Digital Twin of Geothermal Assets Assisting the Production and Operational Decisions

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Abstract

Efficient production and operation of geothermal systems, aimed at minimizing total costs, emissions, and environmental footprints, are crucial for the global adoption of geothermal energy. Operational challenges like scaling, corrosion, and equipment degradation significantly impact operational expenditures (OPEX). Mitigation measures often negatively affect the environmental footprint. Therefore, proactive monitoring and mitigation considering multiple objectives are vital for sustainable geothermal asset performance. Digital twin technology, proven in industries like chemical, manufacturing and petroleum, offers a solution for optimizing operations and reducing emissions. This paper demonstrates the development and application of digital twin technologies for real-time monitoring, performance optimization, and multi-objective process control in geothermal systems. The developed framework deploys open-source tools to create an open-source digital twin framework for the sector. The proposed architecture, real-time data integration, and functionalities such as process monitoring, event detection, forecasting, and optimization are further discussed in this publication.

Keywords: digital twin, operation optimization, predictive maintenance, real-time production optimization, geothermal assets.

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Introduction

Low and mid-enthalpy geothermal energy has great potential to contribute to the heat transition and to make the heating of horticulture sector and built environment free from natural gas [1]. Typical geothermal system configuration is a geothermal doublet comprising components such as electrical submersible pump (ESP), casing, filters, and heat exchangers [2]. Various sensors monitor these components to track geothermal performance. Efficient production and operation of geothermal systems are essential to minimize total costs, emissions, and environmental footprints, thereby enhancing the global adoption of sustainable heat and power. Challenges like scaling, corrosion, and ESP failures significantly impact Operational Expenditure (OPEX) [3]. Some mitigation measures can negatively affect the environmental footprint, underscoring the importance of proactive monitoring and balancing multiple operational and environmental objectives for sustainable performance. While most processes are sensor-monitored, critical processes often lack continuous oversight, making real-time data analysis challenging for operators. Continuous monitoring of critical processes and sustainability parameters, like real-time CO_2 emissions, would enable better real-time decision-making.

A digital twin framework involves creating a virtual representation that mirrors the physical infrastructure. The key difference between digital twin and computer simulation is the automated bi-directional data exchange between the physical asset and digital asset [4] which enables real-time insights and interaction between the two assets. Digital twin technology, proven in industries such as petroleum [5], optimizes operations and minimizes emissions. However, geothermal applications of digital twins are limited, mainly focusing on drilling processes [6] or subsurface and reservoir management [7]. To support the operation of geothermal assets, digital twin technology can provide real-time insights into the plant performance and critical processes which adversely impact the performance of the plant. The geothermal sector is a growing sector with a steep learning curve to optimize the operation of the geothermal assets. By providing an accessible and open-source platform for collaboration, such an open-source digital twin accelerates innovation and reduces costs in geothermal energy projects. In this paper, we aim to develop open-source digital twin technologies for proactive monitoring and optimization of geothermal production and operation. Monitoring assists daily operations by interpreting performance issues, like filter clogging or skin formation near wells, enabling timely maintenance and reducing operational costs and emissions. In the next section, a proposed architecture for the digital twin is demonstrated and explained. The data management and model integration are briefly described followed by some examples on the status of the digital twin framework. In the final section of the paper, the added value of the open-source digital twin technology is discussed.

PROPOSED ARCHITECTURE FOR THE DIGITAL TWIN

The proposed architecture for the digital twin is shown in

Figure *1*. This framework consists of multiple layers and components that interact seamlessly to provide real-time monitoring, simulation, and optimization. The architecture is designed to be flexible, scalable, and efficient, leveraging modern technologies such as containerization, web servers, and workflow management tools. The building blocks of the architecture are further described below.

