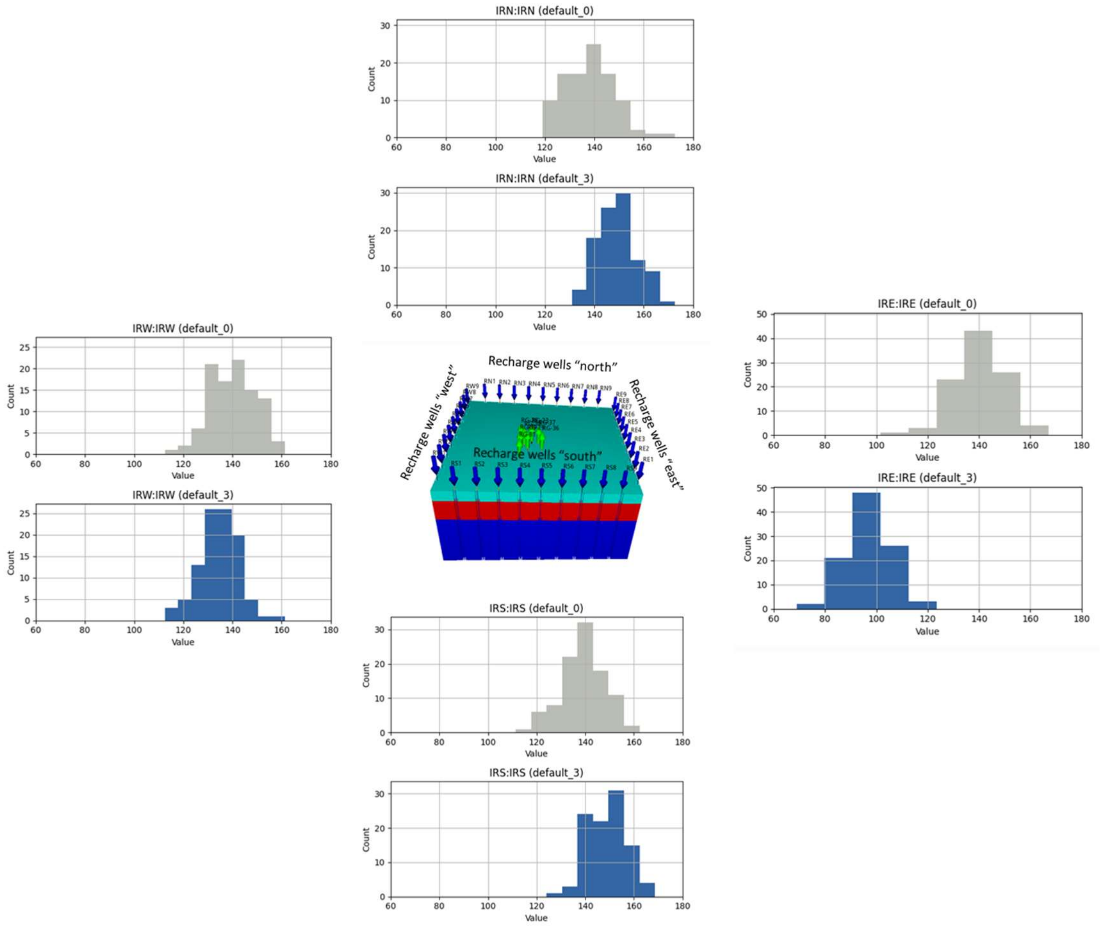

Figure 8: Results of model calibration with ensemble-based data assimilation. 8 figures divided into pairs representing direction of recharge. Each pair shows distribution of well injection rate for single well in a row for initial numerical models (grey) and updated numerical models (blue).

