Technology Collaboration Programme
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Technology Collaboration Programme on Heat Pumping Technologies (HPT)

Annex 56

Digitalization and IoT for Heat Pumps

Task 2: Interfaces and platforms

Task Report

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Preface

This project was carried out within the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP), which is a Technology Collaboration Programme within the International Energy Agency, IEA.

The IEA

The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a programme of energy technology and R&D collaboration, currently within the framework of nearly 40 Technology Collaboration Programmes.

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) forms the legal basis for the implementing agreement for a programme of research, development, demonstration and promotion of heat pumping technologies. Signatories of the TCP are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

Under the TCP, collaborative tasks, or “Annexes”, in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex.
The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

Disclaimer

The HPT TCP is part of a network of autonomous collaborative partnerships focused on a wide range of energy technologies known as Technology Collaboration Programmes or TCPs. The TCPs are organised under the auspices of the International Energy Agency (IEA), but the TCPs are functionally and legally autonomous. Views, findings and publications of the HPT TCP do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries. This report has been produced within HPT Annex 56. Views and findings in this report do not necessarily represent the views or policies of the HPT TCP and its individual member countries.

The Heat Pump Centre

A central role within the HPT TCP is played by the Heat Pump Centre (HPC).

Consistent with the overall objective of the HPT TCP, the HPC seeks to accelerate the implementation of heat pump technologies and thereby optimise the use of energy resources for the benefit of the environment. This is achieved by offering a worldwide information service to support all those who can play a part in the implementation of heat pumping technology including researchers, engineers, manufacturers, installers, equipment users, and energy policy makers in utilities, government offices and other organisations. Activities of the HPC include the production of a Magazine with an additional newsletter 3 times per year, the HPT TCP webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:
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The Annex is operated from 01/2020 to 12/2022. Further information is available on the Annex website https://heatpumpingtechnologies.org/annex56/

Participating countries

The following countries participate in Annex 56:

- Austria
- Denmark
- France
- Germany
- Norway
- Sweden
- Switzerland

A detailed presentation of the national teams and their research work is available on the Annex website https://heatpumpingtechnologies.org/annex56/participants/

Participants and contributors to this report

This task report is the result of a collaborative effort with contributions from various authors that are listed in the table below. The report was coordinated by the Task leader Reinhard Jentsch, Reinhard.jentsch@ait.ac.at

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Foreword

Today, more and more devices are connected to the Internet and can interact due to increasing digitalization – the Internet of Things (IoT). In the energy transition, digital technologies are intended to enable flexible energy generation and consumption in various sectors, thus leading to greater use of renewable energies. This also applies to heat pumps and their components.

The IoT Annex explores the opportunities and challenges of connected heat pumps in household applications and industrial environment. There are a variety of new use cases and services for IoT enabled heat pumps. Data can be used for preventive analytics, such as what-if analysis for operation decisions, predictive maintenance, fine-tuning of the operation parameters and benchmarking. Connected heat pumps allow for demand response to reduce peak load and to optimize electricity consumption, e.g. as a function of the electricity price. Digitalization in industry can range from automated equipment, advanced process control systems to connected supply value chains. IoT enabled heat pumps allow for integration in the process control system and into a high level energy management system, which can be used for overall optimization of the process.

IoT is also associated to different important risks and requirements to connectivity, data analysis, privacy and security for a variety of stakeholders. Therefore, this Annex has a broad scope looking at different aspects of digitalization and creates a knowledge base on connected heat pumps. The Annex aims to provide information for heat pump manufacturers, component manufacturers, system integrators and other actors involved in IoT. The Annex is structured in 5 tasks:

Task 1 – State of the Art:

This task summarizes the state of the art and gives an overview on the industrial Internet of Things, communication technologies and knowledge engineering in automation. It reviews the status of currently available IoT enabled heat pumps, heat pump components and related services in the participating countries and provides information on information security and data protection.

Task 2 – Interfaces:

This task identifies requirements for data acquisition from new built and already implemented heat pump systems and provides information on types of signals, protocols and platforms for different heat pump use cases in buildings and industrial applications.

Task 3 – Data analysis

This task gives an overview on data analysis based on examples of IoT products and services, Different targets for data analysis are derived, data analysis methods are categorized and assessed, starting with visualization and manual analysis reaching to machine-learning algorithms. The report provides insights in the pretreatment of data, the use of data models, meta data and BIM (building information modeling).

Task 4 – Business Models

This task evaluates market opportunities created by connected heat pumps and presents different types of IoT services and business models based on literature and market research including detailed SWOT analyses (strengths, weaknesses, opportunities, and threats).

Task 5 – Dissemination

This task aims at reporting results and disseminating information developed in the Annex. Interactions and synergies with other Annexes or Tasks in the IEA Technology Collaboration Programs are sought.

IoT for heat pumps

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1 Introduction

An application or a service that generates or adds value utilizing an IoT – or connected – heat pump or heat pump component can be described by a complete cycle of data acquisition, data processing, inference, and action based on that inference. Similar to other information processing frameworks, e.g., the PDCA (Plan–Do–Check–Act)-cycle for quality control in business management or the OODA (Observe-Orient-Decide-Act)-loop in military decision making. Although in many cases the feedback (inference and action) can be weak, long term and indirect. For example, data analytics may affect the design of later heat pump generations or human behavior changes based on visualized data, and therefore does not act directly on the actual heat pump operation. In other cases, such as digital twins for HP operational management, the cycle may be clearly defined and fully automated. Without closing the cycle no value, e.g. revenue, energy savings, comfort gain, etc., can be added or generated by an IoT application.

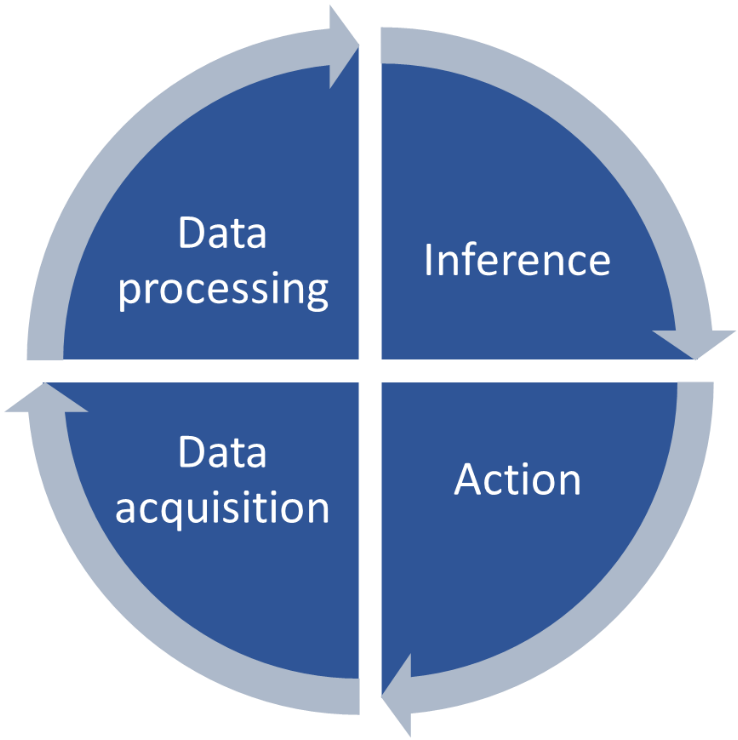

Figure 1: Decision making framework of an IoT application

A service or application can have several subcomponents, again services or applications. An example would be predictive maintenance using digital twins.

The topics subject to Task 2 originate from providing the structure (communication and processing capabilities) for the methods described in Task 3 which in turn are determined by the value cycle or IoT service described in Task 4.

A selection based on specific use cases out of the plethora of possible IoT applications and concepts will be presented. The use cases cover the following topics:

- Digital twins of heat pumps
- Connected heat pumps in building automation
- Heat pumps in grid services
- Retrofitting

The examples presented are either commercially available or part of research projects. Based on these examples some common challenges and their possible solution are elaborated.

2 Digital Twins of heat pumps

2.1 Digital Twin for heat pump performance prediction

This use case demonstrated in an Austrian national research project (DIGIBatch) is an example for the integration of a heat pump digital twin in a legacy industrial SCADA system.

2.1.1 Application

During performance testing of heat pumps according to EN-14528 and EN-14511 the performance data is evaluated at certain temperature and part load conditions. A special case occurs if the compressor speed cannot be reduced, either by design or because of reaching the minimum compressor speed. In this case the performance is evaluated at a different temperature that emulates the target temperature under on/off operation conditions. This new temperature in turn is dependent on the heat pump performance and therefore can only be determined iteratively. A plant operator assistance system based on a digital twin of the heat pump suggests simulated plant operation data, mass flows and temperatures, and therefore can save operation time and resources by avoiding wrong decisions, and non-optimal iterations in the real world. The digital twin was implemented into an accredited lab infrastructure, therefore minimal invasiveness was a key element.

2.1.2 Structure and orchestration

Data acquisition: The sensors and actuators, all part of an accredited lab infrastructure, are connected via either analogue or digital I/O-Modules to a PLC System. Originally the digital twin was demonstrated on a legacy TAC-Xenta system that was already scheduled for end of life. The TAC-Xenta was communicating over LON-Bus with the SCADA software TAC-Vista. In addition, some sensors were connected via GPIB-Bus to LabView. For the further connection both systems were augmented with software gateways for OPC Unified Architecture (OPC-UA). Therefore, the system was ready to be replaced by a PLC from B&R Industrial Automation which supports OPC-UA natively. The collected data describing the state of the physical entity of the heat pump digital twin are:

- sink and source temperatures
- sink and source mass flows
- electrical power consumption

The data then were acquired via OPC-UA by aX-System, a proprietary SCADA system from automationX, located on a dedicated server (SCADA VM according to Figure 2). The aX-System is a full but modular industrial SCADA and PLC system that is specialized for recipe-oriented batch processes. The whole heat pump test process is modelled according to ANSI/ISA-88 in the aX-System. The operator provides additional metadata about the testing procedure and the heat pump via the HMI for each test procedure. All data is stored in a Microsoft SQL-Database.

