Project: Digital twins for large-scale heat pump and refrigeration systems
Work Package 1 - Deliverable 1.2

“Recommendations for suitable framework for digital twins of large-scale refrigeration systems and heat pumps”

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Executive Summary

A digital twin is a virtual representation of a physical system that can potentially be used to supply different services, such as enhanced monitoring, fault detection and diagnosis, predictive operation and maintenance, control optimization, and system reconfiguration. The purpose of this report is to bridge the gap from abstract concept description of digital twins towards specific steps for the development and implementation of digital twins and the surrounding infrastructure for the case of large-scale heat pumps and refrigeration systems.

Chapter 2 of this report gives an overview of different digital twin concepts and standards that have been proposed in literature. The general digital twin architecture for energy conversion plants defined by Steindl et al. [1]is found to be a good basis for the further description of a possible implementation of a digital twin for large-scale heat pumps and refrigeration systems. It defines six layers relevant for the implementation of digital twins, starting from the physical asset and its integration, via the communication and information handling to the functional layer that includes all models and algorithms used to represent the physical plant in the virtual space. The top layer is denoted by the business logic. This proposed infrastructure is in line with the reference architecture model Industrie 4.0.

Chapter 3 classifies relevant services potentially provided to large-scale heat pumps and refrigeration system using digital twins according into five concerns; monitoring, diagnosis, prediction, control, and reconfiguration. Further, the different services are evaluated regarding their expected reaction times. The service concern and the required response time give an indication of on which system level the service may be implemented most efficiently. Services with short response times concerning local controllers or subsystems should be implemented at lower control levels of the system, while services with need for external data input and with longer response times may be implemented in the high level control or externally, e.g. as a cloud service.

Chapter 4 explains three possible implementations of the digital twin infrastructure with the existing SCADA system. The first approach considered is the lumped digital twin architecture. Here all levels are implemented externally and are connected to the plants SCADA via an API. The lumped approach is especially relevant during development of the digital twin and as a add-on to existing systems, since it can be easily modified. It is however limited to services with response times slow enough to communicate via the API. The distributed digital twin architecture aims at implementing the different services and modules of the digital twin architecture at the system level where they are used. The digital twin is therefore “distributed” across the system control levels. This approach ensures suitable response times of the digital twin, system security, and a lean implementation. It is however not suitable for retrofitting. Finally, an IOT based digital twin infrastructure is presented that is implemented in parallel

to the existing SCADA system. This approach is the most flexible and scalable, it is however deemed to not comply with the security requirements of energy conversion plants. Finally, the proposed workflow to develop a digital twin is described, consisting of three major steps; definition of the purpose of the digital twin, modelling of the digital twin and implementation of the communication infrastructure.

Finally, we comment on possible challenges regarding system maintenance and security and discuss open questions to be clarified within the following work packages of this project.

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Nomenclature

Abbreviations			
API	Application Programming Interface	MQTT	Message Queuing Telemetry Transport (Protocol)
DT	Digital Twin	OME	Observable Manufacturing Elements
FMI	Functional Mock-Up interface	OPC UA	OPC Unified Architectur
FMU	Functional Mock-Up Unit	PLC	Programmable Logic Controller
GDTA	General Digital Twin Architecture	RAMI 4.0	Reference Architectural Model Industrie 4.0
HMI	Human-Machine-Interface	REST	Representational state transfer (Software architecture standard)
HTTP	HyperText Transfer Protocol	RPM	Rounds Per Minute
HTTPS	HyperText Transfer Protocol Secure	SCADA	Supervisory Control And Data Acquisition
IIOT	Industrial Internet Of Things	SSP	System structure and parametrization standard
IOT	Internet Of Things	VPN	Virtual Private Network
LAN	Local Area Network		

1 Introduction

1.1 What is a digital twin?

Physical entities may be represented by digital entities. This is common practice in the engineering field, where systems are modelled and simulated, especially during design and engineering of new systems. Simulation is increasingly used during operation and maintenance of the physical systems. The development of digital twins is in line with this trend that aims at reducing development time, higher operational performance, less downtime and fulfilment of quality requirements and customer needs. A Digital Twin in this context refers to a description of a physical system based on engineering data, operational data and a set of executable numerical models of the system that evolves with the physical system over time and provides functionalities to support design, engineering, operation optimization and maintenance of the physical system [2]. Further, an important part of the digital twin concept is the communication infrastructure that is the basis for synchronization between the physical entity and the virtual entity. A more detailed description of the different elements of a digital twin and how they relate to each other is given in section 2.

The concept of digital twins has been mainly used for highly complex and expensive systems, such as aircrafts or space shuttles [3]. Another field of application that has been discussed broadly in literature is manufacturing, where digital twins are used to track the state of manufacturing elements, i.e. products, equipment, material, processes, facilities, environment, personnel and supporting documents [4]. Increased available computing power, machine learning and advances in hardware architecture support the development of digital twins for other industrial and domestic applications.

1.2 What is the motivation to use digital twins for large-scale vapour compression systems?

The motivation to develop digital solutions for large-scale heat pumps and refrigeration plants is to exploit the information and communication technology to increase operational performance of the systems, optimize maintenance and lifetime of the components, improve the design and optimization process of plants and simplify the integration with the smart grid. Large-scale heat pump systems are still produced in low numbers and often adapted to the specific site. This is necessary as typically natural heat sources or industrial excess heat sources are used that have site-specific characteristics. Large-scale refrigeration plants are more frequently employed, e.g. in supermarkets or cooled warehouses. Their design does however vary according to the site-specific needs, too. The main components and general system layout is however similar in all cases, which makes the development of digital twins of these systems promising as long as they are easily adaptable to the site-specific conditions.

1.3 What are the main characteristics of large-scale vapour compression systems relevant to the design of digital twins?

Large-scale heat pumps and refrigeration systems are typically operated as stand-alone units to supply heat or cold directly to the end-customer or are part of larger industrial systems supplying heat or cold to downstream processes. Large-scale heat pumps and refrigeration systems are utility plants that are often owned and operated by non-specialists. Maintenance and systems surveillance is therefore often provided by external service providers, e.g. AK centralen or by the contractors associated with the plant manufacturer, e.g. Johnson Controls Køleteknik.

The stakeholders that could make use of a digital twin for large-scale heat pump systems and refrigeration plants are the owner and/or operator, the maintenance service provider and the manufacturer. The owner or operator of the plant are utility companies or industrial and commercial companies that operate their own utility plants, such as supermarkets, breweries, drying facilities, etc. Most owners/operators are therefore expected to be interested in a high-level overview of the plant performance and high level of automation regarding problem handling and operation optimization. Maintenance service providers are typically plant experts, in order to deliver high-level maintenance service they are expected to have an interest in in-depth insides into the state of the plant, online availability of data for remote surveillance, as well as applications regarding fault detection and predictive maintenance. Finally, the manufacturer of the plant is interested in operational data in order to improve its products and processes. Here, a digital twin may be of use for classic simulation tasks, such as plant design and controller design, and beyond that to optimize the (re)design process and simplify the development process of new projects. The digital twin of a plant could be based on the models used for plant design, thereby the digital twin would not have a physical counterpart in the beginning[2, 3]. The digital twin could then be commissioned alongside the physical plant to assist with plant operation, monitoring and maintenance of the plant. This means, that the data needed for the services supplied using the digital twin during the operation phase needs to be considered already when designing the plant and the digital twin, such that e.g. all relevant sensors are included and the corresponding measurement data is transferred to the digital entity.

The relatively low number of systems and the high degree of individualization require a structure of the digital twin that can be easily adapted to new systems. Further, it should be possible to cost efficiently add the digital twin to existing plants, as energy utility plants as large-scale heat pumps have planned lifetimes of 25 years [6] and commercial refrigeration systems often have expected lifetimes of 10 to 15 years.

1.4 Aim of this report

There is not one clear definition of concepts and capabilities of digital twins, due to the vast options of applying digital twins throughout the different steps of a system's life cycle [1]. To implement a digital twin for specific systems (like large-scale heat pumps and refrigeration systems) it is necessary to bridge the gap from abstract and general concept descriptions towards specific steps for the development of a digital twin and the surrounding infrastructure.