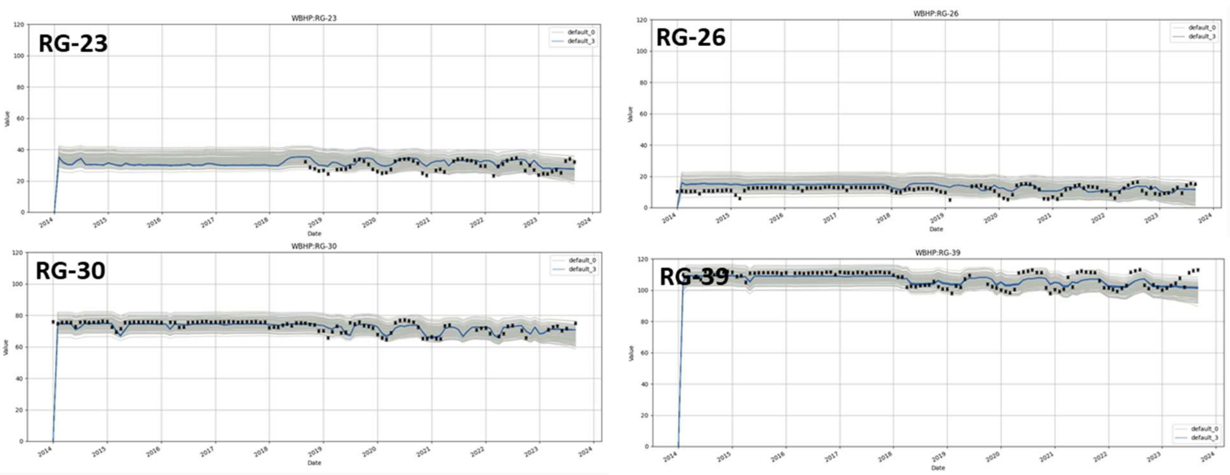

Figure 9: Results of model calibration with ensemble-based data assimilation. Bottom-hole pressure values over time for selected wells from the simplified reservoir model of the Elliðaárdalur site: historical observations (black dots), initial numerical models (grey) and updated numerical models (blue).

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While the computer-assisted data assimilation helped to find models that better match the available data and identify general trends to better understand the reservoir recharge and pressure support in the field, it also revealed that relying on simplified reservoir models might not be sufficient to fully capture and explain the specific behavior of the geothermal energy production from the subsurface reservoirs.

For more information on this case study, we refer to RESULT-D6.2 and RESULT-D6.6 reports, available on the project website[4].

[4] https://www.result-geothermica.eu/home.html

3 Lessons-learned and recommendations

This chapter summarizes the main lessons learned and recommendations collected from the methodological research work performed in the RESULT project.

3.1 Well concept alternatives

Throughout the project, practical experience from drilling in previous geothermal sites has been collected (see RESULT-D2.1 report[5]) to outline the well design options available to boost the productivity and business case of future geothermal projects.

While other well technologies to achieve that do exist (e.g., hydraulic stimulation, advanced completions), the focus in RESULT was on the geometrical design of well trajectories, namely on the comparison of sub-vertical (i.e., slightly deviated, < 60° inclination), sub-horizontal (i.e., up to ~85° inclination) and multi-lateral wells.

A robust well trajectory optimization approach was used to support the selection of the well concept for site-specific cases, by enabling a more meaningfully informed and conclusive comparison of the expected business case of the three well concepts considered based on optimized configurations for each of them.

3.2 Modelling advanced well designs

Screening and comparing the techno-performance of various well designs requires the ability of modelling them realistically, in terms of their geometry, costs and impact on productivity. This can be particularly challenging when considering advanced and innovative well designs, as these require specialized modelling tools for the proper quantitative analysis. During the RESULT project, TNO has worked towards that by developing and combining key components of a modelling framework for advanced well designs. Next, we refer to two of those.