Data processing: The aX-System monitors the real time data if stationary conditions according to the standard are achieved. If so, model calibration of the heat pump model is triggered. This is done over REST-Interface calling a Python application that is hosted either on a virtual environment machine (Simulation VM according to Figure 2) or docker container. After data from all already available stationary operating points are pulled via SQL-Query from the SCADA System an adaptive parameter selection and parameter fitting algorithm is performed. The process of parameter selection and fitting needs multiple simulations of the heat pump model, that partially can be parallelized. Therefore, a functional mock-up unit or FMU of the heat pump model is used. This allows simulating the model without having the full simulation environment available, which in this case would be Dymola/Modelica. The FMU reduces the footprint for the virtual environment of the digital twin. For simulating the FMU the open-source library FMPy is used. The fitted parameters are stored within in the virtual environment thus providing highest fidelity representation of the physical heat pump currently available.

Inference and Action: When the operators need to decide on the settings for the next operating point, they can trigger the prediction algorithm of the digital twin in the HMI. The determination of the temperature and mass flow settings is done iteratively by the digital twin. The results are fed back to the HMI which the operators can either accept or overrule.

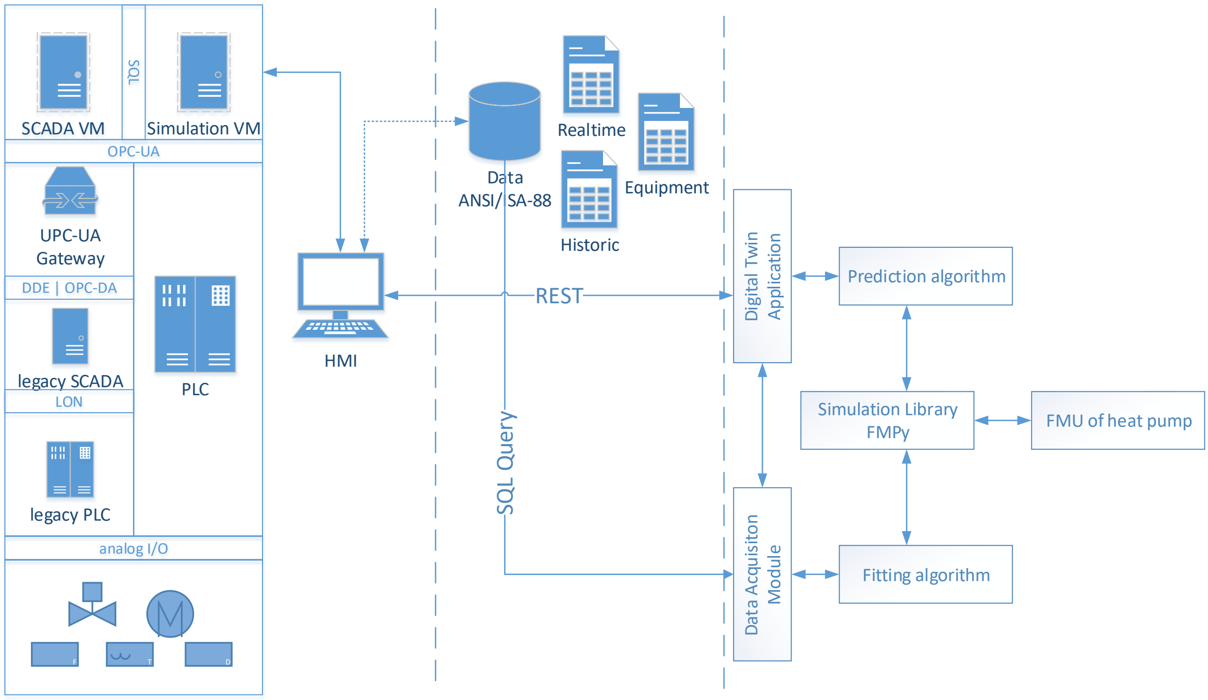

Figure 2: Functional and information structure of the DIGIBatch heat pump digital twin

2.1.3 Summary and Outlook

The digital twin application saves time and resources by performing an iterative process in the virtual environment which then can be avoided in the real environment. It was implemented as an assistance system, keeping the operator in the loop, in addition to an industrial SCADA system. The IT-framework provides process enhancements based on the performance model of a heat pump without interfering in otherwise critical control infrastructure. Due to the long timeframe of the overall process, changing operating points is a matter of hours, there are no hard requirements to speed and determinacy of the digital twin. This would change when applying a fully automated control, e.g. using MPC based on the heat pump model.

2.2 Distributed Digital Twin

This chapter describes a suggested functional architecture and provides comments regarding a possible implementation for a distributed digital twin. This investigation has been made as part of the R&D project “Digital Twins for Large-scale Heat Pumps and Refrigeration Systems“ (http://digitaltwins4hprs.dk/), where Lars Larsen from Danfoss has provided key inputs to the distributed digital twin idea.

2.2.1 Background

We define digital twins as a set of models of the physical asset or parts of it that are updated based on current measurement data and used possibly together with further inputs to provide different services. These services may serve internal optimization of the plant’s operation or they may serve to communicate the plant’s status to external entities, e.g. the plant operator or the maintenance service provider.

Based on the kind of service different information needs to be provided by the model at different response times. It is therefore reasonable to have different models for different services, instead of trying to have one extremely detailed model to provide all information for all services. This would result in computationally extremely heavy models that require large amounts of time to be developed and calibrated to the respective plant.

Such a modular digital twin further allows integrating the digital twin with the existing plant control infrastructure by integrating the models directly on the control level, where they should be used. Compared to implementing all digital twin modules externally (in the cloud, external computers, etc.), the amount of data that needs to be transferred between the plants local control system and external data bases may be reduced. Further, the need for data storage and for meta data explaining internal variables from the low-level controllers is less.

An example would be the detection of malfunction of a cooling cabinet in a supermarket refrigeration system. At the cabinet controller all available measurement data and control parameters for that cabinet are available and could be used as input for a model to assess the state of the cabinet.

In principle, the same service could be supplied when implemented in the cloud. This would however require that all the local data, which is not currently available at the higher control levels, is transported via the plant control system to the cloud and possibly that controller set point are send back to the local controller. In terms of plant security, it is an advantage if the low-level controllers are not accessible from outside.

A distributed digital twin is thus an implementation of the digital module that is based on the current plant control structure and is divided to the different control levels according to the respective service that should be supplied and the required response times. A possible functional architecture and implementation of the proposed distributed digital twin will be described in the following. It has not been implemented yet, therefore only the conceptual set-up is described.

2.2.2 Functional architecture of a distributed digital twin

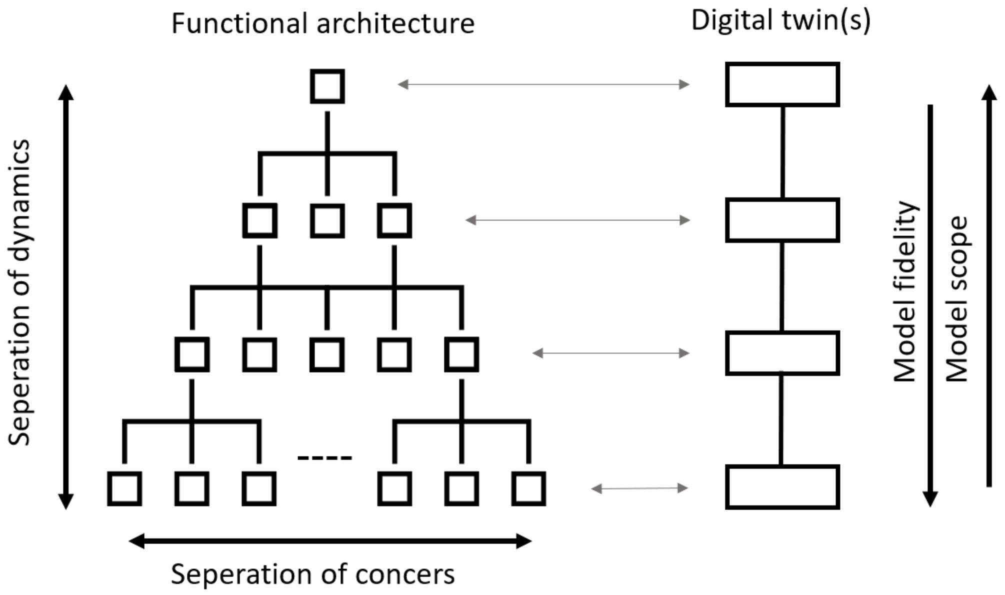

Figure 3: Functional architecture and digital twin.

The functionalities of a digital twin for large-scale vapor compression systems may be categorized by the type of services, according to the principle of "separation of concerns" and by the required response times of the different services, denoted here as "separation of dominating dynamics". The separation of concerns and of dominating dynamics is graphically presented in Figure 3.

The top layer in Figure 3 contains functionalities requiring the slowest update frequencies, while the layers below are requiring faster and faster update frequencies to fulfill their objectives. Note that the latter is also a reflection of the requirements to the scope and fidelity of the underlying models. At lower layers, detailed and accurate sub-system models to support the operational optimization as well as condition monitoring are needed. At higher layers, the scope of the model is larger, meaning that it covers a larger part of the system but in less detail, as here the interconnections of the underlying sub-systems are handled.

Within the "Digital Twins for large-scale heat pumps and refrigeration systems" project a number of relevant services supplied by digital twin were identified. Figure 4 shows a categorization of these services according to the scope of the service (concern), the required response time (dominating dynamics) and the relevant system layer on which the respective service is required. It may be seen that different services require vastly different response times. Further, the location where a certain service is supplied is on the low-level controller levels for services requiring fast response, while it may be in the cloud or on a remote machine for the slow services. This clearly indicates that the digital twin should be set-up out of different models and service modules that are designed for the respective services. The appropriate model used for a specific service, will thus depend on the information required to provide a certain service and the acceptable computational time to execute the respective model.