Here, we firstly present general digital twin architectures defined in literature. In order to apply these to the specific case of large-scale heat pumps and refrigeration units, the intended applications of the digital twin are described. Based on these we propose three specific implementations of the general architecture of a digital twin to large-scale heat pump and refrigeration systems. This includes the description of the required communication infrastructure and the model set-up within the virtual part of the digital twin.

2 Review of digital twin architectures

2.1 General requirements of a digital twin

ISO 23247-1:2021 [5] defined general requirements that digital twins for manufacturing applications should meet, that are presented in Table 1. The requirements apply similarly to digital twins of large-scale heat pumps and refrigeration systems. The explanations in Table 1 have been adapted to the case of large-scale heat pumps and refrigeration systems.

Table 1 General requirements of a digital twin as defined by ISO 23247 [5]. *The descriptions have been adapted to fit the case of large-scale heat pumps and refrigeration units.*

Accuracy	A digital twin shall describe the state of its corresponding plant or component at an appropriate level of fidelity.
Communication	A digital twin should be connected to the corresponding plant or component using communication protocols that enable synchronization.
Data Acquisition	A digital twin shall collect data from sensors installed on or around the plant's components.
Data analysis	A digital twin shall enable analysis of the state of the plant and plant components.
Data integrity	A digital twin shall correctly describe the state of its plant and plant components.
Extensibility	A digital twin shall be extensible to new applications.
Granularity	A digital twin shall provide insights into the state of the plant and plant components at appropriate levels of detail.
Identification	A digital twin shall contain data that uniquely selects its plant and plant components.
Management	A digital twin shall enable optimization of resources.
Product life-cycle	A digital twin shall support information continuity throughout the product life-cycle including design, planning, manufacturing, and maintenance.
Security	A digital twin shall only communicate with authorized resources.
Simulation	A digital twin shall enable simulation of the plant and plant components in operation
Synchronization	A digital twin and its physical counterpart shall be updated to each other's value using an appropriate event-based or time-based method.

Viewpoint	A digital twin shall support different views for different objectives. A view is a projection of a model, from a given perspective, which omits entities that are not relevant to this perspective (ISO 23247-1:2021).

Further, the scalability of the digital twin architecture as well as the ability of integration with surrounding systems should be considered. This includes several dimensions as indicated in Figure 1. Integration along the lifetime of an asset includes reusing models from the design phase during the operation phase, as proposed by Boschert et al. [2]. This means that different virtual representation of the physical asset throughout the lifetime may be connected. This may include the possibility to add and remove service applications and or simulation models (virtual representations) from the digital twin framework. This would allow to adapt the service during the lifetime of an asset if needed and allow to shift to other digital tools as these are being developed further. This is an essential feature in order to make the digital twin of an asset future proof.

Integration across hierarchies refers to communication of the digital twin of a certain asset to digital twins of sub-components or higher level cyber-physical systems controlling e.g. a set of similar systems. In order to enable this integration the different hierarchical levels need to have a common interface.

Finally, scalability may refer to applying the digital twin developed for one system of its kind to many similar systems. Here, models and algorithms are needed that can automatically adapt to new systems. A large number of units connected to the same digital twin infrastructure may further allow for the supply od aggregated services.

Key to all the integration and scalability aspects are clearly defined interfaces and communication standards.

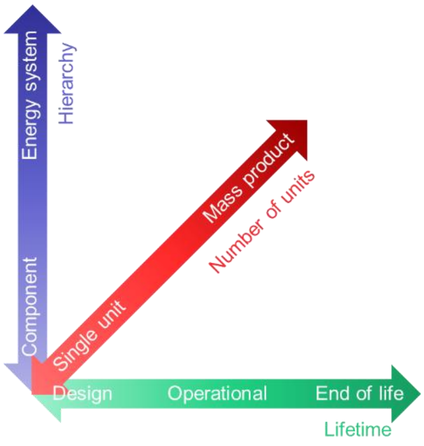

Figure 1 Dimensions of scalability and integration of digital twins.

2.2 General Digital Twin framework

The topic of digital twins has developed rapidly in recent years, as can be seen by the number of publications found when searching “digital twin architecture”, which has increased tenfold since 2017 (status: February 2022). Different digital twin architectures have been proposed. The different proposed architectures differ in their level of detail, where some remain on the conceptual level with a high level of abstraction, while others discuss the implementation of digital twins in more detail.

Three dimensional approaches

The most basic concepts define a digital twin based on three main domains, the physical space, the virtual space and the connection between the two (Figure 2).

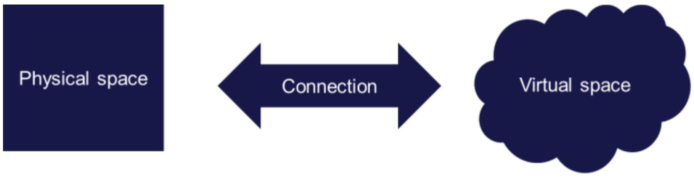

Figure 2 Schematic representation of the three dimensional approach to a digital twin architecture

This concept has been introduced by Grieves et al. [7]. The physical space includes the observed elements, e.g. a large-scale heat pump. Further, all measurement devices and actuators are included in the physical space. The virtual space contains the virtual representation of the physical system plus additional programs or applications to fulfil the desired services (e.g. fault detection). Further, the data storage and data handling is part of the virtual space. The bidirectional connection between both part allows for synchronization of the virtual representation with its physical counterpart and to feed operation set-points back to the physical plant. Note that the "digital twin" is part of the virtual space, while the "digital twin concept" refers to the entire set-up, including the physical space, the virtual space and the communication.

This digital twin concept is closely related to the concept of cyber physical production systems, as defined by Monostori et al [8]: "*They are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data- processing services available on the Internet.*" That means digital twins are part of cyber physical production systems and Uhlemann et al. postulate that digital twins are actually the prerequisite to build up cyber physical production systems [9].

Recently, the Standard ISO 23247 has been published defining a digital twin framework for manufacturing. It defines a reference architecture of the digital twin itself and proposes a suitable infrastructure for information exchange. The proposed general digital twin framework for manufacturing is similar to the three dimensional approach and is depicted in Figure 3. Here, the physical space includes the observable manufacturing elements (OME), i.e. personnel, equipment, material, process, facility, environment, product and supporting documents. In the case of energy conversion units, the observable object is the energy conversion plant itself, its connection to the surrounding systems and the environment. The virtual space is called the digital twin entity here. The virtual space includes the digital representation of the OME as well as applications supplying the services delivered using the digital twin, as real time control, off-line analytics, health checks, predictive maintenance, etc. The device communication here, corresponds to the connection defined in the three dimensional approach. The ISO 23247 part 2 defines, the different functionalities included in the digital twin framework and part 3 defines suitable infrastructure for information exchange in-between the different entities and sub-entities. Both are targeted at manufacturing use cases and are not directly applicable for energy conversion units. When looking at the details of the included functionalities and the information exchange, it becomes clear that the division into only three parts is highly simplified and only useful for conceptualizing the idea.

