Guideline about digital twin services with experiences

Deliverable 8.4
Digital twin for large-scale HPs and refrigeration systems

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Introduction

Heat pump and refrigeration systems support the decarbonization of the global energy system by promoting electrification and sector coupling. However, a deeper understanding of their dynamic operating conditions and interactions among their components is needed to fully exploit their potential, while enhancing their efficiency and cost-effectiveness.

In this respect, the **"Digital Twin" project** aimed to leverage the potential of data analysis and digital technologies to develop adaptable, modular, and reusable digital tools that enhance heat pump and supermarket refrigeration businesses by offering:

- advanced monitoring capabilities;
- efficient fault detection and diagnosis;
- optimized operational performance.

Within this framework, **digital twins** have emerged as a promising technology, capable of transforming data into insightful information that supports business decision-making and improves operational performance, improving efficiency and reducing costs.

Digital twin technology

Digital twins are digital counterparts of physical systems that can represent their behaviors in detail, thus serving as simulation platform for product design, surveillance, system integration, and operational optimization. Moreover, the integration of digital twins with real-time data and advanced analytics allows to provide operational insights to support decision-making at every stage of the lifecycle of a system and its components, from the design to the deployment and operation.

Overview of services enabled by digital twins

Digital twin-based services for heat pumps and supermarket refrigeration can include:

Real-time monitoring and analysis: continuous collection and analysis of data from temperature sensors, energy meters, and control systems. This enables the identification of potential inefficiencies, such as anomalous consumption patterns, and offers the possibility to implement corrective measures, thus enhancing the overall system performance.

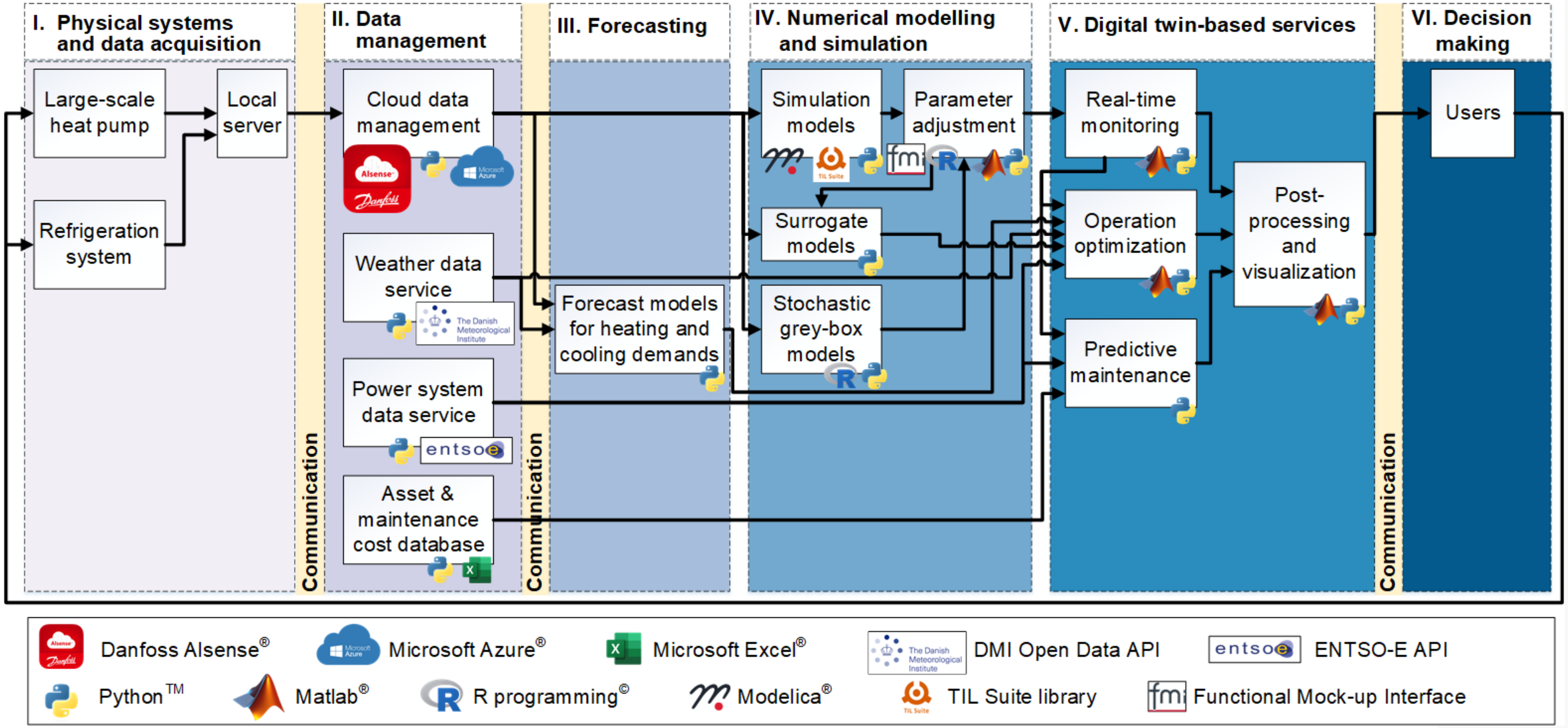
Operational optimization: use of simulations and scenario testing to adjust the operational parameters and scheduling of a system to enhance its energy performance and cost-effectiveness. The operational schedule of a system and parameters such as controller set points can be recursively adjusted over time. This can result from changes on the boundary conditions of a system and/or the degradation of its performance. Such recursive adjustment can prove beneficial for enhancing the energy efficiency of the system and reducing time-dependent performance degradation due to component aging or faults.