3.2.1 Semi-analytical model for well productivity and injectivity

In order to facilitate a fast performance of advanced well designs, a reliable semi-analytical alternative to rigorous numerical reservoir simulation was put in place to provide the required information for the purposes of techno-economic assessment. The well productivity and injectivity is modelled by a semi-analytical model approach based on the Analytical Element Model (AEM). An existing AEM model available at TNO has been modified for geothermal wells, assuming a mass balance between produced and injected brines. A laterally infinite aquifer of constant thickness and homogeneous (but possibly anisotropic) permeability has been considered. The developed AEM approach has been benchmarked against results obtained with reference analytical solutions (DoubletCalc1D).

The AEM method allows to incorporate an anisotropic permeability field and enforce spatial constraints in flow (e.g., no flow barriers). The AEM can also be extended to incorporate frictional losses in the right hand side based on the solution for q_i. This requires an iterative solution and needs to model the exact well segment pressure. The solution achieved in 3D is based on a single reference well pressure P_p and P_i relative to the ambient pressure, and neglects potential vertical variation in

[5] https://www.result-geothermica.eu/home.html

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pressure in the wellbore compared to the ambient reservoir pressure. This is considered a valid assumption for geothermal reservoirs. The resulting PI and II can be compared to a reference simple well layout (i.e. vertical, without laterals, following cf. DoubletCalc).

The developed semi-analytical model allows to assess the productivity and injectivity performance of more complex well configurations (see Figure 10). For more information, we refer to the RESULT-D2.3 report.

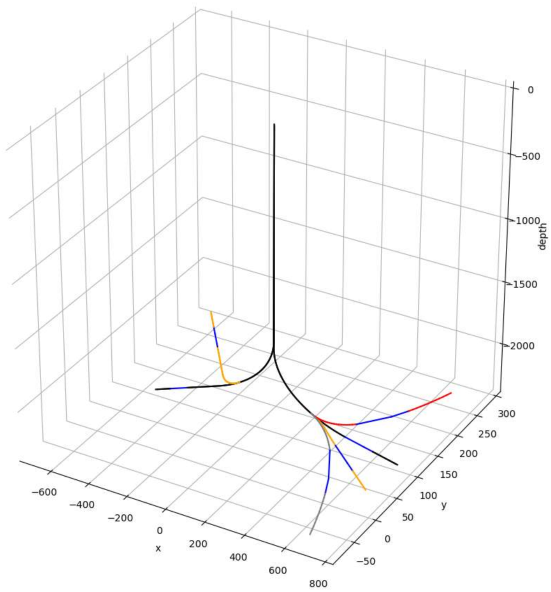

Figure 10: An example of perforated sections in the reservoir (blue) with a AEM segment length of 100 m for a multilateral well design.

3.2.2 Geothermal economic model for business case calculations

A key step towards the assessment of the business case of geothermal projects is to compute their associated net present value (NPV) and levelized cost of energy (LCOE). This requires a coordinated calculation coupled to the flow performance of the geothermal reservoir given a certain well design / doublet configuration, detailed economic parameters encompassing various sources of CAPEX and OPEX costs and a reliable cashflow calculation procedure. In the RESULT project, TNO put together all these ingredients to create a structured and dedicated module for geothermal economic calculations.

The Excel-based techno-economic well cost model and pressure-loss-based NPV model (see RESULT-D2.2 report) were combined into a Python program. Other slightly simplified calculations (harmonized with publicly available tools, such as ThermoGIS) have also been integrated into the same module.

The resulting techno-economic calculation module developed in RESULT includes the following elements depicted in Figure 11. The main inputs are: (i) the production profiles obtained from numerical reservoir simulation model, (ii) deviation files describing the well geometry design, (iii) economic parameters defining costs and revenues of the geothermal development project. The calculations consist essentially of: (a) well cost calculation, (b) along-well pressure drop calculation (incl. related energy consumption) and (c) cashflow calculations.