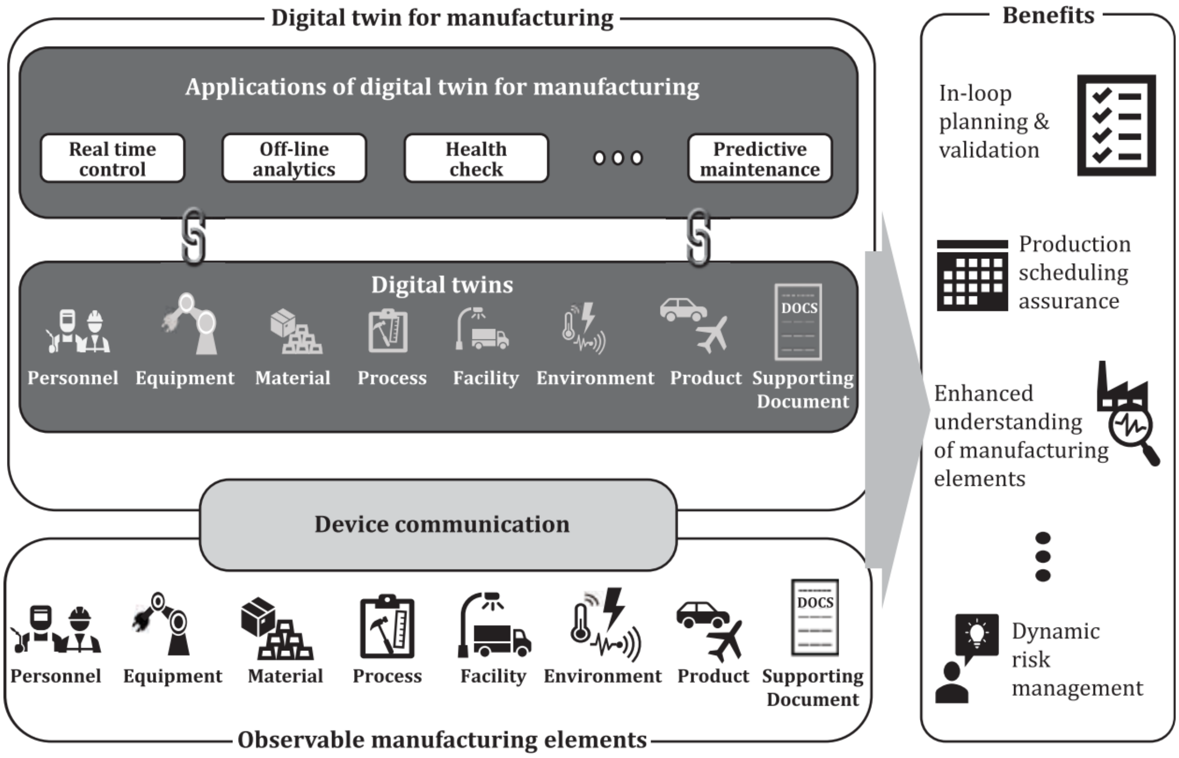

Figure 3 IoT framework for digital twins in manufacturing defined in ISO 23247, illustration taken from [5]

Five dimensional approaches

Tao et al. proposed a five-dimensional approach to describe the digital twin concept, including more details, about the role of data and the differentiation between the virtual entity and the supplied services. The five entities included are: the physical entity (e.g. refrigeration unit), the corresponding virtual entity (virtual representation of the physical system, i.e. a set of simulation models), data, services and the connection between the different parts. Data exchange is essential in order to exploit the potential of the digital twin concept; it is therefore depicted as central element. Further, it is noteworthy that they propose to separate the services from the virtual entity. Services are programs or applications used to fulfil certain tasks, such as detecting faults in measurement data or optimizing the controller set-point taking the current boundary conditions into account. The separation of the virtual entity and the services entity makes sense, as some services may be provided solely based on measurement data, while others may need to use the capabilities of the virtual entity, i.e. simulation of the physical system.

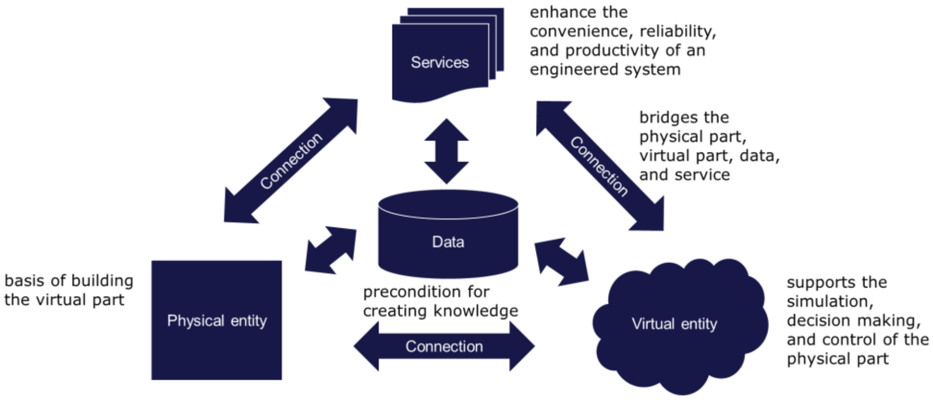

Figure 4 Schematic representation of the five dimensional approach to a digital twin architecture

A comprehensible general digital twin architecture (GDTA) has been proposed by Steindl et al [1] based on the five-dimensional approach presented by Tao et al. It is in line with the Reference Architectural Model Industrie 4.0 (RAMI 4.0, [10]) that defines a reference framework for digitization of industrial processes (Figure 5). This alignment is advantageous as confusion between different terms and definitions may be reduced. Figure 6 shows the graphical representation of the proposed GDTA using the layers defined in RAMI 4.0, which are described in the following:

Asset – The physical entity, in our case this would be the real heat pump or refrigeration plant (or parts of it).

Integration – The integration level describes the transition from the real world to the digital world. This is achieved through data collection and exchange. The data may be divided into run-time data and engineering data. Run-time data means operational data describing the state of the system, typically changing with time and often available in form of time series. Engineering data describes the physical entity and does typically not change over time, this could be type and design specification of components, plant layout, etc. Engineering data will often require manual input from analog sources.

Communication – On the communication level the exchange of information is managed. Different standard communication protocols may be used (also in parallel). Industrial communication or Industrial Internet of Things (IIoT) may be applied in this context, such as OPC Unified Architecture (OPC UA).

Information – The Information layer is the central provider of information about resources and services and makes this information available to the functional layer. According to the proposed GDTA data should be stored in the original format in suitable repositories and the contextual and semantic information is contained separately within the shared knowledge base. Further this layers includes modules to retrieve information from the knowledge base and provide it to other services and to add or change information from the upper layers of the digital twin.

Functional – The functional layer contains the function of the asset. The proposed GDTA structures these functions according to service types provided by digital twins, i.e. reconfiguration, control, prediction, diagnostics and monitoring and simulation. The service management module takes part of registering, discovering and monitoring the status of the services included in the digital twin. Further, a Human-machine-interface (HMI) is an essential part of the functional layer of a digital twin.

Business – the business layer is located above the functional layer of the digital twin and the business logic is contained. This may also manage several digital twins and defines the overall objectives that should be reached through the digital twin operation.

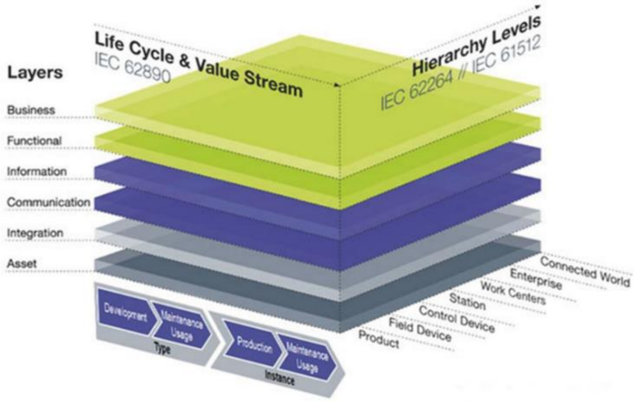

Figure 5 Schematic representation of the Reference Architecture Model Industrie 4.0 [10]

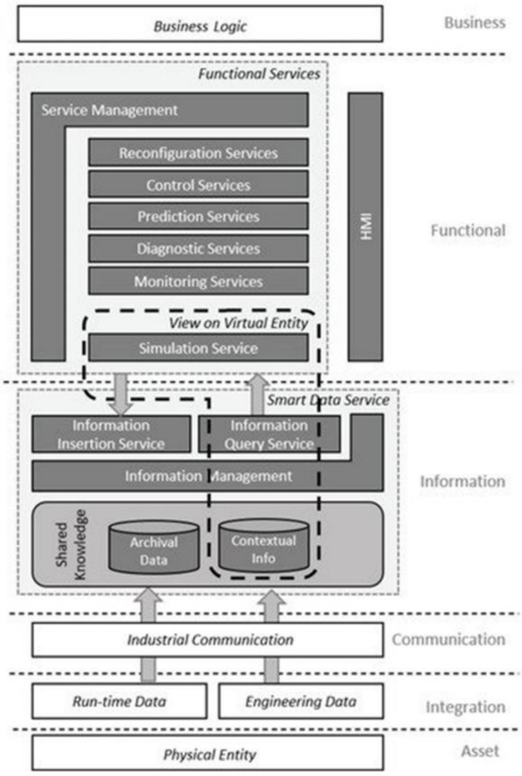

Figure 6 Generic Digital Twin Architecture proposed by Steindl et al. [1]

The GDTA has been defined specifically for digital twins of energy conversion units and will be used to propose possible implementations of digital twins for large-scale heat pumps and refrigeration units in the following chapters.