Predictive maintenance: digital twins can assist fault detection and diagnosis by integrating real-time monitoring with simulation and predictive analysis. This allows to detect and diagnose fault mechanisms before or at an early stage of their occurrence, reduce unexpected failures and equipment downtime and extend the overall lifetime of systems and components.

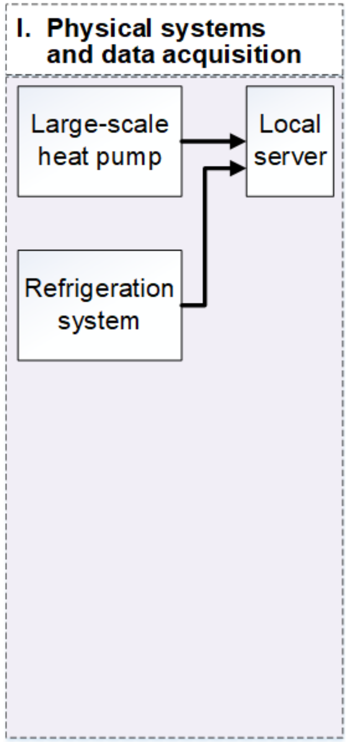
Development and implementation

Developing a digital twin requires a comprehensive framework that encompasses various components and stages. Here is a summary of the key elements involved based on the experience gained through the project.

Digital twin framework



Development and implementation



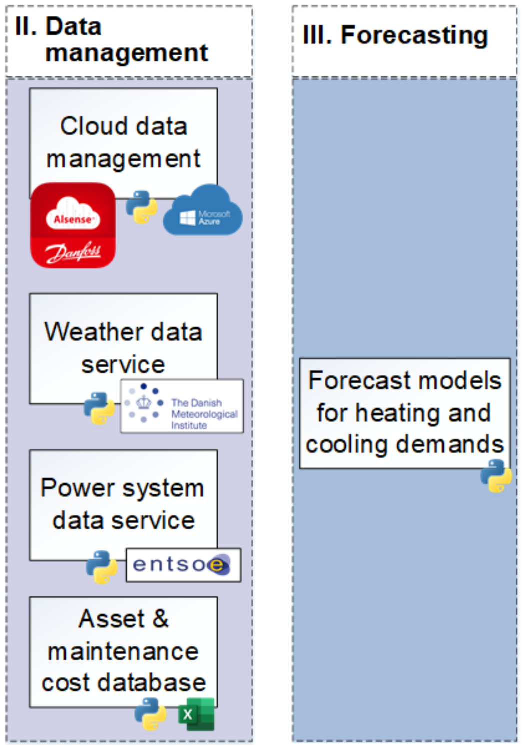
I. Physical systems and data acquisition