1) Data Layer;

- Data Storage: The data layer connects to various types of databases for structured and unstructured data, such as MySQL for relational data, MongoDB for non-relational databases and InfluxDB for time-series data. This layer is designed to be extensible, allowing integration with additional databases and data platforms in the future (such as OSDU [8]).
- Data Ingestion/Collection: Application Programming Interface (API)s facilitate communication between different databases and the computational backend, ensuring seamless data flow and synchronization.

2) Backend;

- Computational Platform: The backend includes computational engines like Python, C/C++, and MATLAB, which are used for simulations and data analysis. This layer can also integrate with other simulators to enhance the framework's capabilities.
- Web Server: Flask serves as the web server, providing a lightweight and

flexible environment for web application development. It handles requests and routes them to the appropriate backend processes.

3) Frontend;
   - Web Interface: The frontend uses HTML, CSS, JavaScript, and Bootstrap to create an interactive and user-friendly interface. This layer ensures that users can access and interact with the digital twin models and applications easily.
   - Authentication: Secure access to the web interface is managed through authentication mechanisms, ensuring that only authorized users can interact with the system.
   - Grafana: it is a platform for visualization of time-series data for monitoring.

4) Workflow Manager;
   - Celery: In the proposed architecture, Celery is used for real-time workflow management, handling asynchronous tasks, and scheduling periodic jobs. This ensures that the system can process real-time data and execute simulations without delays.
   - Task Queue: Celery uses a task queue to manage and distribute tasks efficiently across available resources, ensuring optimal performance.

5) APIs;
   - Communication: APIs are the glue that connects all components of the architecture. They enable data exchange between the data layer, backend, and frontend, and ensure that different parts of the system can communicate and function together.
   - Extensibility: The use of APIs makes the system extensible, allowing for easy integration of new components and services as the framework evolves.

Plugin: Digital twin architecture works isolated from company's IT infrastructure. The connection is only between databases during data collection process (stream/batch) via APIs.

6) Containerization;
   - Docker: The entire architecture is containerized using Docker, which encapsulates each component in its own container. This approach provides consistency across different

environments, simplifies deployment, and enhances scalability.
- Orchestration: Docker Compose or Kubernetes can be used to orchestrate and manage the containers, ensuring that all components work together harmoniously.

The proposed digital twin architecture is organized into four layers, including configuration, analytical, integration and visualization layers. Within the analytical layer the steps are organized into three process steps: pre-processing, calculation, and post-processing. In the pre-processing step, modules ensure that raw data from sensors is clean and consistent by performing tasks such as data imputation for missing data, averaging, interpolation, and spike detection. In the calculation step, modules which contain models for different geothermal plant equipment (such as pumps, filters, and heat exchangers) or processes ongoing in the geothermal production (such as corrosion, scaling, and erosion), provide additional information to the operator, including:

- Inflow Performance Relationship (IPR) for monitoring well inflow, injectivity back to the reservoir, and potential formation damage due to scaling.
- Vertical Lift Performance (VLP) to monitor resistance and friction in the production and injection casing.
- Pump and ESP performance module to monitor pump head, performance, and power consumption in real-time, and detect anomalous pump behavior.
- Pressure drops and flow calculations in the surface facilities, including heat exchangers, separators, and filters.
- Fluid tracking along the geothermal facilities and auxiliaries' equipment such as combined heat and power (CHP), heat pump and boilers.
- Well casing and pipeline integrity module to assess integrity issues such as corrosion and erosion in the pipeline and casing.
- Flow-chemistry scaling module to estimate scaling and corrosion types and potential in various system locations.

In the post-processing step, modules provide Key Performance Indicators (KPIs) that directly display results to the operator. These include a model and measurement error module, an operating window alarm module, and a system overview module, which offer indicators for operational excellence, safety, and sustainability (emissions).

DATA MANAGEMENT AND MODEL INTEGRATION

Geothermal asset consists of several components connected from production reservoir to injection reservoir via topside facilities for heat exchange with heating grids. JSON file is used to describe each component information and asset configuration. This format is chosen because its simplicity and readability.