2.3 Implementation of digital twins

The implementation of digital twins involves establishing the required communication infrastructure as modelling the virtual entity and developing the required service modules. The implementation process may follow an evolution from a digital model of the plant to a digital shadow of the plant to an actual digital twin of the plant [11]:

- Digital Model: A virtual representation of an existing or planned physical entity. There is no information or data exchange between the physical asset and the digital model. The model may be used for developing or analysing the physical asset, but changes in the model will not result in an effect on the physical asset.
- Digital shadow: Here the virtual representation of the physical asset and the physical asset are connected via a one-way connection from the physical asset to the virtual representation. This allows representing changes in the physical asset or its operation in the virtual representation. However, there is no information being send back from the virtual representation to the physical set-point.
- Digital twin: In a digital twin the virtual entity and the physical entity are synchronized with each other in both directions. This requires automated exchange of data between them and allows using the virtual entity to control the physical entity.

These steps may be useful, especially for testing the functionality and different services of the plant before allowing full synchronization of the virtual space with the physical space. In order to safe double work and redefining standards late in the development process it may however make sense to take the requirements of the fully integrated digital twin in to account when planning the implementation steps of the digital twin, as well as the model architecture and interfaces. The ISO 23247 [5] defines which interface standards should be defined when establishing a digital twin:

- Selection of a digital identification method for the assets that are to be twinned
- Selection of standards and technology for the data collected from the asset
- Selection of standards and technology for the control of the asset
- Selection of standards and technology for the digital representation of the asset
- Selection of standards and technology for communication between the asset, device communication and digital twin levels
- Selection of standards and technology for communication with the user applications of the enterprise.

Translating these steps to large-scale energy conversion units, it may be seen that some of the proposed steps are already in place to control the plant and extract data into the business logic, as further detailed in section 4.1.

3 Application/Use cases of digital twins of large-scale vapour compression systems

In order to develop and implement a digital twin for a plant the purpose of the digital twin should be defined clearly [2]. This helps to target the development. To do so the following questions should be answered.

1. What are the intended applications (i.e. provided services) of the digital twin?
2. What are the governing dynamics of the respective service?
3. In which lifecycle is the application relevant? What is the corresponding user group (designer, SW/HW developer, test engineers, operators, maintenance personell, etc.)?
4. What additional requirements can be derived (HMI, e.g. visualization, …)
5. What kind of data input /output is needed for the respective application?

The services that may be provided using digital twins are multiple. They 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 7

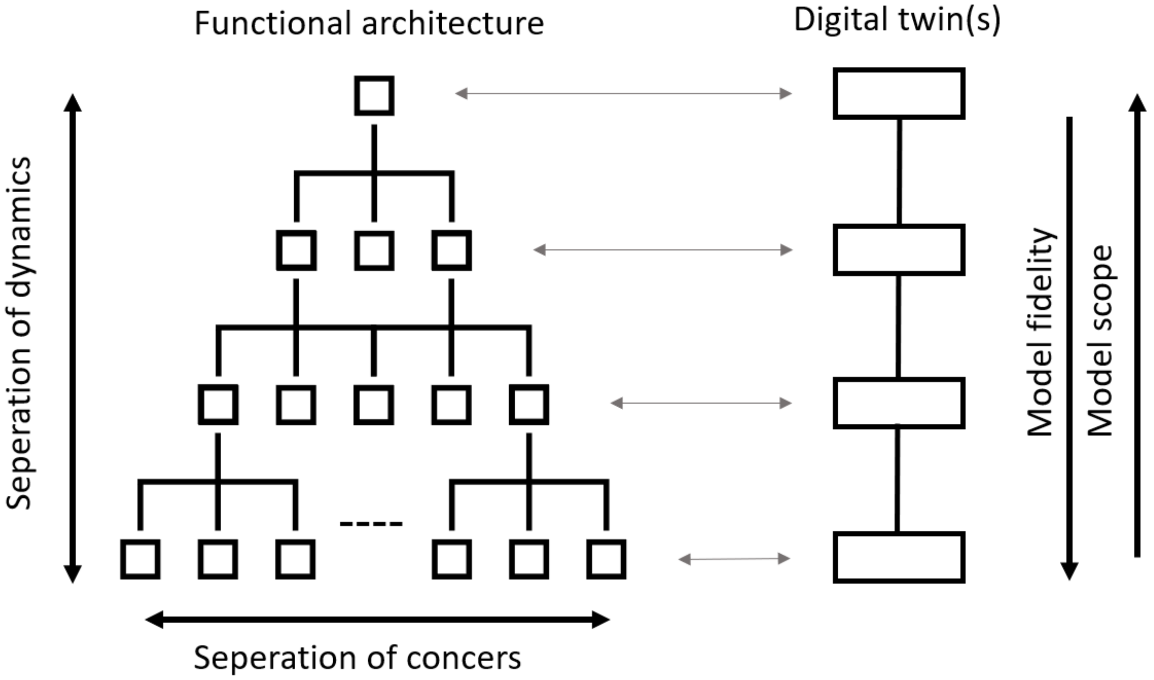

Figure 7 Functional architecture and digital twin

Here, we have clustered them into five areas of concerns as proposed in GDTA presented above [1]:

- Monitoring services
- Diagnosis services
- Predictions services
- Control services
- Reconfiguration services

These fields may include services that require different response times. In Figure 7 the top layer contains functionalities requiring the slowest update frequencies, while the layers below are requiring faster and faster update frequency 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 less accurate, as here the interconnections of the underlying sub-systems are handled. This aspect will be further discussed in section 4.2.

In the following, a short conceptual description of services relevant for large-scale vapour compression plants is given and the services are categorized according to their dynamics and concerns.

3.1 Monitoring services

3.1.1 Performance monitoring

Performance monitoring is done for most plants. Key indicators like COP, heat flow rate at sink or source and supply temperature are typically available via the SCADA system. For some purposes this level of information may be satisfactory, while others may require additional information, such as detailed knowledge of the conditions in the plant or benchmarking of the current performance compared to theoretically possible performance. Operators, maintenance service providers and manufacturers (designer, test engineer and HW/SW developer) are potentially interested in performance data, as this allows to identify, how well the system is operating and constitutes the basis for decision of plant maintenance and delivers information regarding potential plant improvements. The performance data should be readable by the operators, maintenance personell and manufacturers (if allowed by the plant owner) through an appropriate HMI, including visualization of the plants state on different detail levels, similar to existing SCADA interfaces. Performance monitoring may both be used to represent the current state of the system in (close-to) real time, which requires a feedback frequency between the digital twin and the plant in the range of minutes, and to evaluate the performance over a longer period of operation, here slower response times are acceptable.

Example: The performance of individual evaporators in a supermarket refrigeration system can be analysed using the insights from a dynamic system model that uses measurement data from the real plant as input. The model enriches the data available from measurements and thereby provides data of the evaporators' energy flow rate, approach temperature differences, pressure drop, etc.

3.2 Control services

Four different control services will be described in the following. The four services are divided according to the time scale of the required response. This way of structuring the optimization logic is meaningful if the external disturbances are split into "fast" (zero mean) and "slow" (non-zero mean). The influence of the "fast" disturbances must be suppressed by the control system, whereas the setpoint and scheduling optimization layers must adapt to the "slow" non-zero mean disturbances. This division is only meaningful if the fast zero-mean disturbances do not contribute (increase/decrease) to the mean cost of energy. If this is the case, the additional cost should be optimized in the coordination optimization layer.