The first step is to determine the relevant data sources, such as sensors, IoT devices, databases, and other systems, that will provide the necessary inputs for the digital twin, as well as for monitoring the actual performance of the system. Data availability is often one of the main barriers to the development of digital twins. In addition to operational data, technical datasheets, P&I diagrams, and control settings are other necessary inputs for the development of digital twin frameworks.

The project showed that the retrieval of these inputs can be done in an straightforward manner for industrial facilities, particularly where off-the-shelf heat pumps are used. For commercial facilities such as supermarkets, the acquisition of the input data can be more complicated due to the extensive number of component suppliers and the lack of standardization on the collection of data.

After the relevant input data have been identified, it is required the implementation of secure and reliable mechanisms for data collection, communication, and storage. This may involve setting up secure communication protocols, data encryption, and fault-tolerant data pipelines.

Development and implementation



II. Data management

The second step is the development of a centralized data infrastructure or a cloud-based data system to store and manage the collected data from various sources. These can also include external data providers like weather and power system data services.

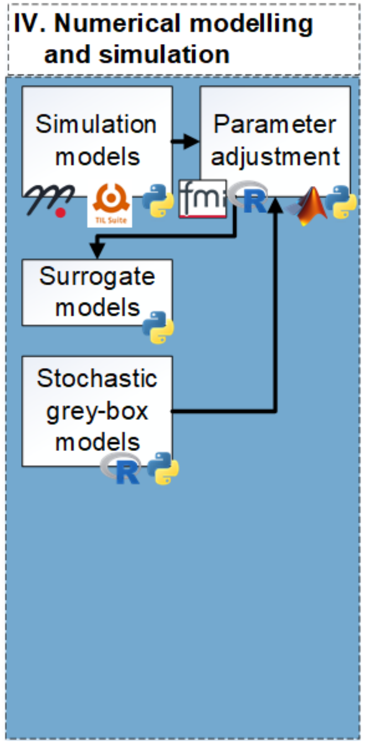
This step also involves:

- Implementing appropriate security measures to protect sensitive data and ensure compliance with relevant regulations and industry standards, such as data encryption and access controls.
- Applying data pre-processing and cleaning techniques to ensure data quality and consistency. This may involve handling missing data, removing outliers, and performing data normalization or transformation as needed.

III. Forecasting

Forecasting models can be used for operation and control optimization strategies like model predictive control (MPC) or operation scheduling. In the project, forecasted heating and cooling demands in the large-scale heat pump system from Case II enabled the optimization of its operation schedule.

Development and implementation

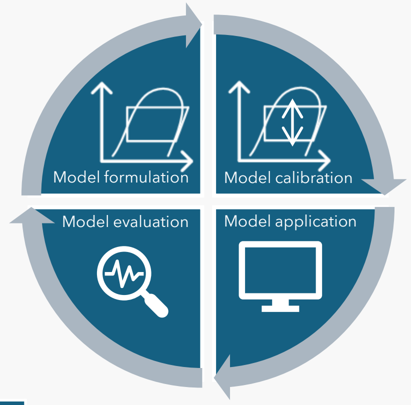


IV. Numerical modelling and simulation

The fourth step is the implementation of the numerical models that can accurately represent the behavior of the physical assets, processes, or systems under various operational conditions and scenarios. This involves incorporating physically-derived and/or data-driven numerical representations, along with design parameters and control characteristics.