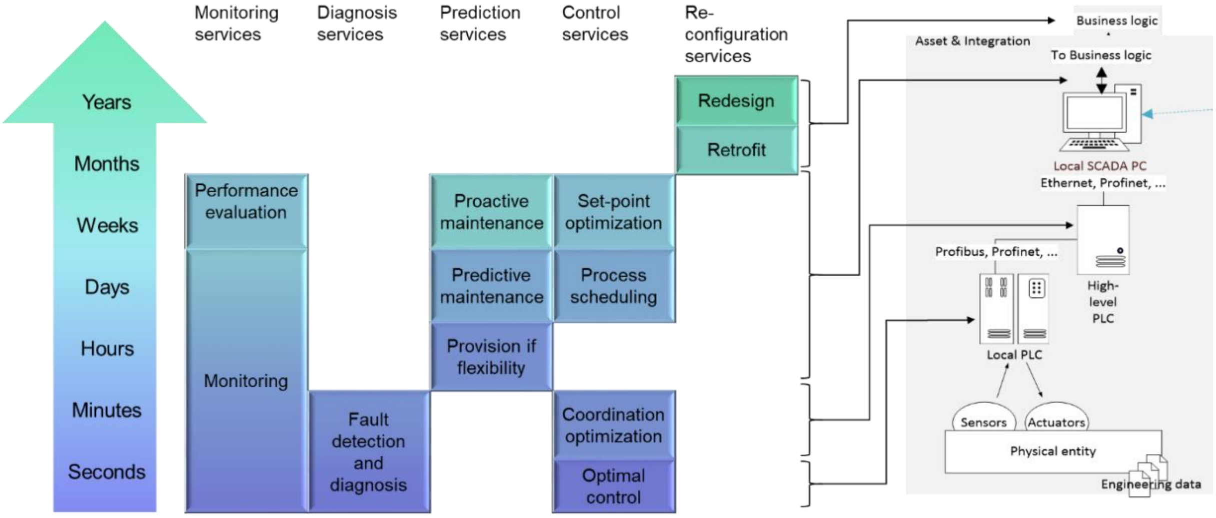

Figure 4: Categorization of services provided by digital twins according to scope, required response time and relevant system level on which the service is executed. The scope categories are based on (Steindl et al., 2020).

2.2.3 Possible implementation of the distributed digital twin

In order to reduce the required data traffic a distributed digital twin implementation is proposed. Different locations of the different digital twin service modules could be relevant according to different use cases:

- Long-term services, such as use of simulation models as a virtual testbench to develop improved controller design could be run on the cloud. As these are not time-critical, and a reduced amount of data is required to supply these services.
- Real-time related services could be integrated within the service manager (SCADA system). Thereby, unnecessary, and possibly slow information exchange via the cloud is avoided. Further, this set-up is more secure as the control signals are not sent via the internet.
- Small, specialized service modules could run on the PLC level (edge computing), E.g. to supervise the performance of single refrigeration cabinets (10-20 data points per cabinet). This could be especially relevant, since the required data does not have to be sent to the service manager and the cloud, which would easily add up to huge amounts of data. Keeping a lean data structure is a relevant aim for cloud-based services/digital services in general.

This approach may reduce the required data traffic considerably as only the data relevant to long-term service modules is send further to the higher level digital twin for further use. A further advantage of this approach is that it allows for a modular structure of the digital twin that could allow adding or removing components from the system with minimum reprogramming effort for the digital twin.

This approach does however require a detailed overview of the desired services provided by the digital twin, as the decision on which data to use locally and which data to send further to the system level is taken early in the development process and is expected to be more difficult to update later on. The respective digital twin modules need to be installed on the hardware, which typically has a live time of minimum 10 to 15 years. So, it is important to take the expected developments of the next couple of years into account when designing local controllers and the upward and downward communication paths. Further, the calculation capacity available at the lower levels need to be designed to fit to the services to be supplied at these levels and is fixed once installed. In the long term, the controllers are likely to be replaced hence opening for the possibility to add sub-models (distributed twins) in the edge controllers. In future control systems the possibility to do remote updates/uploads of smart algorithms on edge devices will render it more feasible to also update already commissioned systems.

The proposed distributed digital twin infrastructure is expected to be especially suitable for the implementation on the plant control systems. Thus, this is only a long-term option as the hardware capable of providing the required additional computing power and possibility to install updates has to be rolled out. Considering that large-scale vapor compression units have expected lifetimes of a least 15 to 20 years, this approach is not feasible as a retrofit solution. For the retrofit of existing plants it is therefore expected that the services that can be provided by the digital twin are limited to services that are not sensitive to the time delay due to data transport and can be provided using the plant data available on the plant level control (SCADA).

2.3 Digital twin

This section provides an overview and the approaches of the government-funded project Digital Twin of Heat Generating Systems as a Pioneer for the Development of Low-Emission Building Energy Technology (DZWi, https://dzwi-waerme.de/).

2.3.1 Overview

The main focus of the project is to develop a digital representation of different energy conversion systems like heat pumps in detail, which will help to shorten R&D times. Based on "hardware-in-the-loop" (HiL) tests, fundamental parameters for heat pumps and fuel cells will be determined. In addition to the metrological analysis, an important aspect is a precise description of the dynamic and static behavior, e. g. of the refrigeration cycle. Here, a generally applicable methodology is to be developed that also takes into account the use of future refrigerants with regard to the F-gas regulation. The core of all development work is a cloud environment, which should enable scalability of the results for the entire life cycle of the system.

2.3.2 Infrastructure

The Fiware open-source platform was used within the project. Fiware provides standardized software solutions for the management of context data in order to significantly accelerate the development of intelligent systems. In order to be able to declare context data uniquely, it must be provided with a universal ID and a data type. In addition, further (optional) attributes can be added. Due to its generic data structure, Fiware offers various software packages (so-called "Generic Enablers") and different functions for implementation in the overall system. To keep the handling of the software packages user-friendly, the FiLiP (Fiware library for Python (Storek et al., 2021) is used. This ensures fast and easy development of individual applications in the IoT area (Internet of Things). For a scalable use of the Fiware software platform that is independent of the operating system, these are started within containers via Docker.

Communication within the software platform takes place via the Open API specification "NGSI" (Next Generation Service Interface), which represents a uniform format for describing an API (Application Programming Interface) for context data. The advantage of this format is that the API can be operated very easily using HTTP commands (POST, GET, DELETE, ...). An actuator can thus be operated via a simple PUT command, for example. The present IoT-structure enables a user-friendly integration of customized micro services such as fault detection (see Figure 5).

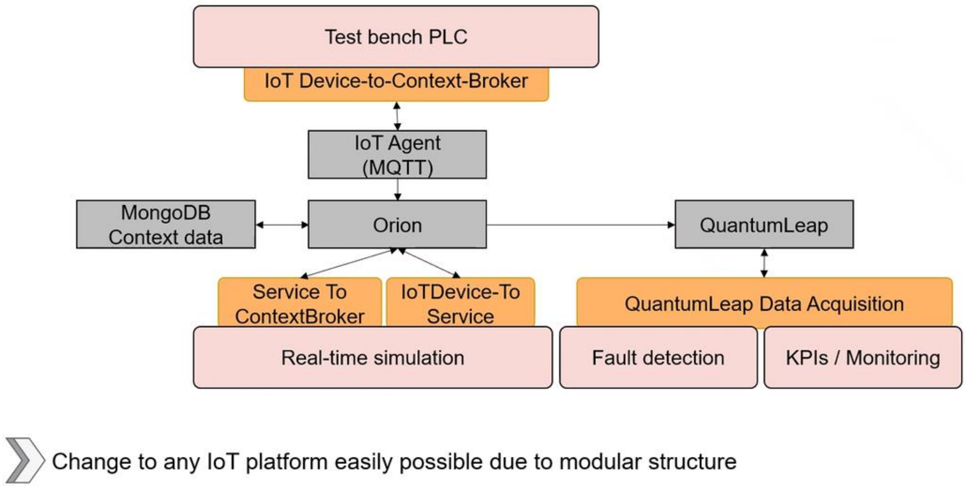

Figure 5: IoT modular concept for connecting real experiment with the digital replica and microservices.

2.3.3 Modelling approaches

The basis for microservices such as fault detection is the heat pump model. Depending on the objective of the microservice, different model approaches are useful. In general, physical models (white-box), data-driven models (Black-Box) and mixed approaches (Gray-Box) can be used. Regarding Gray- and White-Box models, the Institute for Energy Efficient Buildings and Indoor Climate in Aachen offers the open-source library VCLib, which allows dynamic cooling circuit simulation (Vering et al., 2021). The steady-state version of this library is implemented in Python, which enables computationally efficient annual simulations by means of integration into transient system simulations in the form of delay elements (Wüllhorst et al., 2022) Furthermore, various methods of fault detection can be used. The validation on the basis of real measurement data has already been started. The automated detection of stationary points in dynamic operation allows the use of more than 100 stationary operating points of the heat pump. The validity is checked by quantifying the measurement uncertainty using GUM (GUM 2008). Similarly, a methodology for simplified parameterization of physical simulation models was presented at the BauSiM 2023 conference, which reduces the effort of recalibration.

With regard to Black-Box approaches, work is currently being carried out to facilitate the integration of the developed micro-services in live operation. For this purpose, for example, neural networks are developed via machine learning tools (Rätz et al., 2019) to map the COP of a heat pump. By comparing model predictions and measured or calculated COP of the real system, conclusions about faulty or suboptimal conditions in the operation of the system can be detected. The methodologies for black box approaches will be extended and published in the future.

2.3.4 Fault Detection and Diagnosis

Fault detection in the operation of a heat pump was successfully tested in the field. The field device was operated by the project partner Viessmann in Allendorf. During operation, an error detection system was connected to determine deviations between the field device and the heat pump model. The 2-sigma method is used for this. A fault is thus only detected if a significant deviation of an indicator (e. g. the discharge temperature of the compressor) lies outside a previously calculated or learned twofold standard deviation (2-σ). Here, the mean value μ as well as the standard deviation σ of the fault-free system behavior are learned accordingly, so that faulty operation characteristics can be distinguished from regular operation. When a significant deviation is detected, the user can choose in the configuration which module should be used to communicate the fault corrections. In the present case, the messenger app Telegram was used through the deployment of a Telegram bot, which sends the fault message (see Figure 6). Other modules could be email, Slack, or e. g. the display of the heat pump itself.