3.2.1 Optimal control

The objective of the control system at the lowest control layer is to stabilize the sub-system, follow the desired setpoint and suppress disturbances. The requires response time is in the range of seconds or lower. At the sub-system level, the control is typically divided to maintain operational objectives of the sub-system. In a supermarket an example of this could be the capacity control of the compressors where the objective is to maintain a desired suction pressure. This type of control is typically done using PI (Proportional Integral) type of control, here the optimization is handled by the commissioning engineer that tunes the controller to the given system to obtain a satisfactory performance. More advanced control "optimal control" methodologies also exist. These relies on a dynamical model that can predict future trajectories of the system given a control sequence, by searching over the possible control sequences and resulting trajectories the optimal control sequence can be found that satisfy the control objective – both on-line and off-line methods exist. Nevertheless, these methodologies rely on high fidelity models that accurately describe the dynamic behavior of the system. The use of models here may be interpreted as the provision of a service to the local controller. It should therefore not be possible for unauthorized stakeholders to change the settings of these models.

3.2.2 Coordination optimization

The "coordination optimization" is tackling the coordination among the bottom level controllers and hence need to be executed with an update frequency in the same range as the control logic. By optimizing the coordination between the different subsystem controllers, optimal tuning of the controllers may be achieved and problem due to unwanted interactions (e.g. hunting due to overlap of controller bandwidth) between subsystem controls may be avoided. The required input is the status and parametrization from the subsystem controllers as well as the set-points for the overall plant. As the previous service, this service is provided to the system itself and should not required human interaction.

3.2.3 Scheduling optimization

The scheduling optimization is intended to plan the operation of the heat pump or refrigeration plant such that the energy cost is minimized while maintaining the required temperature. The scheduling is optimized according to energy prices, ambient conditions, energy storage capacity, predicted heating or cooling demand, etc. Typically, the scheduling is conducted on an hourly basis. Therefore, very fast exchange of data between the physical entity and the virtual entity is not required. The service requires the current status and the predicted state of the plant for the time horizon the scheduling should be provided for. It outputs an optimal operation schedule. The scheduling optimization helps the plant operator with choosing the right operation strategies according to the predefined targets (e.g. minimization of cost or emissions). The service should therefor allow for interaction with the plant operator and the results should be accessible, and it should be possible to override the schedule if the operator deems this necessary.

3.2.4 Set-point optimization

Set-point optimization is a service that may help operators to run their system at the maximum possible efficiency under the current boundary conditions and state of the system (including wear, deposition on heat exchangers, etc.). The current boundary conditions and state of the system are loaded into the digital twin, where a model of the plant is coupled to an optimization algorithm to determine the optimal controller set points (typically: forward temperature, compressor speed, pressure levels). The optimal values may then be send back to the plant as a control signal. This service would allow to run the plant at maximum possible efficiency at all times. Information regarding the changes made through this service and the effect (saved energy compared to standard settings) should be archived and accessible for the operator.

3.3 Diagnosis services

3.3.1 Fault detection and diagnosis

Faults may be detected and diagnosed on the sub-system level, on the system level or even remote. On which level the service should be implemented depends highly on the type of faults and the expected development of the fault with time. Mission critical faults should be detected and accommodated for at the low-level controller level, such that fail-safe operation may be upheld. Faults at this level are typically sensor or actuator faults. These may be accommodated for by using an average historical set-point value instead. This requires that this type of information is available to the local controller. On a system level it might be possible to correctly diagnose the fault by combining the information from several subsystems.

For the low- level controller to do fault detection high fidelity models representing the fault free scenario that can be used as baseline for comparison must be available. The difficult part is typically obtaining a fault free model. This could however be a “service” that could be provided from a high-level parameter estimation layer that can overview a larger history of data. For high level diagnosis a system-wide model is required that explains how sub-systems are tied together and how they dynamically interact. Further, algorithms are required that can detect a deviation between the model and the current state of the system. The output of fault detection and diagnosis service will always be an information on a fault in the system that should be conveyed to the plant operator and the maintenance service provider.

3.4 Prediction services

3.4.1 Provision of flexibility

Large-scale heat pumps and refrigeration systems may be operated flexibly according to variable electricity prices, thermal boundary conditions or the requirement of the electricity grid for regulation power. In all cases, it is relevant to predict the operation of the plant, to optimize as to when to operate so that the production cost is lowest (electricity prices, thermal boundary conditions), the energy efficiency is highest (thermal boundary conditions) or the plant is available for current changes of the load (regulation power). In order to be operated flexibly, the plant needs to be coupled to a thermal storage, such that demand and supply of heat or cold can be decoupled. A corresponding service module needs to be able to predict the plants performance (e.g. by calling the simulation model) and optimize using a suitable routine taking electricity prices, heat/cooling demand, expected reimbursement for ancillary services and weather forecast into account. Further, optimization criteria could be used instead, e.g. minimizing the CO2 emissions related to the power usage of the plant.

3.4.2 Predictive maintenance

In order to provide predictive maintenance, a diagnosis service needs to be coupled with an optimizing routine that determines when the plant should optimally undergo maintenance, e.g. cleaning of heat exchangers exposed to fouling. Predictive maintenance can thereby help to determine the optimal cleaning schedule for the heat exchanger. The predictive maintenance service module therefore needs to be able to call the simulation service using inputs regarding the state of the diagnosed state (e.g. the heat transfer resistance due to fouling). That means, the simulation model called to determine the performance of the system needs to be prepared, such that the predicted fault/state is an input to the model. Further, it needs to include a suitable optimization routine that take predicted electricity prices, heat demand and possibly weather conditions into account. The output would be a recommendation to the operator.

3.5 Reconfiguration services

3.5.1 Virtual test bench for controller design

The simulation models composing the virtual entity of the digital twin may be used as a virtual test bench for further development of the plant or single components. One example is that the controller could be coupled to the simulation model to optimize the controller design or parametrization using the predicted dynamic reaction of the plant. Accordingly, this service requires dynamic models that mimic the plants behaviour precisely. This service is mostly relevant for manufacturers and developers.

3.6 Categorization of services

Figure 8 shows a categorization of the previously described services supplied by digital twins for vapour-compression plants 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 concern and response time. Further, it may be an advantage to run different parts of the digital twin at different locations in the system. This will be further discussed in the following chapter.

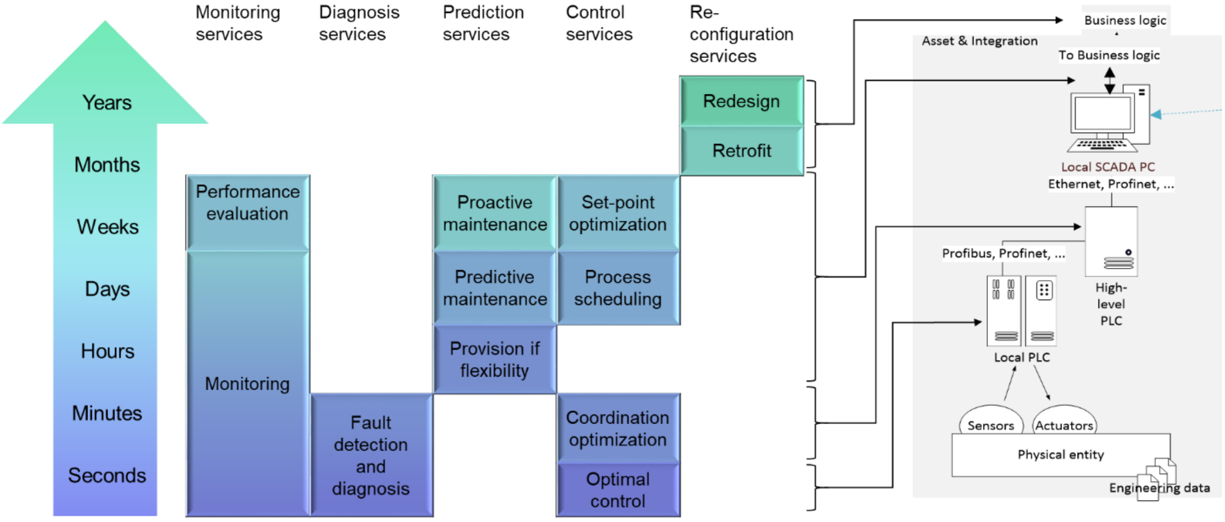

Figure 8 Categorization of services provided by digital twins according to scope, required response time and relevant system level on which the service is executed.

4 Proposed implementation of framework for large-scale heat pumps and refrigeration systems

The proposed implementation is based on the general digital twin architecture proposed by Steindl et al. We do therefore refer to the layers they have defined and try to show how the layers are thought to be implemented for the current case.