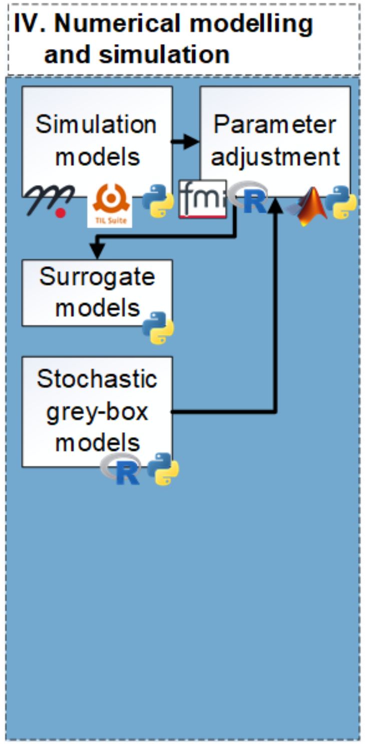
Depending on the scope of use of the digital twin, different modelling approaches can be chosen, as seen in the following table:

Simulation model type	Quasi-steady-state (e.g. Python, EES, Matlab)	Dynamic (e.g. Modelica, Matlab)
Design	▪ Dimensioning of system/component characteristics (e.g. Sizing of heat exchangers, compressors) ▪ Performance benchmark under design operational conditions	▪ Calculation of control parameters ▪ Dimensioning of system/component design characteristics related to dynamics (e.g. volumes of vessels, refrigerant charge estimations)
Operation	▪ Operation monitoring of extended periods of operation ▪ Real-time performance monitoring ▪ Model predictive control, operation scheduling and maintenance scheduling ▪ Control optimization (eg. set points) ▪ Detection and diagnosis of faults related to slow dynamics (e.g. fouling, refrigerant leakage)	▪ Operation monitoring under fast dynamic conditions (e.g. start-up, shut-down, provision of ancillary services) ▪ Detection and diagnosis of faults related to fast dynamics (e.g. compressor failure, unstable secondary streams) ▪ Control optimization (eg. set points)



General modelling procedure

Development and implementation



IV. Numerical modelling and simulation

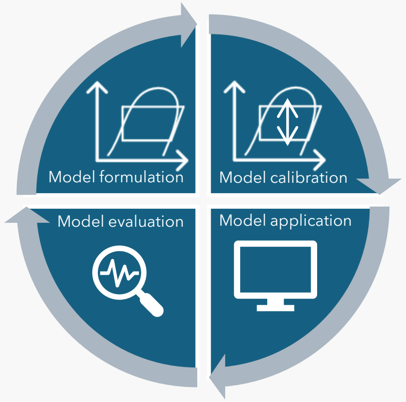
Different models were used during the project, which are briefly described as follows:

Dynamic models were developed in Modelica using TIL Suite, a software package developed by TLK-Thermo which contains a wide range of thermodynamic systems and components. These models are based on mass, momentum, and energy balances, along with empirical representations of heat transfer and pressure drop phenomena. Dynamic models enabled the representation of detailed phenomena with highly transient behavior such as rapid changes on the thermal heat demands.

Quasi-steady-state model, developed in Python, enabled to represent the operation of a large-scale heat pump in real-time and over extended periods of time due to their lower computational requirements compared to the dynamic models. Like their dynamic counterparts, quasi-steady-state models applied energy and mass balances, along with design parameters of the system.