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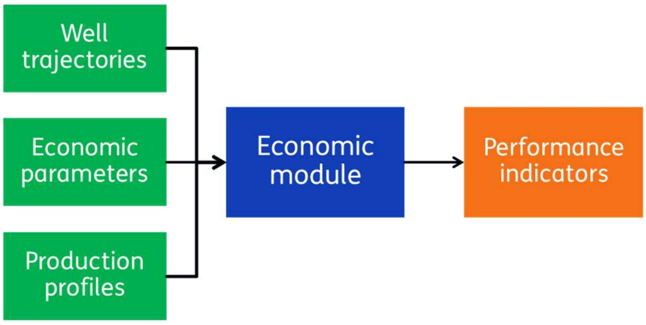

Figure 11: Schematic representation of the geothermal economic calculation module developed in RESULT.

3.3 Well trajectory optimization

Finding an optimal well trajectory, especially for more advanced well concepts (deviated wells, horizontal wells, multi-lateral wells, etc.), is an arduous time-consuming exercise when performed manually due to the large number of degrees of freedom a designer of a well can choose from. The challenge in describing well trajectories mathematically is related to the complexity of their geometry. A high-resolution description is needed to represent well paths with realistic curvature. In order to preserve realism of trajectories while using a minimum number of points to describe them, TNO has proposed a general parametrization which allows to represent various types of well trajectories. This is the well trajectory parametrization approach implemented within the open-source optimization framework EVEREST (https://everest.tools/), co-developed by TNO and Equinor.

The well trajectory parametrization approach relies on the use of a few guide points, which control the overall span of the trajectories, and polynomial interpolation to reconstruct the fine-resolution well path. Following the interpolation, an additional step is performed to ensure curvature constraints for the well trajectories. Once the trajectories honoring the dogleg constraints are generated, the connection of the well with the grid of the numerical reservoir simulation model (called connection factors) for the well trajectories needs to be calculated. The connection factors depend on the flow properties of the intercepted grid blocks (permeability, among others), but also on the geometric correction factor that accounts for the length and position of the segment of the well trajectory inside each individual intercepted grid block. Finally, this information is written in the input format expected by the reservoir simulator. The complete workflow to automatically generate any type (vertical, deviated or horizontal) of well trajectory that honors practical drilling constraints and is exported in a format understandable for the required reservoir simulator is illustrated in Figure 12. Once the reservoir simulation input files are generated, the reservoir simulation can be performed to forecast production profiles for the selected well trajectory configuration. This allows the calculations of the optimization workflow to be based on 3D reservoir simulations for the physical phenomena associated with the geothermal heat production. Objective functions (or performance indicators such as NPV and LCOE) can then be derived from the economic models (described in Section 3.2.2) to guide the optimizer in the search of improved well configurations.

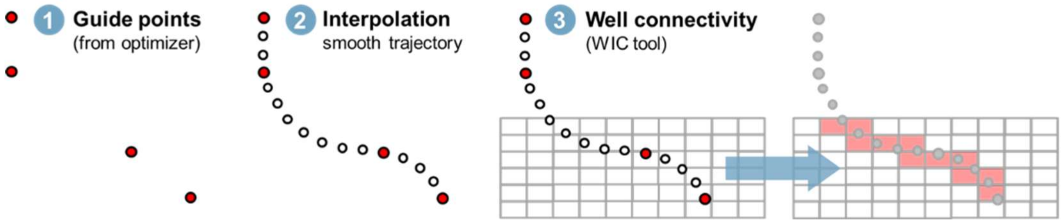

Figure 12: Illustration of the EVEREST well trajectory optimization workflow used in RESULT.

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For more information, we refer to the RESULT-D3.1 report. This is the optimization workflow used as a basis of the computational methodology for well concept selection applied to the Zwolle and Dublin case studies previously described in Sections 2.1 and 2.2.

While the well trajectory optimization workflow based on EVEREST and used in RESULT does include the impact of geological uncertainty on the techno-economic performance through the consideration of an ensemble of geological model scenarios (or realizations), one possible enhancement refers to the quantification of technical risks associated with the execution of various well concepts and design configurations. If such extension is enabled, a more comprehensive evaluation and a more holistic optimization of well design alternatives can be done, by combining the reservoir engineering and well engineering perspectives to derive quantifiable trade-offs between the advantages and disadvantages of advanced well designs.