4.1 Existing SCADA system

Today, usually a SCADA (Supervisory Control And Data Acquisition) system is used to control and monitor plants like large-scale heat pumps and refrigeration plants. To do so, it requires the same levels as the digital twin architecture. The main difference is that the services supplied by a digital twin are more advanced compared to the services provided by SCADA systems.

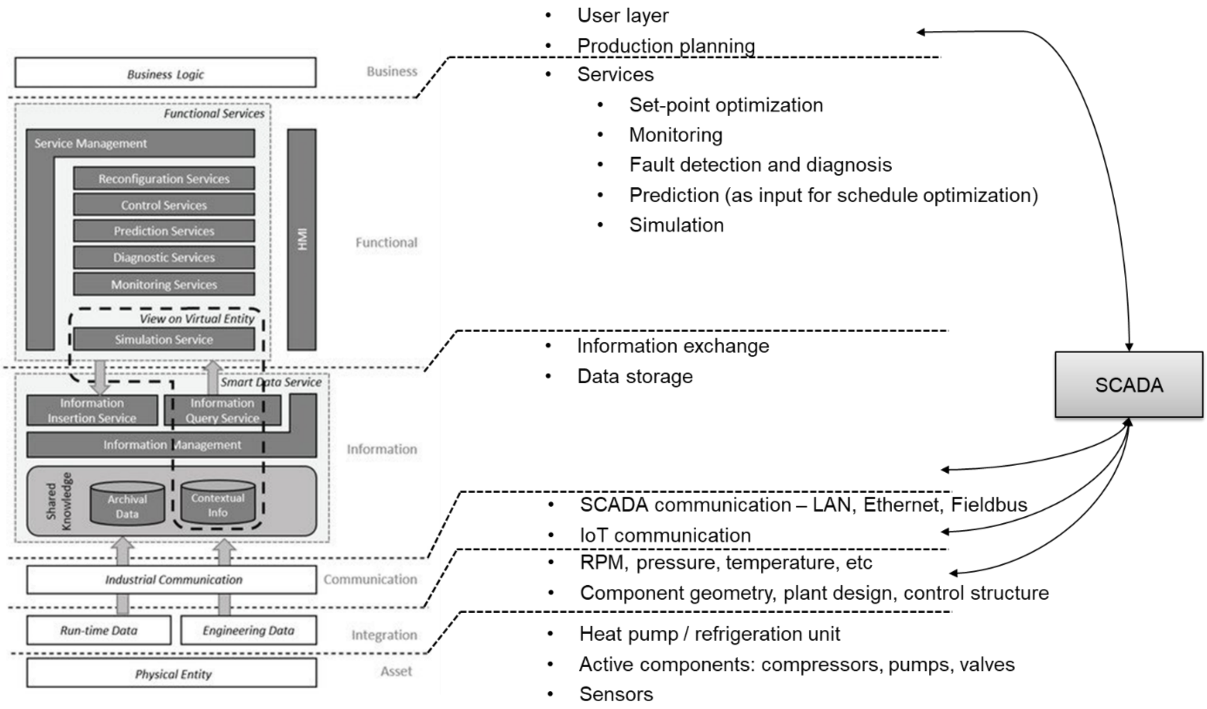

Figure 9 Levels of operation: Digital Twin vs. SCADA

Real-time communication between sensors and actuators at the plant and the plants control (PLC) is typically happening via fieldbus networks, such as Profibus, Modbus, etc. Real-time Ethernet connections may be used as an alternative. The PLC communicates with the local SCADA computer via Ethernet based protocols, this could both be implemented as a wired or wireless connection. The SCADA system is connected to the business logic, e.g. via a VPN tunnel.

The current control/communication hierarchy may be divided into three major levels:

- Bottom level: Local controllers (case and Pack control in the supermarket, PLC in heat pump systems). Objective: Secure robust control of key subsystem parameter – acts autonomously and secures robust stable operation
- Intermediate level: System manager/SCADA. Objective: Receiving and transmitting alarms, optimizing system wide control and coordination of the operation of the bottom level control by adjusting references/setpoint to the bottom level controllers and schedule certain operations like e.g., defrost, system startups etc.
- Top level: Cloud. Objective: Monitor alarms and for remote alarm handling.

The reason for the current control hierarchy and distribution of the logic is mainly driven by robustness consideration. By default, communication lines/fieldbus are not considered reliable, meaning that fallout or unplugged controllers can appear. To ensure fail-safe operation even under communication breakdown, the control logic is implemented locally.

4.2 Information exchange

Digital twins require synchronization between the virtual entity and the physical entity. This means data needs to be gathered, processed and fed into the digital twin continuously and automatically. This requires appropriate software set-up that allows handling the flow of data and the update of models and service modules. Further, the digital twin may possibly send commands back to the physical entity autonomously, i.e. automated and without the involvement of human operators. This could e.g. be of relevance for an automated set-point optimization that maximizes the plants performance despite changes in its state or boundary conditions.

To synchronize a digital twin with the physical entity, operate service modules on it and send settings back to the plant, data on the plants state needs to be generated (integration level) and information needs to be exchanged between the plant (physical entity), the data bases (information level), the digital twin service modules (functional level) and the users (business logic, humans).

The digital twin architecture may be integrated with the existing system, including physical components, controllers, communication infrastructure and data management in different ways. Within the projects different approaches have been discussed, a lumped architecture, a distributed architecture and an IOT based architecture:

- Lumped digital twin architecture

  In the lumped approach all virtual components of the digital twin concept (virtual entity, service modules, data management, etc. are lumped together and only connected to the physical asset via a single communication link. This approach represents the operators perspective, that looks at the plant as one unit, but still needs inside information into the different components to monitor, optimize and maintain the plant. The digital twin infrastructure is connected to the plant via the SCADA system. This will most likely be the case in the development of digital twins, such as in this project, where the uncertainties regarding the abilities of the digital twin are high, the cost for implementation should be low and the safe operation of the plant is secured independently of the digital twin platform. The lumped approach may be easily added to existing systems, as all digital modules are lumped externally and do not have to be installed on the local or system controllers. It does however mean that the infrastructure that needs to be added may be different for different customers. For example, may some customers have a cloud based solution to manage their data in place, i.e. they have a secure way to retrieve data and could extend this to send it further to the virtual entity via standard internet or IoT protocols. While for other existing solutions the option to retrieve data to new applications may not yet be in place. In principle, the digital twin could also be integrated locally as part of the existing SCADA system. This would however require larger local resources, e.g. regarding computing power, data storage capacity, licenses for simulation applications, etc. Further, the scalability and flexibility of the digital twin cannot be fully exploited.

  This approach may be advantageous for services at system level supplied by the digital twin, as the plant data may be easily combined with external data, e.g. electricity price forecast and weather forecast. In this approach all available information may be accessed via the digital twin. This will allow for in-depth analysis of the plant behaviour and possible causes of faults. A lumped digital twin may be advantageous, when not all digital services are developed yet. As the digital twin may be easily updated and new services may be added, since all data (current and historic) can be accessed and the available computational capacity may be increased if necessary and the same services may be provided to similar systems due to the cloud based implementation. The single connection between the physical and the virtual entity helps to ensure system security.

  The disadvantage of this approach is the large amount of data that needs to be transferred between the physical entity and the virtual entity. It may further be expected that this communication is too slow for some possible services that could be supplied by digital twins, especially those related to real time control.

- Distributed digital twin architecture

  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 to add or remove 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 upwarts 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 on one hand are more 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.

- Integration using IOT based infrastructure. In this case, the lower control levels (sensors, actuators and PLC) communicate directly with the digital twin platform via wireless networks using IoT (Internet of things) protocols, such as MQTT, CoAP, HTTP, etc. This requires that the devices are equipped to be able to communicate via suitable protocols. This may require additional investments. The potential benefit will be that the secure operation via standard SCADA systems is still available, while the additional abilities of the digital twin platform can be exploited better, since the PLC (or even actuators) can be addressed by the different services of the digital twin if necessary (e.g. automatic set-point optimization). Devices (sensors, actuators), applications (e.g. simulation programs), data storage, and service modules (small programs run on data) using different native protocols can be connected via an IoT communication platform. This would allow to exchange or add any of the devices, applications, etc. if needed and is easy to scale if necessary.