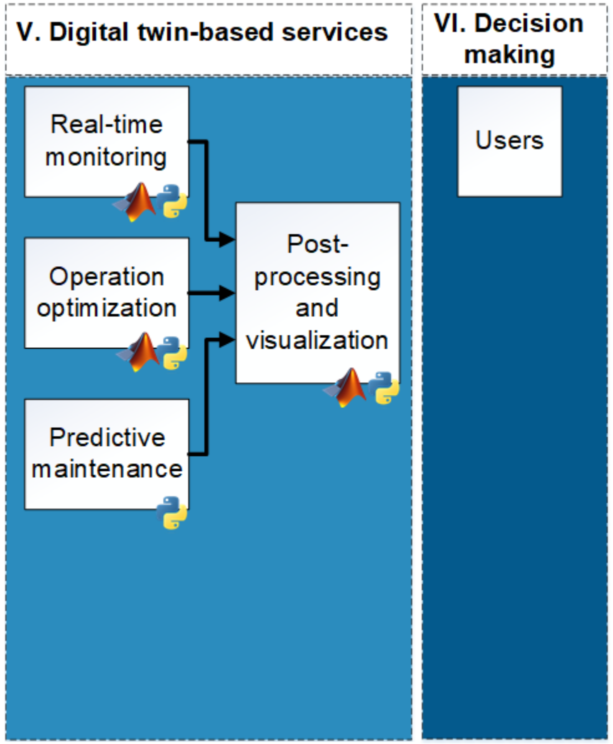
Surrogate model, based on a polynomial regression, was derived from the quasi-steady-state model. The surrogate model offered lower computational requirements than the quasi-steady-state model and was implemented for set point optimization.

Stochastic grey-box models were used to model the display cabinets of supermarkets. These models integrate both physical understanding and statistical methods and estimate the unknown parameters of a defined model structure (derived from prior physical knowledge) from data using statistical parameter estimation techniques.



General modelling procedure

Development and implementation



V. Digital twin-based services & VI. Decision making

Once the digital twin is in place, it is possible to use it for several purposes (services):

- simulated operation of the system
- scenario analysis
- development of algorithms for operation optimization, fault detection and predictive maintenance
- real-time performance monitoring