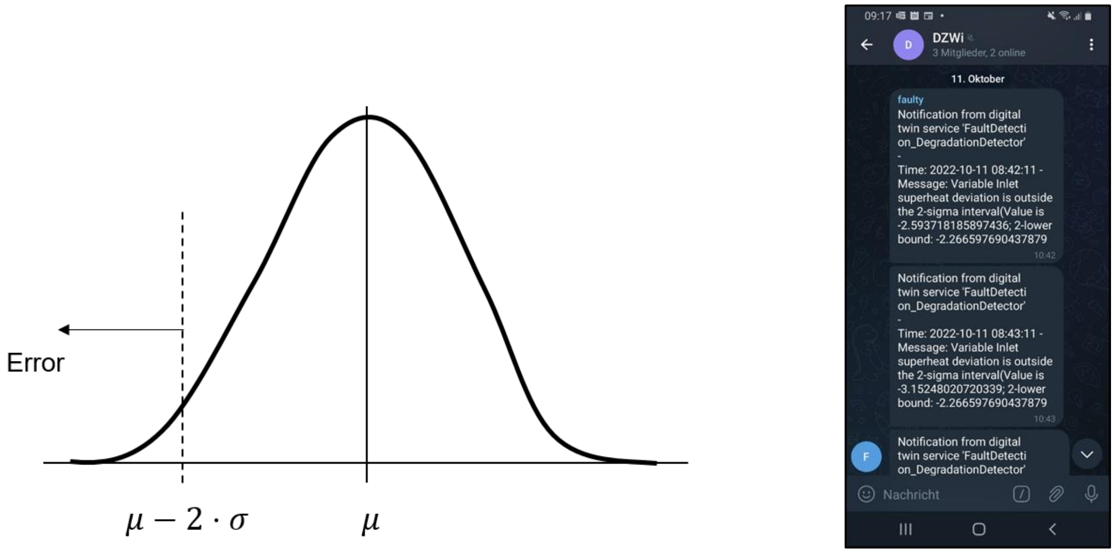

Figure 6: Left: Trained mean value and standard deviation of a certain system behavior. If (in this case) the value falls below the 2-σ interval, an error is detected. Right: Output or notification when fault detection is triggered via the Telegram messaging service.

The results of the fault detection are shown in the Grafana dashboard in Figure 7. The graphs describe the course of the simulated (green) and measured (yellow) refrigerant temperatures of the outlet from the compressor as well as the inlet and outlet temperatures into the evaporator. The time period is limited to approx. 20 minutes, during which the fault-free state of the system was learned (blue box) and the fault was injected by holding cardboards in front of the evaporator (red box). In the learning process, the deviation of the simulated and measured value of the fault indicator (in this case, superheat) is thereby classified as normal operating behavior. After a fault indication, a drop in the evaporator outlet temperature on the refrigerant side can be seen, so that the value of the fault indicator is below the 2-σ range. The fault detection module detects the deviation and sends and issues a message about the incident to a predefined target group at regular intervals (red circles) via the Telegram bot.

Furthermore, it can be seen that further notifications are issued after the cardboard is removed and thus the fault-free state is restored. This is due to the fact that the 2-σ range is exceeded, but this time due to an increase in the outside temperature, which leads to a deviating system behavior compared to the trained state. In the future, therefore, the entire fault-free operating range must be measured and classified so that fault detection can be used robustly. In addition to the physical models used for commissioning, data-driven models are a promising alternative, which learn the system behavior or the relationship between input and output variables without expert knowledge and a set of measurement data suitable for training. The identification of a suitable method, which can also be used in the field, will be forced in future.

Figure 7: Period of fault indication in the Grafana dashboard. On the left are the simulated (green) and measured (yellow) ambient temperature, the supply temperature of the heating water and the discharge temperature of the compressor. On the right are the temperatures at the inlet and outlet of the evaporator on the refrigerant side. The blue boxes represent the training period, the red ones the time of fault indication. Red circles are notifications by the Telegram bot.

2.4 Live Digital Twins

The company EnergyMachines (https://da.energymachines.com/) can deploy Digital Twins by using the platforms numerous (https://www.numerous.com/) and Energymachines.cloud which are further described in this chapter.

2.4.1 Overview

Numerous is a platform for setting up cloud-based simulations, optimization, digital twins, automatic reporting tools and many more applications. Simulations and analytics tools can be developed using the numerous python SDK and shared with other users. Via the web application users have access to configure and run the tools and explore the results. On the platform the tools run on cloud resources provisioned by the platform. In this way multiple users can run the tools in parallel and share their results without installing anything locally. Numerous is available as software-as-a-service.

Energymachines.cloud is a SCADA/HMI platform, which enables sensor logging on the heat-pump system, visualization for operators, setting alarms, and reporting results back. It also is the key gateway into accessing all historical data logged on connected systems.

Combining the powers of numerous and energymachines.cloud allows running simulations with live sensor readings as inputs and deploying multiple instances each configured for a specific system. This way energy machines have live digital twins for their heat pump systems and use the results to augment the real measurements with data from the simulations.

2.4.2 Modelling heat-pumps

To run a digital twin of a heat-pump, there first needs to be a model. EnergyMachines have several models of our heat-pumps. The best candidates are based on so-called Long-short term memory (or LSTM) neural networks. Figure 8 shows an example of such an LSTM model trained using data from energymachines.cloud on one of our many installations.

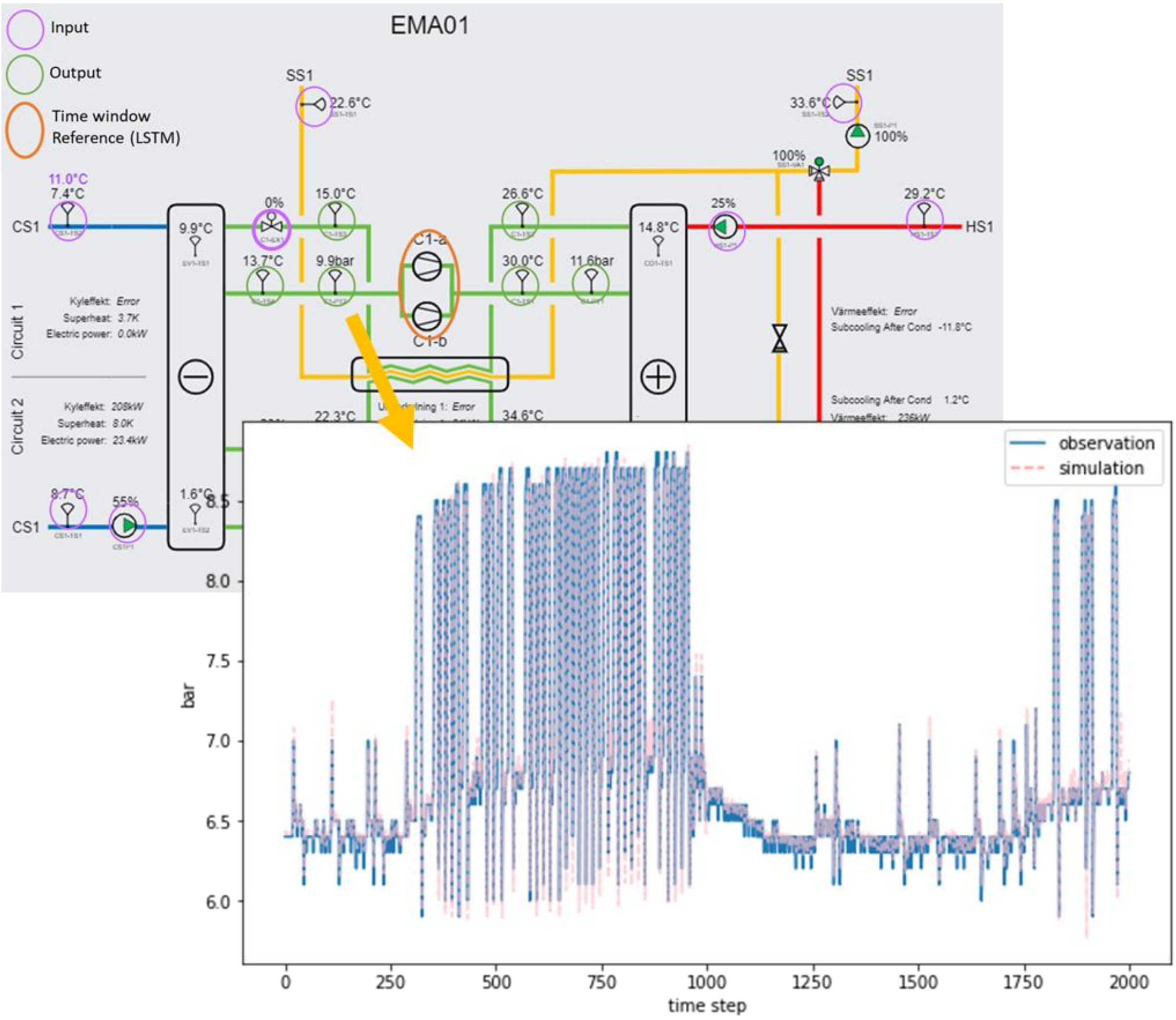

Figure 8: An example of a trained LSTM model which shows that transient operation is captured by the model

2.4.3 Infrastructure for running digital twins

Numerous was created out of a need internally to easily make available the simulation and analytical tools to application engineers and to deploy these tools in a structured way as digital twins, continuously adding the power of advanced analytics to systems in the field. The current architecture for running the heat-pump digital twins can be seen on Figure 9. The users range from the developer who wants to execute their digital twin application, to the user who wants to take advantage of the digital twin, for example for the purposes of predictive maintenance.