  This approach is highly flexible, but is disregarded within this project as the accessibility of lower control levels of large-scale energy conversion plants via IOT (or any other optional connections) is undesired as these may jeopardize system security.

<u>Example</u>

A possible set-up of the communication infrastructure for the implementation of a digital twin on top of the existing SCADA system (light grey area) is shown in Figure 10. It assumes that the data retrieval *and archival is automatized using a central API management (dark grey area). The runtime data is assumed to be part of the current SCADA system, it is therefore highlighted in blue. The actual virtual representation of the digital twin is shown with white background.*

The communication layer includes the communication between the plant and the information layer. Here, it includes the connection of the local SCADA to an API management (Microsoft) (or similar systems) and the connection of potential IoT devices at the plant (wireless sensors and actuators) to the information layer. To connect the IoT devices an additional MQTT broker may be used. The MQTT broker enables bidirectional publish-subscribe communication between multiple clients (devices, programs, etc.). Thereby, application and devices can exchange data and be flexibly added and removed from/to the platform. The connection to the virtual entity could be used to directly import measurement data into the simulation model. However, at the current state no IoT devices are implemented in the case study plants and thus the communication via the MQTT is not needed yet.

Within the GDTA it is defined that the information layer contains a shared knowledge base, including data repositories, and a smart data service managing the information exchange between the shared knowledge base and the functional level. It is proposed that the shared knowledge base used for the digital twin is the same as the existing data management platform. Central to this platform is the API manager. It is used to manage data access and data storage in the long term and short term data bases. Further, additional engineering data (e.g. piping and instrumentation diagrams) can be accessed via this platform.

In order to provide the smart data service between the shared knowledge base and the different modules of the functional level it is proposed to use a central platform that allows bidirectional publish/subscribe communication between the different modules, to keep the communication flexible and efficient. One platform that could be used is the context broker (FIWARE) that uses http, https protocol (or similar systems). External applications and devices, such a simulation tools or additional sensors can be connected via the IoT Agent that manages the access of the incoming data and translates it into http, https. The information layer can be cloud based or run on local servers.

In the described case, control commands can be send from the digital twin platform to the plant via the SCADA system (conservative approach) or directly via the brokers in case the actuators or PLC is connected via the IoT network.

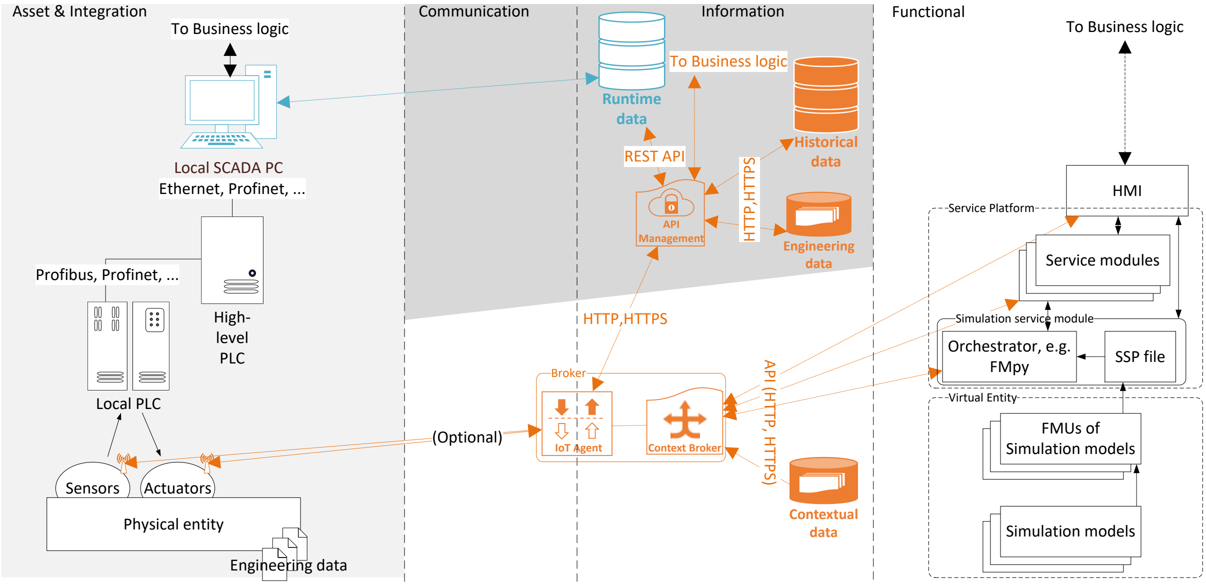

Figure 10 Possible communication infrastructure for IOT based infrastructure

4.3 Proposed software set-up

It is proposed that the functional layer of the digital twin is set-up of the following elements:

- Simulation models of the respective plant. The set of simulation models used to mimic the behaviour of the physical entity is called virtual entity. In this project detailed dynamic models of the plants were developed in Modelica using the TIL library and the models were simulated in Dymola. Further, grey-box models will be derived from the detailed models and/or measurement data where required.
- Service modules, i.e. small programs used to fulfil the services provided by the digital twin using measurement data and simulation data as input. This could e.g. be a fault detection algorithm written in Python. This may also include optimization algorithms, machine learning algorithms, etc. according to the type of service provided (see Chapter 3). Here, it is proposed that the different modules are gathered on a common service platform (Python).
- A Human-Machine Interface (HMI) that allows to visualize the simulation results as well as the results of the service modules.

For the lumped digital twin approach and the high-level parts of the distributed approach, the simulation models may either may run in their native environment and communicate with the service modules via the central context broker or they may be packed into Functional Mockup units (FMU) and be imported to the Python environment. In case multiple simulation models are needed to describe the overall plants behaviour, an FMU could be generated for each model and they would be combined in a common SSP file (SSP – System structure and parametrization standard) as proposed by [12].

The contextual information of the different service modules would allow the context broker to discover and register service modules and obtain the status of the individual modules. This requires, that the service modules are written such that these information is available. The first implementation step within the current development project will however most likely leave out the context broker and handle the information exchange directly within the digital twin platform (e.g. written in Python, see chapter 4.4). It may further be practical that the different modules can communicate between each other directly in some cases.

The programs that are used to provide the desired services may run on any computer or in the cloud. This does however require that the author of the simulation models has the appropriate license to export FMU to others that do not have a corresponding license.

For the lower levels of the distributed digital twin approach, it is important that the models implemented and executed on the edge are requiring small computational power. They should be specifically targeted to the local services and all additional analysis should be done at higher levels. Further, they should be written in languages compatible with the local controller design.

Figure 11 shows an example of how different parts of the digital twin may be divided between different implementation levels.