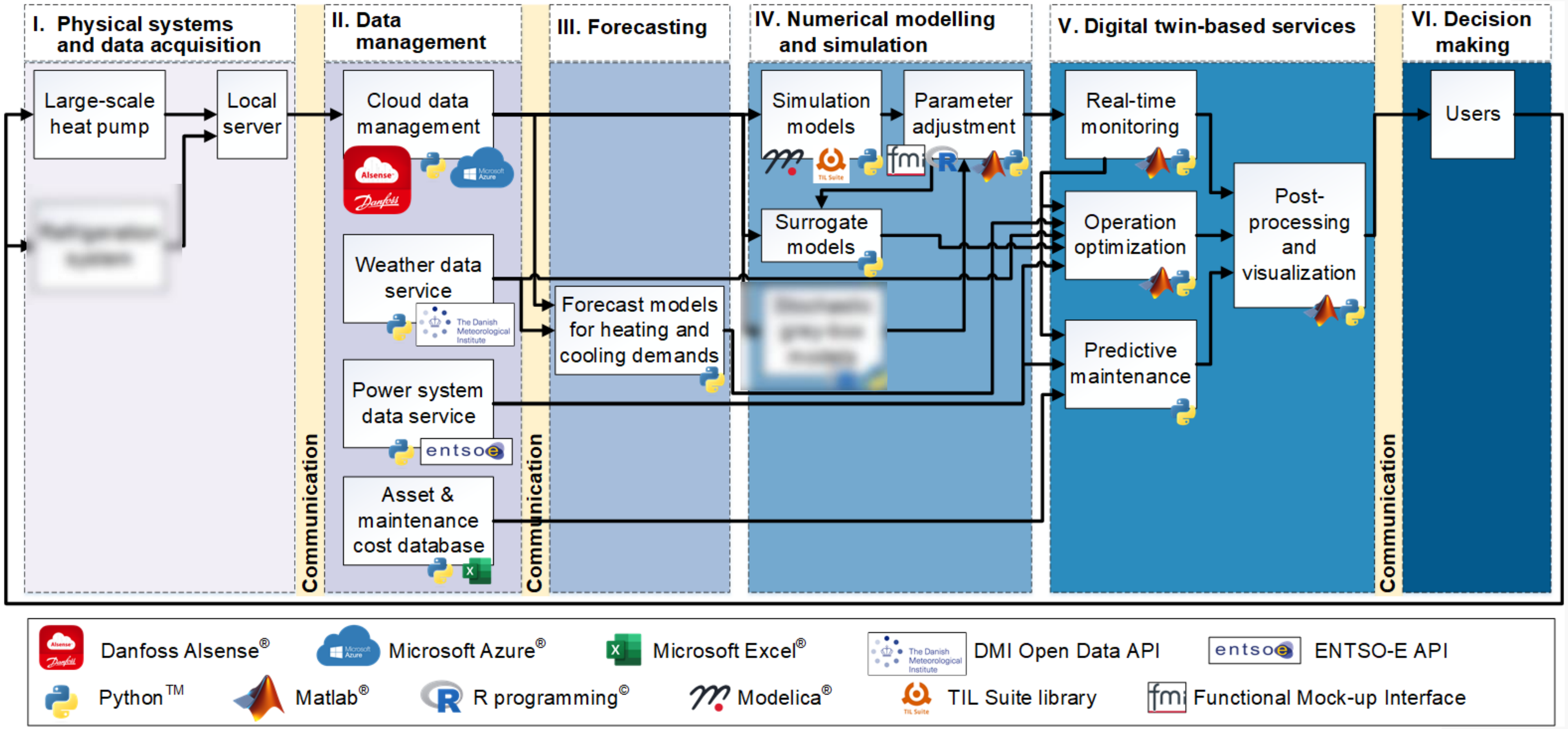
It is recommended to develop intelligible and intuitive interfaces to facilitate the interaction of stakeholders with the digital twin. For example, incorporating data visualization techniques like dashboards, automatic reports, and interactive charts, where results and insights are presented in a clear and understandable manner, facilitates the communication and interpretation of results and supports the decision-making process. The digital twin interface also facilitate remote monitoring and control, thus enabling real-time decision-making and interventions.

Remote monitoring and control can also be used to establish feedback loops that allow the digital twin to continuously learn and adapt based on real-world data and user inputs, enabling continuous improvement and optimization of the system or process being modeled.