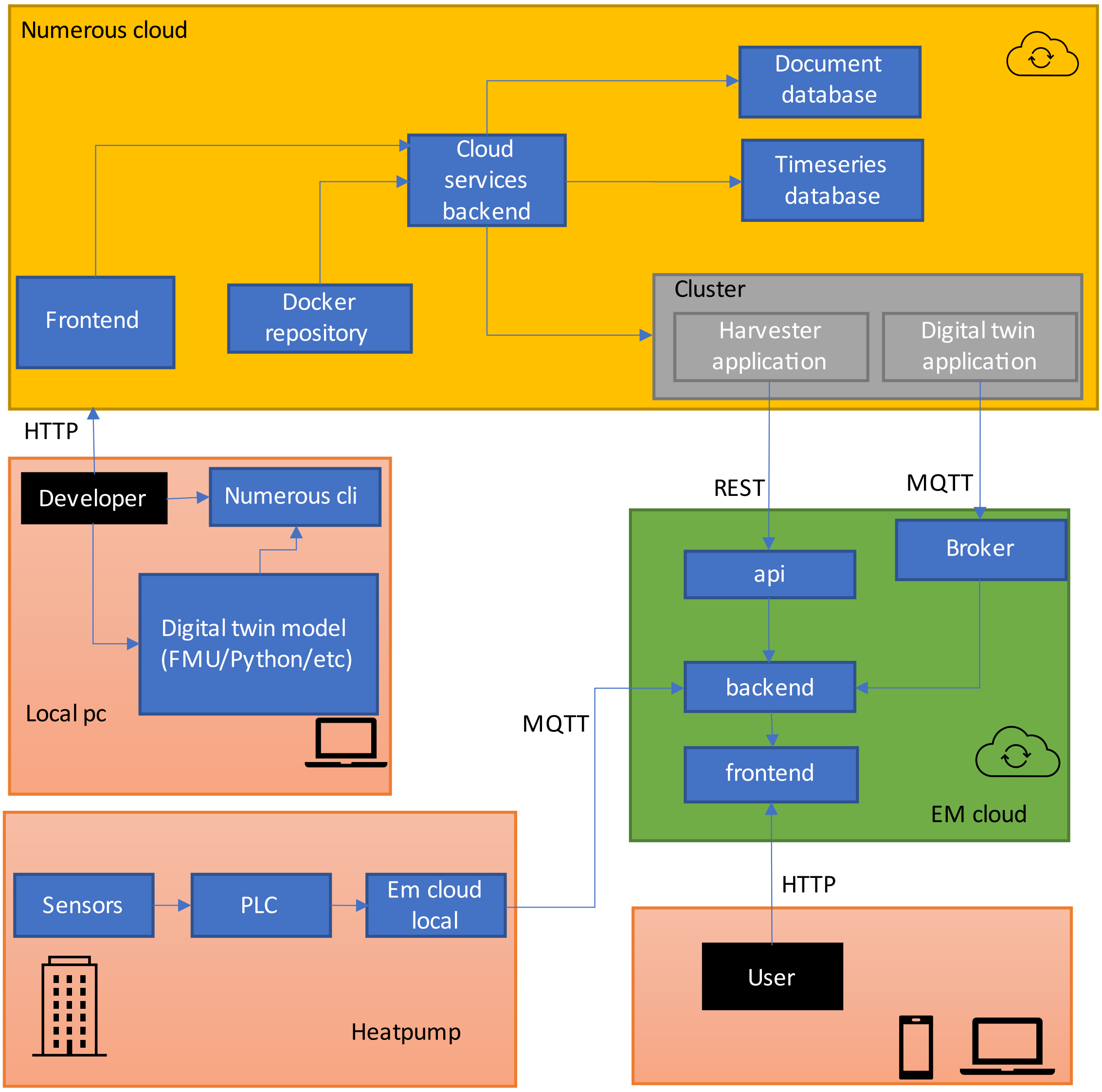

Figure 9: The digital twin infrastructure at energymachines, which shows how the model developer configures the applications (harvester and digital twin) using the numerous.cloud platform and how energymachines.cloud polls sensors from a heat-pump connected to the cloud via a local client and publishes its data on its backend using MQTT. The flow is described in more detail in the text.

2.4.4 Packaging the model for numerous

The model developer creates a model using any application which can be interfaced from python and integrates it with the numerous platform using the python SDK (software development kit). The developer then deploys the digital twin from the numerous web application. Python was chosen as the most popular programming language with the largest ecosystem of packages available for data science and analytics, as well as its ability to run on most operating systems.

The developer uploads the application to numerous using the numerous command line interface.

2.4.5 Running the model as a digital twin

A main feature of numerous is the ability to run any model in real-time as a digital twin. There is in-fact no distinction between a simulation using static data and one running as a digital twin. EnergyMachines's definition of a digital twin is a simulation which runs continuously with input data coming from a real system. Typically, simulations can run in multiples of times faster than real time and so resources consumed for a digital twin is much less CPU intensive as the application only does its calculations a fraction of the time. When running as a digital twin, there is the advantage of the hibernation functions, to save resources, which will be described later.

2.4.6 Configuring the application on numerous

Accessing the numerous web application, users set up two application scenarios: A harvester, which extracts data from energymachines.cloud, a standard tool included with the platform, and the second is the digital twin which uses the outputs from the harvester as inputs to the digital twin simulation. After configuring relevant parameters, the digital twin can be set up to run either continuously, or periodically (every hour, every day, etc.), to conserve resources. A screenshot from the numerous platform is shown in Figure 10.

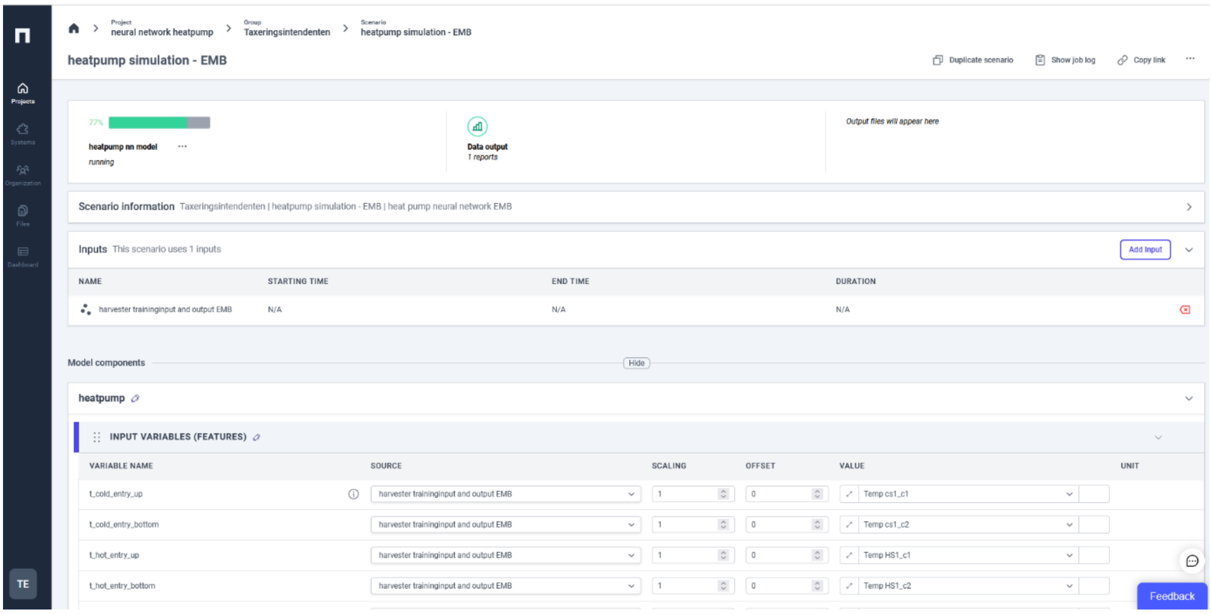

Figure 10: Screenshot from numerous where a heat pump model is executed. In this example, the simulation is not executed as a digital twin, but there is no marked difference between a digital twin application and simulation application, as so far as the UI is concerned. The difference is the progress bar will show the message "running as digital twin" instead of a percentage completion

2.4.7 Running applications in the cloud

The two application scenarios are then launched from the frontend: first the harvester application is started, so that data is available when launching the actual digital twin application. Then, naturally the digital twin application is launched. In either case, the 'numerous' frontend calls the backend, which configures the applications to run on cloud resources. The cluster pulls the images containing the developer's application code from an image repository and deploys them on provisioned resources.

2.4.8 Handling data flow between numerous, the applications, and externally

Both applications communicate with the platform via the numerous SDK, using the GRPC protocol. Outputs are sent back and are saved in numerous timeseries database service.

As mentioned, when setting up the application in the frontend, outputs can be shared between applications, so that the output from the harvester, can be used as inputs in the digital twin. In practice, the application running on the cluster requests the data from the numerous platform using the numerous SDK. The digital twin application furthermore writes its output to the energymachines.cloud using the MQTT protocol.

2.4.9 State-full applications

If the harvester application is set to execute periodically, it can hibernate, which triggers the listener (digital twin) application to hibernate as well. The numerous platform then schedules the application to re-launch based the configured schedule. When hibernating, the model states are saved before closing the application. The model states are then reloaded once the model is re-launched. This is important, as models are typically not stateless.

2.4.10 Monitoring the results

Results from the digital twin applications can be integrated with the energymachines.cloud pages, but are also available on the numerous platform. Energymachines.cloud is directed towards plant operators, and is therefore more intuitive towards operation, whereas numerous is a general analytics platform, and is directed towards simulation developers who want to monitor progress, configure application and explore, document and share results.

3 Connected heat pumps in building automation

3.1 ENERGETIKUM - living lab

The use case demonstrated by FH Burgenland shows the integration of a Data-driven Predictive Control (DPC) strategy into the office building ENERGETIKUM in Austria. The integration was carried out within the PRELUDE project (Grant Agreement No. 958345 of the Horizon 2020 research and innovation program).

3.1.1 Application

The Building Management System of the ENERGETIKUM allows the integration of an intelligent Energy Management System (see Figure 11) and connectivity with various systems via API-interfaces (e.g. Weather Forecast). The developed Data-driven Predictive Control (DPC) strategy is an approach, which minimize the operational costs of the heat pump while ensuring at the same time the thermal comfort in each thermal zone. Because of the large glass facades on the south and west side of the building, the shading devices have a big impact on the room air conditions. Therefore, the DPC considers in particular the following systems to ensure thermal comfort in all thermal zones:

- Shading elements on the outside
- Reversible heat pump for heating respectively cooling
- Hot water storage tank respectively cold water storage tank
- Floor heating systems respectively near surface cooling system