The component’s properties include:

- identifier or id
- type
- parameters
- tagnames
- connections

These properties are used by the modules and applications as inputs. Below is an example of the data structure for an ESP:

```
"type": "Pump",
"id": "XXXX",
"name": "esp_123",
"parameters": {
    "esp_depth": 500,
    "esp_head_coeff": "1.1e2;2.3e-1;5.4e1",
    "esp_max_flow": 150,
    "esp_bep_flow": 100,
    "esp_min_flow": 60,
    "esp_no_stage": 12,
    "esp_power_coeff": "0.8e1;1.5e-2;4.3e-1",
    "esp_tubing": 0.254,
    "esp_type": "REDA D1150N 400 Series",
},
"tagnames": {
    "calculated": {
        "esp_efficiency": “<tagname_value>“,
        "esp_head": “<tagname_value>“,
        "esp_power": “<tagname_value>“},
    "measured": {
        "esp_voltage": “<tagname_value>“,
        "esp_current": “<tagname_value>“,
        "esp_flow": “<tagname_value>“,
        "esp_frequency": “<tagname_value>“,
        "esp_inlet_pressure": “<tagname_value>“,
        "esp_inlet_temperature": “<tagname_value>“,
        "esp_motor_temperature": “<tagname_value>“,
        "esp_outlet_pressure": “<tagname_value>“,
        "esp_outlet_temperature": “<tagname_value>“,
        "esp_vibration_x": “<tagname_value>“,
        "esp_vibration_y": “<tagname_value>“,
},
“connections”: {
    "source": {
            "id": "<component_ID>",
            "type": "well" },
    "target": {
            "id": "<component_ID>",
            "type": "filter" }
}
```

Parameters field consists of information needed to perform calculation by the modules. Tagnames field gives a reference to the database which data value needs to be taken for the input or output of the module.

Sometimes the module also needs information from previous or subsequent component, thus this relation is described in connections field. Each component's properties in the geothermal asset are stored in the project folder of MongoDB.

Real-time data stream from sensors are collected from production database to internal database via API. InfluxDB is chosen to store timeseries data because its query performance, write throughput, and storage compression. The data is divided into 3 categories: measured, filtered, a calculated with format described below.

Timestamps: 2024-01-01 00:00:00

Field key: <plant>_<asset_id>_<tagname>_<unit>

Field value: XXX

CURRENT STATUS

This section provides an overview of the status of the digital twin, including the configuration of assets and the real-time monitoring capabilities via a Grafana dashboard.

- Configuration of Assets: This includes a detailed diagram of all components in the geothermal facilities, wells, and reservoirs. Each asset is linked to a real-time data source and key parameters for real time monitoring and specific applications.
- Real-time monitoring dashboard: The connection with Grafana dashboard provides continuous insight into the performance of geothermal assets, by tracking key metrics. Figure 2 showcases real-time data visualization for the injection well component.
- Applications: several applications are developed to monitor assets based on functionalities listed in Section 0. This application is used by the user for tuning the model, forecasting, offline simulation, etc. For example, production well monitoring application to help user finding optimal operating points of the operation or performance degradation.

The process data is calculated by modules framework every X minute defined by the user. Currently the digital twin is deployed, tested, and running in Cloud. The way that the model are integrated can be seen in Figure 3. The real-time data (RT) and configuration parameters hosted on configuration database will be connected to component models, e.g. filters, heat exchangers, pump, wells, and other equipment. Within each equipment, the different processes which are of interest for monitoring can be coupled, such as corrosion, erosion, and scaling. The models will make use of real-time data to perform the calculations or estimation on the status of each component. The output of each component will be connected to the next components to continue the calculations. The parameters which are set to be transferred from one components to the other ones are pressure (P), temperature (T), flow rate (q) and composition (x). Depending on the component model and requirement of connected components, some of these variables might not be needed to be transferred and it can be disabled. A solver will be required to combine all the components and process together and solve for the entire system in order to provide insights on the status of the plant.