3.4 Drill & Learn approach

In field development planning, the decision maker will always choose to implement the best development scenario that one can conceive. Because this best scenario is identified through an analysis performed with models (i.e., limited representations of the ground truth), the incorporation of the learning from the actual observed behavior of the real system (i.e., gathered measurements) through model updates acts as a feedback loop. This feedback loop allows the remainder of the development plan to be re-evaluated and revised to ensure that the best possible development scenario is implemented for the subsequent wells to be drilled. The sequential alternation of optimization, implementation and information feedback leads to what is often referred to as closed-loop control (from systems and control theory) and is shown to result in control strategies (i.e., here the development scenarios) that consequently improve the performance of the real system (Figure 13).

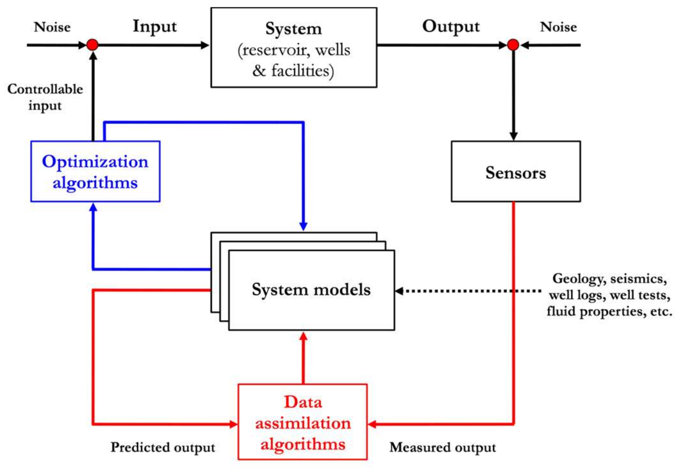

Figure 13: Closed-loop reservoir management as a combination of life-cycle optimization and data assimilation. (extracted from Jansen et al., 2009)

In the implementation of the Drill & Learn workflow within RESULT, the (well trajectory) optimization step is performed with EVEREST, as described in Section 3.3. The data assimilation (or model calibration) step to update the ensemble of models based on permeability well-log observations is performed with the open-source Ensemble Reservoir Tool data assimilation framework (ERT, https://github.com/equinor/ert) which uses state-of-the-art ensemble-based methods such as ES-MDA.

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The Drill & Learn workflow has been tested and validated with a synthetic toy case study in WP3, and applied to the Zwolle demo case study in WP4. For more information, we refer to RESULT-D2.3, RESULT-D3.1, RESULT-D3.2 and RESULT-D4.2 and reports[6].

3.5 Data-driven analysis of reservoir behavior

Computer-assisted data assimilation or history matching uses well log data and/or production data from the drilled wells in order to minimize the mismatch between the observed data and the simulated data from the ensemble of models characterizing the initial (prior) uncertainty. Currently, the state-of-the-art method for ensemble-based history matching is the Ensemble Smoother with Multiple Data Assimilation (ES-MDA) proposed by Emerick and Reynolds (2012). Permeability, porosity and any other model parameter can be handled as the uncertain parameters to be updated, and usually can be represented in a vector $\mathbf{m}_i = (m_1, m_2, \dots, m_n)^T$. An initial ensemble of geological model realizations $\mathbf{M}_{\text{prior}} = [\mathbf{m}_1, \mathbf{m}_2, \dots, \mathbf{m}_N]$ (e.g., generated in Petrel or any other geo-modelling / geostatistical package) or a range (and distribution) of the uncertain parameters need to be provided, along with the selected type of measurements or observations (which can be stored in a vector $\mathbf{d}_{\text{obs}}$) to be gathered and the expected measurement uncertainties (which can be expressed in a covariance matrix $\mathbf{C}_{\text{d}}$). The ES-MDA method is capable then to produce an updated (posterior) ensemble of model realizations according to a modified version of the ensemble Kalman filter update: $\mathbf{M}_{\text{post}} = \mathbf{M}_{\text{prior}} + \mathbf{M}'_{\text{prior}}\, \mathbf{Y}'[(\mathbf{Y}'\mathbf{Y}') + \alpha \mathbf{C}_{\text{d}}]^{-1}[\mathbf{D} + \mathbf{Y}]$.