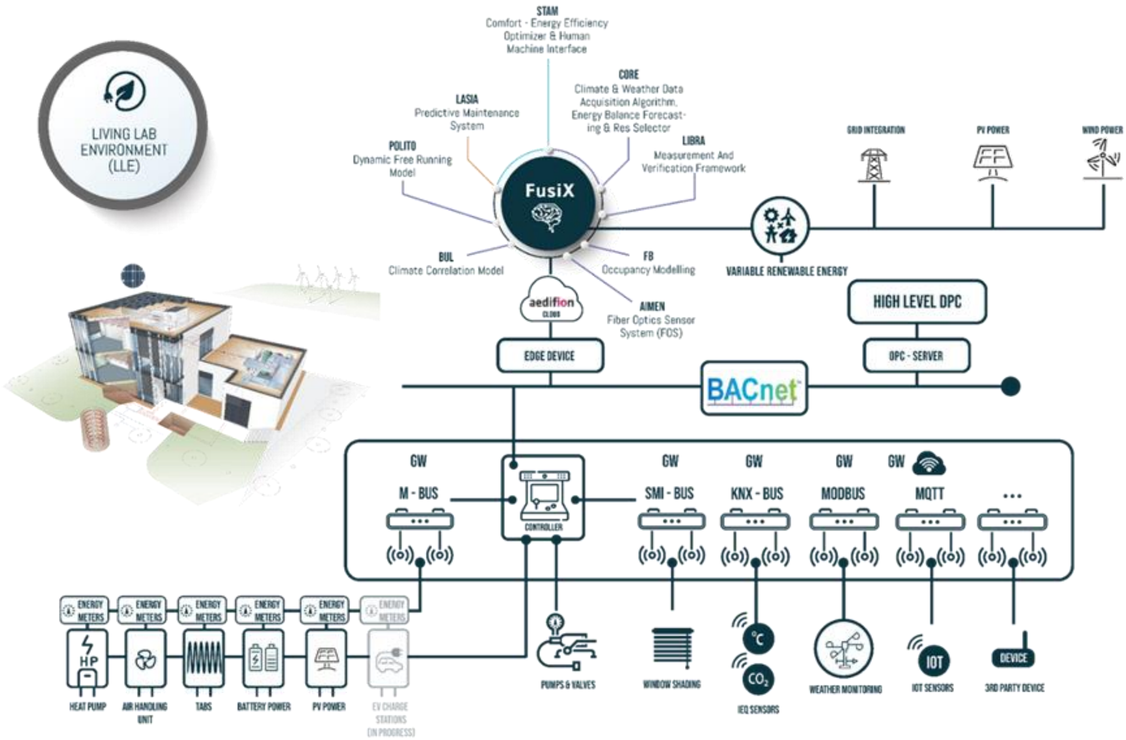

Figure 11: Data management architecture of the intelligent Energy Management System (cf. PRELUDE, Grant Agreement No. 958345)

3.1.2 Structure and orchestration

Data acquisition: The used cloud-based data acquisition system collects massive data from the open Building Management System of the ENERGETIKUM. The change of a datapoint value triggers a new record with the corresponding timestamp, which reduce the data-traffic compared with polling data acquisition.

Data processing: With the resampled values of the required data from the cloud-based data acquisition system the measurement data was prepared (e.g. removal of outliers, data gap filling). To map the future behavior of the systems and minimize the operations costs with the DPC approach, the needed models and information listed in Table 1 are necessary. Furthermore, Table 1 shows what data for the models are essential.

Table 1: Main models and information of the DDPC approach

Models	
Grey-Box model of one thermal zone (needed several times because of the existing thermal zones)	
Grey-Box model of the photovoltaic cell (five-parameters model)	
Grey-Box model for the hot or cold water storage tank	
Past and future data	**Usage**
Historical data of ENERGETIKUM	For parameter identification of the models and for load prediction
Weather forecast	To calculate the thermal zones behavior and the PV system yield
Inner load prediction	To calculate the behavior of the thermal zones
Electricity purchase price profile	Used in the objective function, to minimize the costs
Feed-in tariff for PV power	Used in the objective function, to minimize the costs
Constraints	
Thermal comfort range (linear constraint)	
Temperature range of the hot or cold water storage tanks (linear constraints)	

Inference and Action:

The demonstrated DPC approach, as illustrated in Figure 12, has been implemented via MATLAB® to the open Building Management System. The identification of the parameters for the Grey-Box-models is done periodically once a day at midnight. To account forecast errors along the day, the optimization is run periodically (once per hour) with a time horizon of 24h in the future. The model gets the information about the current values of the ENERGETIKUM (e.g. room air temperatures). The received weather forecast is used to make a forecast of the energy production of the PV-system with a self-developed five-parameter model of the photovoltaic cell. The historical measurement data of the ENERGETIKUM will be used to make a load prediction of the internal loads and the ventilation. With the identified parameters for the Grey-Box-models, the determined objective function, constraints and the predicted data, the coefficient of the matrices and vectors for the solver-based optimization are calculated. With the chosen mixed-integer linear programming solver, the most cost effective operation mode of the heat pump for the next 24 hours is calculated (central optimization). The corresponding control variables are fed back to ENERGETIKUM building control system.

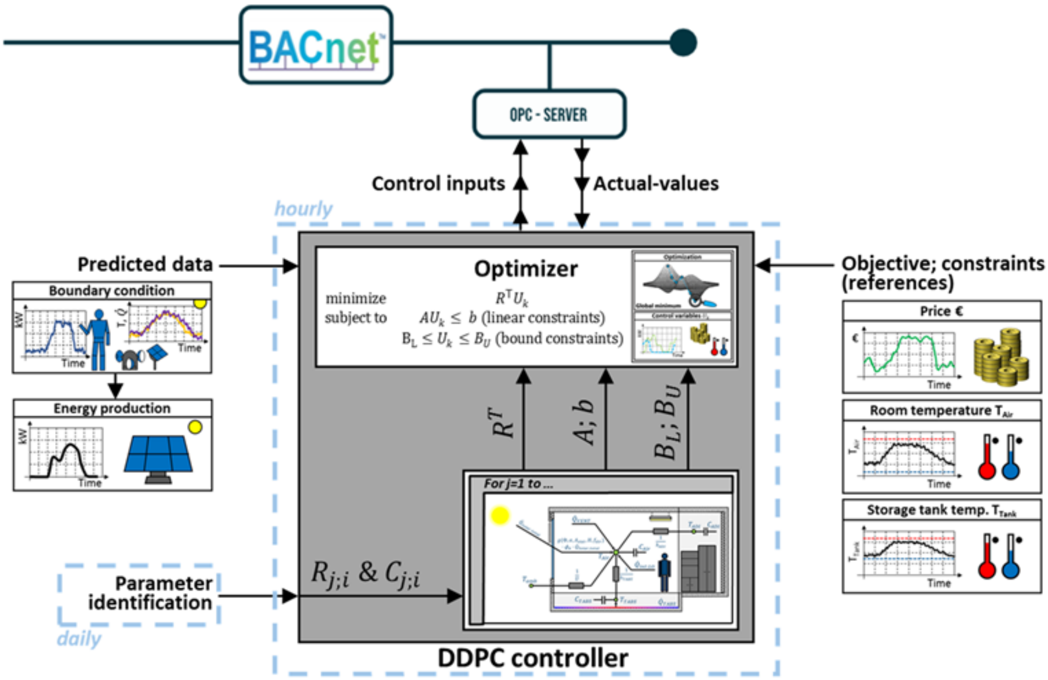

Figure 12: Schematic depiction of the DPC approach

3.1.3 Summary and Outlook

The introduced DPC approach considers also the possibility to reduce (in summer) or increase (in winter) the solar irradiance by changing the position of the shading blinds on the outside of each thermal zone of the ENERGETIKUM separately. The result of the demonstrated approach is a reduction of the heating and cooling energy demand of the thermal zones and subsequently the most cost effective operation mode of the heat pump.

The focus of our future work is the reduction of the numerical effort of the central optimization approach by using a decentral optimization approach while ensuring comparable results at the same time.

3.2 ZEB Laboratory

The use case demonstrated by SINTEF is an example of an integration of heat pumps and other building automation devices with a time-series platform to perform consistent analytics and to help develop services that optimize the operation of the heat pumps as well as the use of on-site generated electricity and heat storage.

3.2.1 Application

The case study combines monitoring data from two heat pump units, the heating plant, energy production and room-level automation controllers with design and as-built information to:

- Analyze the heat pump operation by extracting time series from a database and writing back model outputs or metrics for visualizations.
- Model the COP and emitted power of the heat pumps, based on the exergetic approach in EN 15316-4-2:2017 informed by manufacturing data, source and sink temperatures.

- Model the heating demand using an RC model informed by as-built engineering documentation (XML of e.g. U-values and surface areas) and operation data.

The modelling framework demonstrated potential in forecasting energy production and energy need for the next day, as well as performing effectively in particle-swarm optimization. These capabilities may be utilized to optimize setpoints and operating strategies, such as defining the optimal time to transition from night setback mode or operating heat pumps based on the predicted photovoltaic production, heating demand and capacity.

3.2.2 Structure and orchestration

Data acquisition: An automation controller makes information available over BACnet/IP messaging protocol integrating data from heat pump units (Modbus), electricity meters (Modbus) and heating meters (MBUS). Other automation controllers provide room-level integration of sensors and actuators by connecting to various field buses. The building automation controllers are Siemens Desigo PXC's. BACnet was chosen because it is widely used and offers efficient communication methods, such as structured datagrams and who-is broadcasts to discover devices. This makes it easy to use for integrating data from different systems and devices on local building automation networks.

Data ingestion is performed by a custom program, „BACnet2Influx", on a server on-site that acts as a gateway writing streams of time-series data and tags to an InfluxDB instance. The tags (key-value pairs) are interpreted from information embedded in BACnet names which follow an Interdisciplinary Tag System in widespread use in public and commercial buildings in Norway (Statsbygg's TFM system). Since it was part of the control delivery, all components, actuators and rooms are labelled according to this system. A spreadsheet is used to provide additional tags or manual modifications in order to fix inconsistencies.

Data processing: InfluxDB combines data from multiple sources and makes data on minute resolution available outside the building automation network. A data processing pipeline was made in Python (Pandas) using the InfluxDB client library. Outliers were removed to produce data for the physical modelling procedure, and hours with missing data were interpolated with the time-of-day mean values from the past seven days. The same averaging approach was used to provide forecasts of, e.g. internal gains and operating setpoints into the future (in combination with weather forecasts). An as-built model running on actual weather provided a benchmark regarding the performance prerequisites made during the design process. At the same time, an operational model was calibrated on measurements and used data collected from the operations to provide forecasts for the next days.

Inference and Action: The inputs and outputs from the heat pump model and the building energy model were written back to the time-series database to provide comparisons with the daily operations. The results of daily or hourly scheduled runs are currently visualized on a dashboard in an observability platform. Next, the operational model will be used for optimization, which requires the ability to override rule-based control setpoints which is currently only possible via the local network through a custom program "BACforsk" (Figure 13).