EXAMPLE

To demonstrate the connected workflow in the digital twin framework an example is provided. The case study is about monitoring the performance of an electrical submersible pump (ESP) in a geothermal plant for direct use application. Real-time monitoring of ESP head (difference between intake and discharge pressure of the pump) and comparing it with theoretical head of the pump can provide valuable insights about the performance and degradation of the equipment. For this purpose, a simplified nodal analysis model was made to link pressure and flow rate over the ESP. This model was included in the backend of the digital twin framework. The ESP model utilized real-time data of the flow rate and intake pressure of the ESP to calculate the pump head using theoretical ESP curve. This calculation was performed in real-time and was compared with the measured head of the ESP. This comparison is shown in Figure 4. It can be seen that the initiation of the degradation of ESP is visible from approximately three months prior to the failure of the pump (occurred in January 2021). This degradation was observed due to mismatch between the ESP theoretical head and measured head, and it was visualized in an easy-to-understand manner.

OPEN-SOURCE

Open-source digital twin technology offers substantial benefits for the geothermal industry by improving efficiency, flexibility, and safety in the design and operation phase through transparent and collaborative tool development. By leveraging open-source models, the development of digital twin tools becomes more efficient, fostering a growing market. This transparency ensures that workflows are trustworthy and reviewed by the entire community, promoting sector-wide learning and innovation.

Additionally, open-source digital twins provide efficient and uniform data for regulators, stakeholders, and benchmarking purposes, facilitating collective learning and accurate monitoring of system performance and emissions. This uniformity is achieved through a common set of public models used for calculating key parameters, which supports reliable and standardized data handling. By accelerating sector learning and fostering an environment of transparency and collaboration, open-source digital twin technology not only enhances operational performance but also drives the geothermal industry towards more sustainable and optimized practices.

Summary

This paper presents a proposed architecture for creating an open-source digital twin tailored to the geothermal sector, leveraging the strengths of open-source tools. The architecture is designed with modular building blocks, each explained in detail, to provide a comprehensive understanding of how these components integrate to form an interconnected digital twin system. The discussion highlights the critical added value that open-source solutions bring to the geothermal industry, emphasizing enhanced collaboration, cost-effectiveness, and innovation. By adopting open-source tools, the geothermal sector can benefit from increased transparency, improved data sharing, and accelerated technological advancements, ultimately driving more efficient and sustainable energy solutions.

References

[1] IEA (2021), Geothermal Power, IEA, Paris https://www.iea.org/reports/geothermal-power

[2] Wasch, L., Creusen, R., Eichinger, F., Goldberg, T., Kjoller, C., Regenspurg, S., . . . van Pul-Verboom, V. (2019). Improving Geothermal System Performance Through Collective Knowledge Building and

Technology Development. European Geothermal Congress.

[3] Octaviano, R., Dussi, S., de Zwart, H., Shoeibi Omrani, P., van Pul-Verboom, V., Elewaut, K., & van Schravendijk, B. (2022). Model-based monitoring of geothermal assets. WarmingUP program final report.

[4] Zhanga, Haiwen; Maa, Lin; Sun, Jiao; Lin, Hansheng; Thürerb, Matthias (2019). Digital Twin in Services and Industrial Product Service Systems: Review and Analysis. Procedia CIRP. 83: 57–60. doi:10.1016/j.procir.2019.02.131. ISSN 2212-8271.

[5] Thambynayagam, M. (2019). Guest Editorial: Digital Transformation: Quest for Operational Efficiency. J Pet Technol 71, 14–15. doi: https://doi.org/10.2118/0719-0014-JPT

[6] Osinde, N., Byiryngiro, J., Gichane, M., & Smajic, H. (2019). Process modelling of geothermal drilling system using digital twin for real time montoring and control. Designs, 3(45).