In this study, we employ the open-source Ensemble-based Reservoir Tool (ERT) framework developed by Equinor (https://github.com/equinor/ert), which supports already state-of-the-art methods like ES-MDA. The same framework has been used to establish the Drill & Learn approach, as reported in Section 3.4.

Ensemble-based data assimilation has been used as one of the key elements of the Drill & Learn workflow applied to the Zwolle demo case study in WP4, and as the main model calibration engine for the Elliðaárdalur site in WP6. For more information, we refer to RESULT-D2.3, RESULT-D3.1, RESULT-D3.2 and RESULT-D4.2 and reports[6].

3.6 Open-source techno-economic models

As a final effort to increase the impact of the research work conducted in RESULT, TNO has prepared and released two open-source Python modules to allow geothermal practitioners to benefit from the specialized techno-economic assessment models described in Sections 3.2.1 and 3.2.2.

The prototype codes developed during the activities of the project have been further polished, tested and documented to make it publicly accessible and re-usable by any interested expert in the geothermal domain. The open-source modules have been disseminated in a public workshop, with a demonstration and walkthrough some tutorial examples to illustrate their practical usage.

The software is available at:

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

Or via the GEOTHERMICA website[6].

[6] https://www.result-geothermica.eu/home.html

References

Hakkeling, S., van der Meer, K., and van Og, G. (2021). RESULT-D2.2: Advanced well concepts.

Barros, E.G.D., Szklarz, S.P., and van Wees, J.D.A.M. (2021). RESULT-D2.3: Drill & Learn Approaches.

Barros, E.G.D., Szklarz, S.P., Khoshnevis Gargar, N., and van Wees, J.D.A.M. (2021). RESULT-D3.1: Optimization Model Framework.

Bruijnen, P. and Leewis, M. (2022). RESULT-D4.1: 3D Reservoir Characterization Model for Zwolle.

Barros, E.G.D., Szklarz, S.P., Khoshnevis Gargar, N., and van Wees, J.D.A.M. (2025). RESULT-D4.2: Optimized well and completion design for demo site (in Zwolle).

Jansen, J.D., Douma, S.G., Brouwer, D.R., Van den Hof, P.M.J., Bosgra, O.H. and Heemink, A.W. (2009). Closed-loop reservoir management. Paper SPE 119098 presented at SPE Reservoir Simulation Symposium, The Woodlands, Texas, USA, 2-4 February. https://doi.org/10.2118/119098-MS

Khoshnevis Gargar, N., Szklarz, S.P., Veldkamp, H., Barros, E.G.D., and van Wees, J.D.A.M. (2023). RESULT-D5.2: Optimized well concept for Dublin area.

Tómasdóttir, S., Friðriksson, Þ., Kristjánsson, B. R., Tulinius, H., Marteinsson, K., Einarsdóttir, Í. E., Kristinsson, T., Þorgeirsson, Þ. A. and Sigurðardóttir, S. S. (2022). RESULT-D6.2: Characterization of the changes in the reservoir in the Elliðaárdalur field.

Khoshnevis Gargar, N., Szklarz, S.P., Barros, E.G.D., Shoeibi Omrani, P., Gil, A.M., van Wees, J.D.A.M., Tómasdóttir, S., Kristjánsson, B.R., Helgadóttir, H.M. (2024). RESULT-D6.6: Analysis of reservoir and production behavior of the Elliðaárdalur field case with data-driven approaches.

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