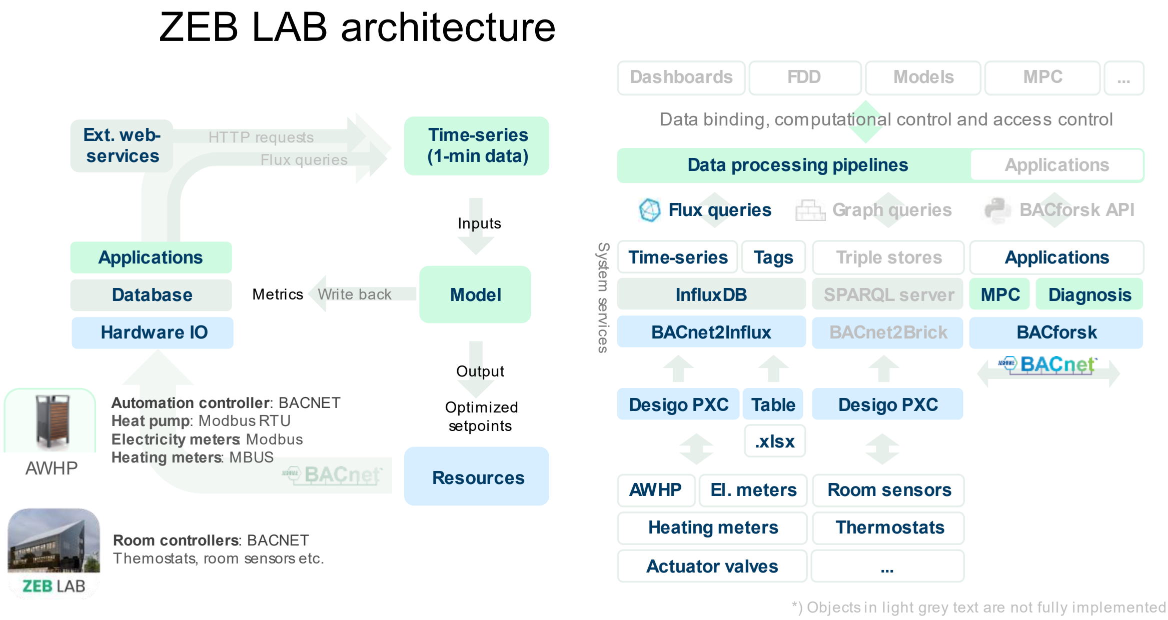

Figure 13: Functional structure and process diagram of the ZEB Laboratory heat pump and building automation case.

3.2.3 Summary and Outlook

The development of data processing pipelines, models and analytics was streamlined by utilizing the time-series platform that integrated data from various sources, including message transfer from BACnet devices, external web services (nearby weather stations and forecasting services) and post-processed measurements and model results.

Considering that many buildings use BACnet for communication, the plan is to improve the robustness of the "BACnet2Influx" application, which retrieves data from building automation networks and formats it for storage in a manner suitable for downstream operational use of the time-series data. Additionally, the "BACforsk" application will be further developed to enable algorithms to exert control over certain aspects of building operations, with the added capability of remote access and computational control. Future work will also explore the implementation of knowledge graph representations to verify the validity of the metadata according to the formalized Brick schema framework and to model and utilize this information in a more automated fashion (Figure 13).

4 Heat pump in grid services

4.1 SLAV project

In the research project SLAV (Storskalig Laststyrning Av Värmepumpar i elnätet, Walfridson et al. 2023) the communication from the Transmission System Operator (TSO) or Distribution System Operator (DSO) to individual heat pumps has been investigated. The project is still ongoing and will be finalized in Q2 2023. It is funded by Energimyndigheten (the Swedish Energy Agency) under the program Digitalisering möjliggör energi- och klimatomställningen.

The prerequisites in the SLAV project are that the heat pump manufactures cloud/API solutions are used with no additional installed equipment and the heat pumps are used just to aid the power system. Outer uses, for example to only reduce cost of electric bills or to interact with other services are not a part of the project.

To use large amount of heat pumps to aid the power system standardization of communication is of highest priority. The flow of communication is seen in Figure 14

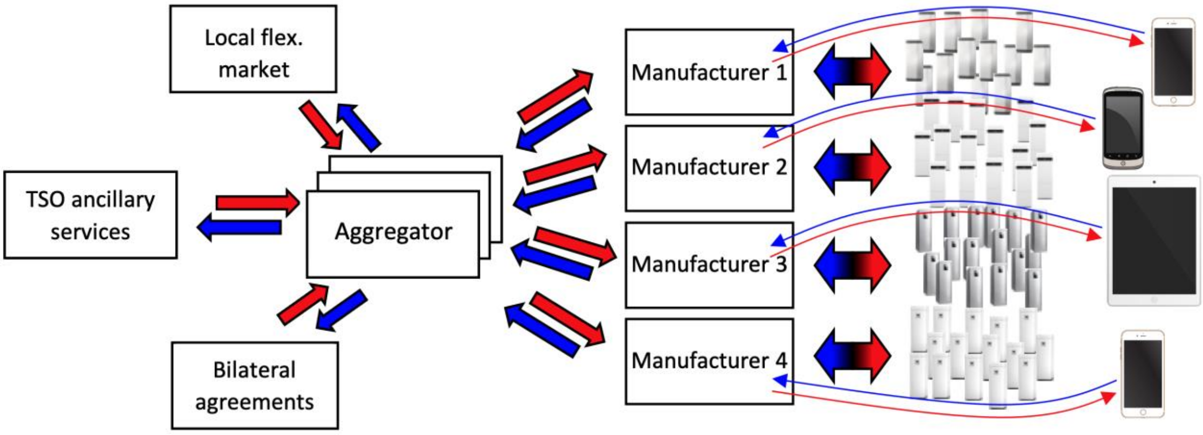

Figure 14: Overview of the communication flow from and to the heat pumps using the manufacturers cloud solution.

The project found that no today available protocol fully fulfils the communication needs from the aggregator to individual heat pumps, but EEBUS and OpenADR are promising. EEBUS is a European initiative and could thus have an advantage in the EU, while OpenADR is sprung from the California electricity crisis in 2002. Lately some cooperation between these protocols is seen and hopefully the gaps in the protocols for heat pump demand response will be filled, as a world standardization would benefit the heat pump industry. Both EEBUS and OpenADR are open access and license free, in opposite to the in power subsystem already used IEC 61850. IEC 61850 is extended with WAN communication and security and should not be ruled out as the solution. If one or more TSOs point on IEC 61850 the heat pump industry must adapt.

The SLAV project also addresses cybersecurity issues relevant to large scale adaption of heat pumps for demand response in the power system. All heat pump demand response initiative will need internet connection of some kind, meaning the heat pumps will be open to cybersecurity risks, as all IoT devices are. Being a generally lower tech industry (looking back 10+ years) the heat pump manufacturers when entering the flexibility market have had the need to adopt both a higher degree of control complexity and at the same time adopting effective cybersecurity measures. This will need a transition, a transition the Swedish heat pump industry mainly has finalized. As heat pumps have long lifespan, they need long time cybersecurity update commitment from the manufacturers, but likely also a plan on how to disconnect old heat pumps when they regardless are getting vulnerable to attacks. At RISE (RISE, 2023) we have seen that a coordinated attack on Swedish heat pumps can cause risks to the power system, and internationally grey-zone activities on power systems have been executed. One example is the attack in Ukraine 2015 (Wikipedia, 2015). The threat is real and should not be underestimated.

4.2 Tiko

This solution developed by the Swiss company tiko Energy Solutions AG presents a heat pump pooling and power grid service use case where a large number of heat pumps and other electric consumer (e.g. domestic hot water heaters) are orchestrated from a centralized backend (a server). The tiko system can be divided into 4 parts (see Figure 15). As actors and sensors, two devices are connected directly to the heating system. The "K-box" measures the power consumption and at the same time serves as a control switch using a relay. The T-sensor is used to ensure comfort, so that the room or water temperature does not drop out of the desired temperature limit due to a switch action. Both devices communicate via power line communication (PLC) with the "M-box" (gateway). The "M-box" collects all data and communicates via 3G/4G network with the private cloud (backend) of tiko. One important heat pump specific aspect in this system is the maximum number of on/off switching actions to prevent compressor damage.

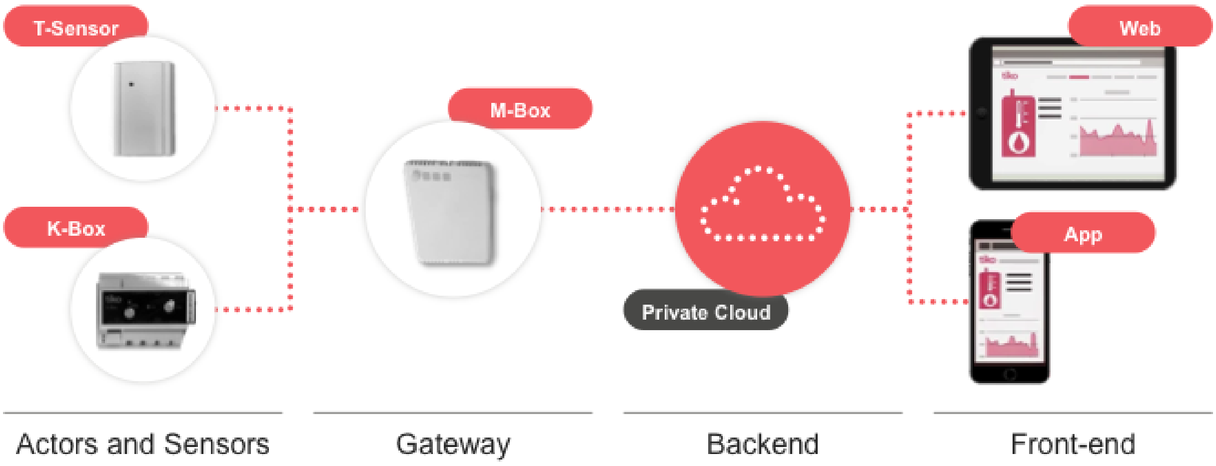

Figure 15: tiko system overview (Geidl et al., 2017)

5 Retrofitting

The following two examples show applications in which existing heating systems (heat pumps and district heating substations) may be retrofitted to enable IoT connection. Both solutions may be deployed in existing but also new installations.