[7] Voskov, D., Abels, H., Barnhoorn, A., Chen, Y., Daniilidis, A., Bruhn, D., Drijkoningen, G., Geiger, S., Laumann, S., Song, G., Vardon, P. J., Vargas Meleza, L., Verschuur, E., & Vondrak, A. (2024). A research and production geothermal project on the TU Delft campus: Initial modeling and establishment of a digital twin. In Proceedings of the 49th Workshop on Geothermal Reservoir Engineering (SGP-TR-227). Stanford University, Stanford, California, February 12-14, 2024.

[8] The Open Group OSDU Forum. (2024). Open Subsurface Data Universe (OSDU) Data Platform. https://osduforum.org/

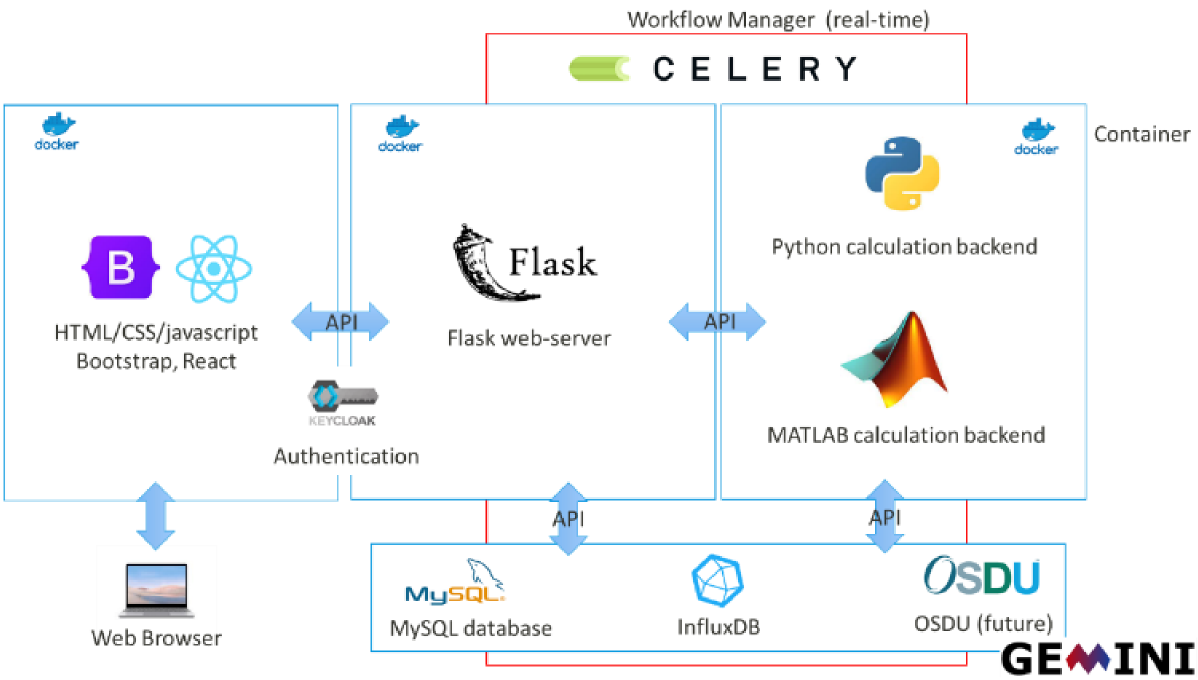

Figure 1. Proposed architecture for the open-source digital twin framework of geothermal assets

Figure 2. A snapshot of a Grafana dashboard for real-time monitoring of an asset, here is an injection well data (including wellhead pressure, temperature, flow rate and calculated bottomhole pressure and injectivity index).