Experience from case studies

Large-scale heat pumps for district heating supply

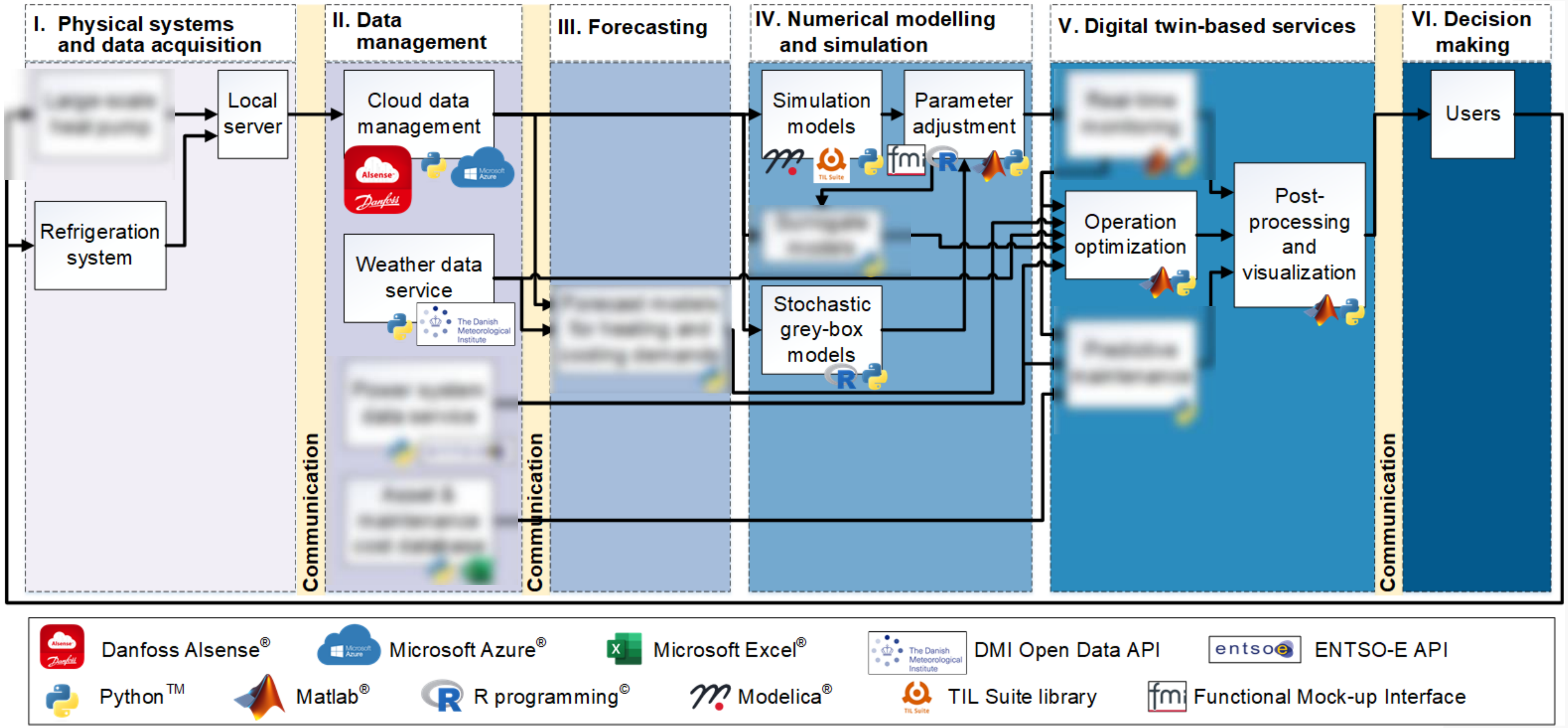
Framework used within the project for the large-scale heat pump case.



Experience from case studies

Supermarket refrigeration systems

Framework used within the project for the supermarket refrigeration case.



Conclusions

Digital twins proved to be useful for improving the operation of large-cale heat pump and refrigeration systems. Unlike conventional monitoring and control strategies in these systems, digital twins enabled the simulation of hypothetical operational scenarios, the provision of services that account for performance degradation over time and detailed operational insights for decision making.

The development of digital twin-based services for refrigeration and large-scale heat pump systems requires a systematic approach that involves several key steps. The step-by-step breakdown of the process was defined based on the experiences gained in the project and includes the following:

- **Data acquisition, integration and management**
- **Modelling and simulation**
- **Analytics and Optimisation**
- **Visualisation and User Interface**
- **Remote monitoring and control capabilities**

Besides these points, the development of digital twins should take into accounts also aspects like:

- **Integration and interoperability:** ensure seamless integration of the digital twin with existing systems, platforms, and applications within the organisation, enabling data exchange and interoperability.
- **Deployment and Scalability:** design a scalable and flexible architecture for the digital twin that can accommodate future growth, changes, and the addition of new features or functionalities.
- **Security and Governance:** Implement robust cybersecurity measures to protect the digital twin and its associated systems from cyber threats and establish access controls and authentication mechanisms to ensure that only authorized personnel can access and interact with the digital twin and its associated data and systems.

Lastly, it is important to note that the specific implementation details and technologies used for each step may vary depending on the industry, use case, and organizational requirements. Additionally, some steps may require iterative or parallel execution, and the framework may need to be adapted to suit specific project needs.