5.1 Remote Diagnostic SmartGuard

This solution developed by the Swiss company Meier Tobler AG provides an IoT extension for their heat pumps offering including remote diagnostics, comfort features and facilitation of maintenance and repair works. It targets new and existing heat pump installation. The heat pumps are equipped with a local installation that connects to the heat pump to the server. The heat pump is controlled and monitored by the so-called heat pump manager. The heat pump manager can redefine various control parameters. In addition, the HP-manager collects over 200 data points of the heat pump in a resolution of up to 1 second. The heat pump manager is directly connected to the MT-Gateway. The MT-Gateway has its own antenna on the building facade and thus communicates via 4G/LTE (LTE CAT1M) with Meier Tobler's remote diagnostics. On the server the data is stored and analyzed manually and automatically. Data is held available for inspection by experts of the company's customer support team and made available to the end costumer (Di Cerbo, 2022).

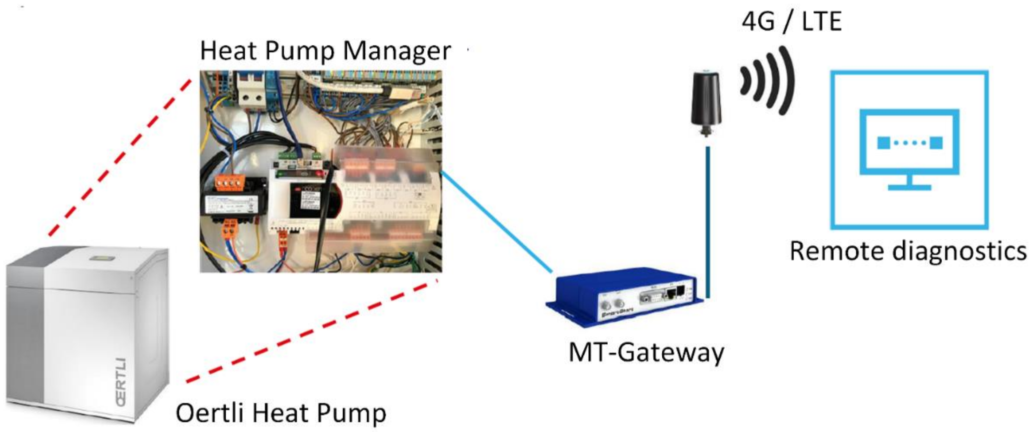

Figure 16: SmartGuard system setup (Di Cerbo, 2022)

5.2 Monitoring of district heating

Besides of heat pumps, for many cities district heating is a key technology to make their energy sectors more carbon neutral. However, efficient operation of decentralized district heating substations is imperative for district heating networks to operate optimally in terms of energy and economy. In typical district heating networks today, heat generation is regulated, controlled, monitored and optimized with modern automation systems, but there is often a lack of transparency regarding the operation of the decentralized substations in the buildings themselves. In many cases, undetected errors and suboptimal control strategies lead to a degradation of energy efficiency and to a worsened economic efficiency for the energy supply companies and the end customer. For example, excessively high return temperatures from district heating transfer stations cause heat and efficiency losses in heat distribution or generation. To address these deficiencies, Fraunhofer ISE developed an IoT and AI-based solution in the AI4CITIES project to help district heating operators and customers identify and prioritize problems in their network more efficiently and quickly. The focus was on monitoring district heating transfer stations, which the project first measured using an IoT-based data logger. The data generated in this way has then been analyzed in a software tool using a patented AI solution for fault detection and diagnosis.

Through such measures the status of district heating transfer stations can be made more transparent, which allows operators and customers to make data-driven decisions and reduce CO_2 emissions. Likewise, similar solutions can be deployed to monitor heat pumps and connected heating systems, where existing measurement equipment is not sufficient, or data is not accessible.

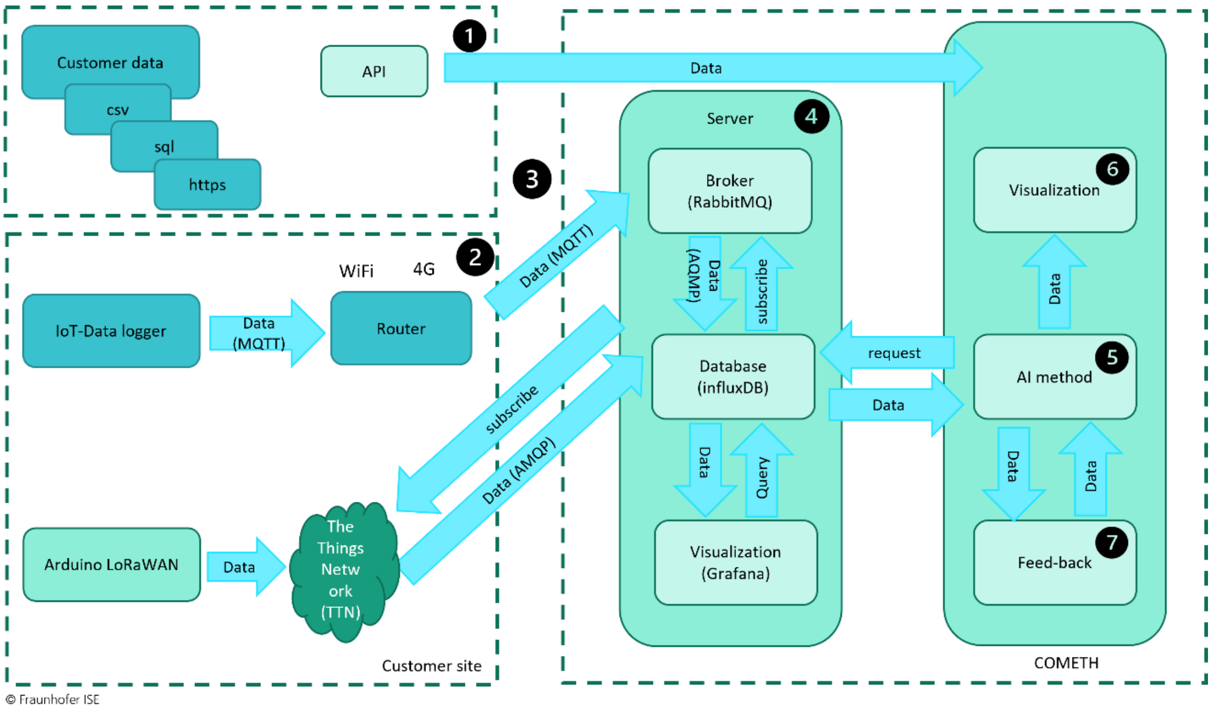

Figure 17: Data paths in the IoT based solution monitoring solution developed by Fraunhofer ISE

6 Discussion and summary

Digital Twins

The four examples presented in section 2 address different aspects of integration of digital twins for heat pumps: from a digital twin of a single heat pump for a single service to multiple services of distributed heat pump assets and their digital representations to general frameworks for energy components. Although the issues addressed in the examples are mainly not specific to heat pumps but can be seen in the context of overall IoT topics – such as security – it becomes apparent that the services around digital twins of heat pumps can have very different requirements, e.g. real-time control vs. predictive maintenance. The need – either because of restrictions in a refitted environment (2.1) or because of different levels of integration (2.2) – for custom digital twins suggest the use of more general digital twin frameworks as presented in 2.3 and 2.4. They aim to make the creation, use and management of digital twins scalable, reproducible, easy to use and applicable to other components of a heat pump environment. Furthermore, such frameworks enable the common management of meta- and engineering data which in turn facilitates the usage of digital twins over the whole life cycle and different use cases.

Different services and different levels of integration lead to specific requirements on data, models, and simulations which in turn lead to different requirements on databases, simulation frameworks and processing power. The usage of central message broker such as MQTT enable the distribution of data and workloads between field and cloud applications or services and are common to many use cases observed in the IoT Annex. Further commonalities are the usage of general purpose and high-level programming languages especially Python and models based on the *functional mock-up interface* called FMU. Reusability of workflows and ease of deployment is the main driver behind the usage of FMUs.

Building Automation

The connected heat pump as part of a building automation system is the subject of the two use cases in section 3. Although many observations and challenges from digital twins – of single or multiple heat pumps – are applicable additional ones arise from the fact that the environment, in which the heat pump operates in, gains even more importance. Usually building automation systems are very heterogenous spanning from small single sensors to more complex systems and the amount of data collected can become very large. With this variety interoperability can be a challenge, with each vendor preferring different connectivity interfaces and protocols, and thus, the integration becomes complex, while also acknowledging the fact that part of the data is sensitive personal data. The need to represent and connect various data sources in a unified way entails the importance of semantic enriched data representation and protocols.

In both presented examples this is addressed by the usage of BACnet/IP, although for streaming of high volumes of data MQTT is preferred due to a smaller overhead. Connecting the various actors and multiple automation protocols to supervisory analytics and control logic, gateways are used. Unfortunately, configuration and deployment of these can be very effortful.

Grid Services

Compared to the other examples in the ones presented in section 4 with heat pumps as part of grid services the service provider is an outside entity per design. This entails either additional effort to be made for interconnectivity by designing and adhering to international standards, as outlined in 4.1 or all in one solution as shown in 4.2. This effort is necessary in order to provide an environment in which manufacturers, service providers vendors can either provide or subscribe to dependable business cases lasting several years. With public energy infrastructure and sensitive personal data affected security is again of paramount importance. The typical separation of this use cases between layman customer – who is usually only minimally involved in the implementation and operation – and expert service provider add to the challenge of data and meta data quality and completeness.

Capable gateway devices connecting various (pre-existing) onsite hardware over the internet is the centerpiece of such use cases. With primarily domestic environments in mind the most wide-spread interfaces and protocols such as WiFi are an obvious choice to provide connectivity, enable over the air updates and enable user engagement.

Retrofit

Retrofit with additional examples provided in section 5 are a common theme among all observed use cases. With the longevity of heat pump devices, the fact that computation platforms, interfaces and protocols must satisfy use cases of connected heat pumps often possibly over a decade later is an apparent issue. Also, often manufactures, with reliability and existing knowledge in mind, chose older more established interfaces and protocols over more recent IoT-Protocols. This is evident in the fact that MODBUS is one of the most common protocols in use.

Therefore, a layered approach to heat pump connectivity is the most common. In this approach gateway devices connect the field level to the internet thus adding additional capabilities to the core functionality of the heat pump. Analytics and control can either be performed on the gateway device itself (edge-computing) or externally (cloud-computing). Common in retrofitting use cases the heat pump is affected only indirectly by a human acting on insights from collected data. The lack of pre-existing connectivity on site makes the use of wireless protocols and interfaces an obvious choice for retrofitting use cases. As is the use of proprietary and non-standard interfaces, protocols, and platforms on the field level the main challenge to overcome.

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