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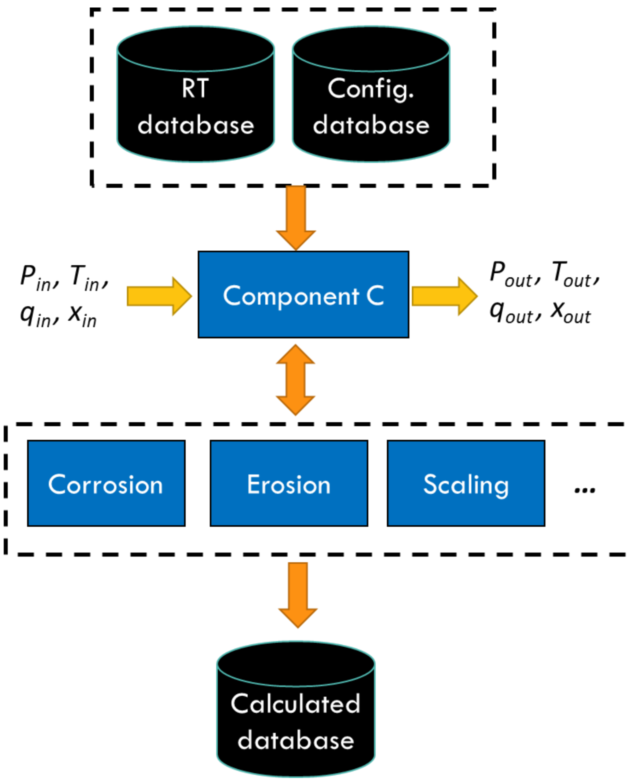

Figure 3. Example of models' connection with databases on the component and process levels

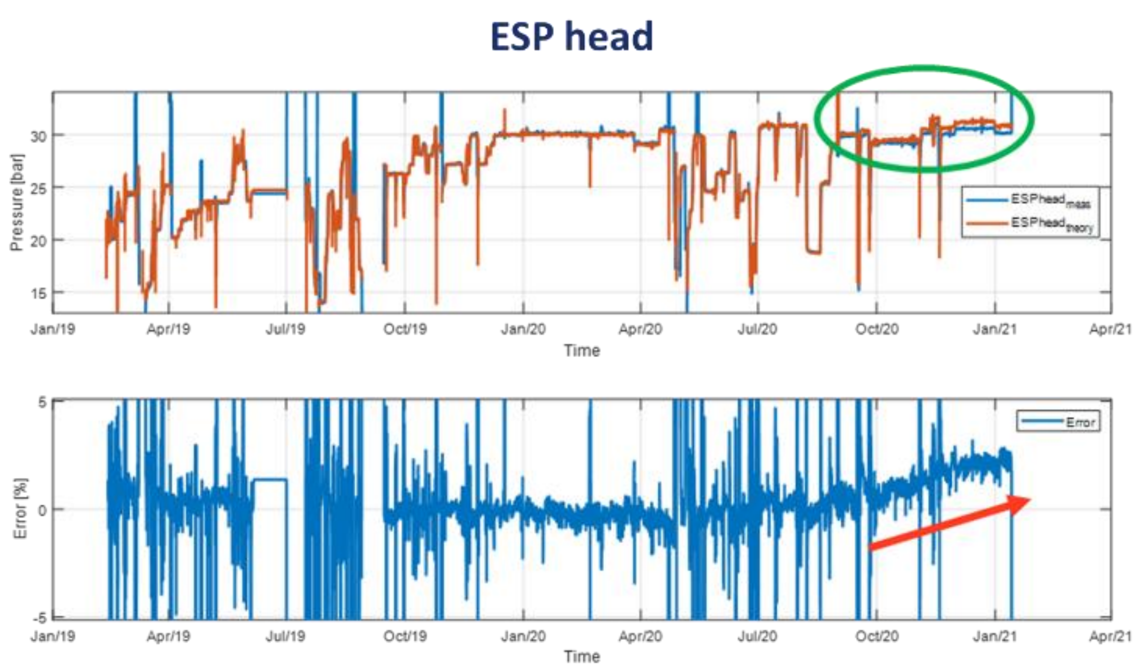

Figure 4.

Monitoring of ESP head based on measured head and theoretical head.

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