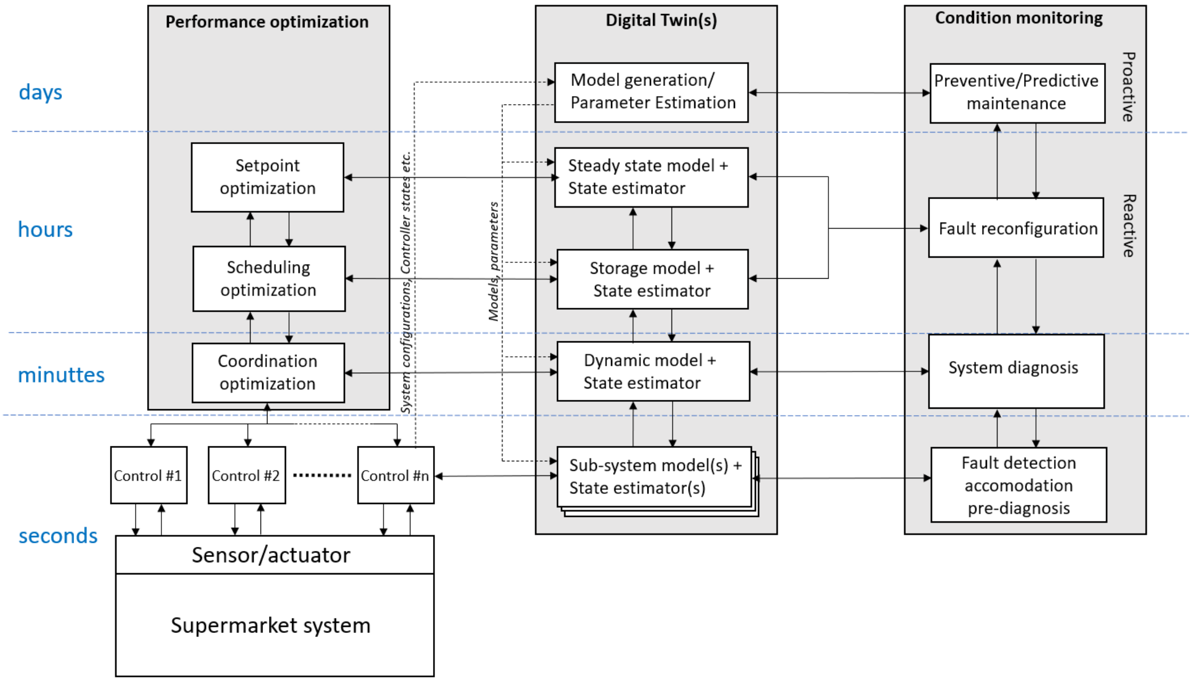

Figure 11 Example of possible division of different element of the digital twin across the different control levels acting on different dominating time domains.

4.4 Proposed work flow

Developing a digital twin for a plant from scratch includes defining the purpose of the digital twin, setting up the communication infrastructure, modeling the virtual entity and developing the desired service modules. As many questions regarding the details of the different implementation steps remain open at the current state of the project, the following workflow is proposed that allows demonstrating the potential of the digital twin without compromising the safe operation of the plant.

1. Definition of the purpose of the digital twin

   Define specific tasks that should be fulfilled using the digital twin. The may include but is not limited to task related to monitoring, prediction, diagnosis, control and reconfiguration.

2. Modelling of the digital twin
   a. Develop a detailed simulation model of the plant in question

      It may be possible to replace this model by simple models in future applications, but this is among the question to be answered by this project. Therefore, we will start with detailed models of the test cases and simplify later on if possible. Further, the detailed models allow us to develop service modules for the digital twin without the need of extensive experimental campaign (possibly including induction of faults) on the real plants. This task includes validation of the model against measurement data.

   b. Develop service modules

      This task includes analysis of the required data input and output from the service module and finding and implementing suitable methods to fulfill the respective service. This task includes validation of the service modules using simulated and measured data. During the development of the simulation model and the service modules, a simplified communication infrastructure may be used, as no automated data flow is needed during the development phase. A possible communication set-up for this purpose is depicted in Figure 12.

    c. Prepare service modules and simulation models for automatic data input/output
3. Implementation of the communication infrastructure
    a. Analysis of the existing data and communication infrastructure and define the communication between physical and virtual entities (including service platform) in both directions.
    b. Implement the infrastructure to extract data from the existing infrastructure (SCADA, API management, etc) to the virtual part of the digital twin
    c. Allow data to be extracted automatically by the digital twin

The final step would be to implement the infrastructure to communicate from the digital twin back to the plant and allow this communication to be automated. Before this happens, the functionality of the service modules should be tested and verified and the communication should be supervised by the plant operator. This is illustrated in Figure 13.

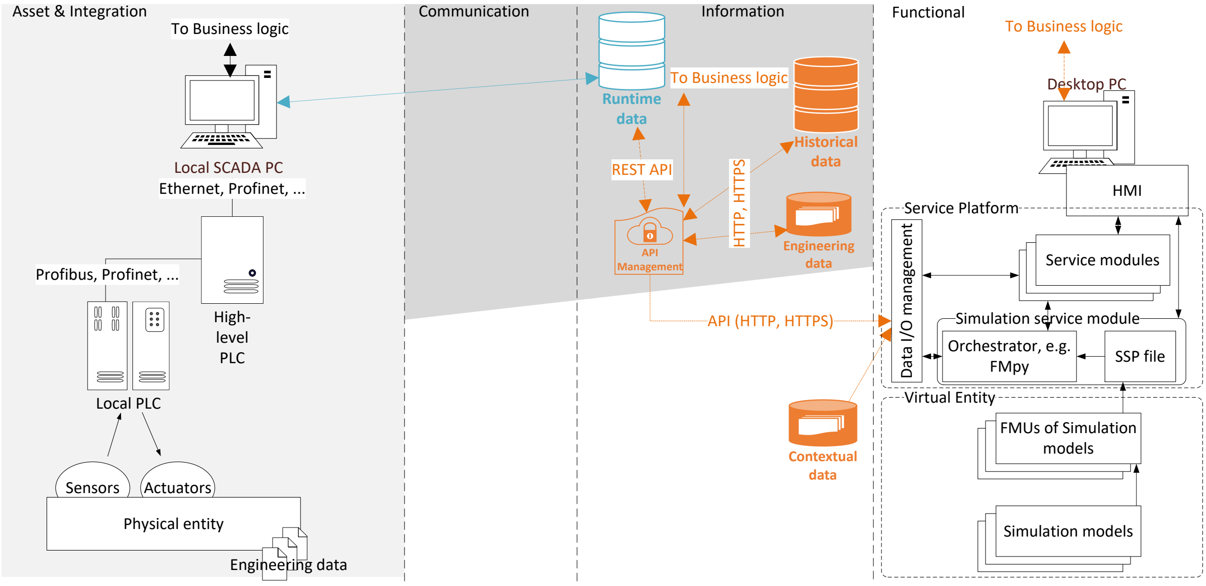

Figure 12 Simplified communication infrastructure during the development phase of the digital twin. The communication via a central context broker is replaced by a simple a simple data input/output script within the service platform that is being developed in Python.

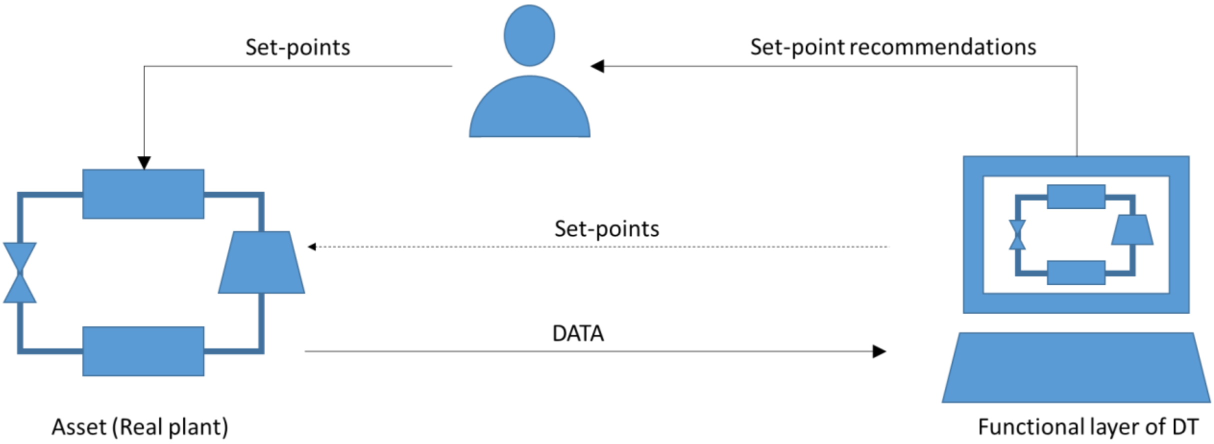

Figure 13 Open-feedback loop between physical and virtual entity via the human operator used to verify the functionality of the digital twin during development and testing phase.

5 System maintenance and security

This chapter touches upon some additional aspect that need to be taken into account when developing and implementing digital twins. These are however not in the focus of the current project and will therefore not be discussed in more detail.

5.1 Authoring and maintaining the digital twin

Authoring and maintaining a digital twin requires highly specialized knowledge in the fields of modelling (of the respective kind of systems), mathematical methods, such as machine learning, stochastic methods, optimization, etc. used within the different service modules as well as communication infrastructure and IoT applications (or similar future pendants). Accordingly, it may not be reasonable that authoring and maintaining the digital twin is the responsibility of the heat pump/refrigeration system owner/operator as these requires a large amount of indoor resources. Instead, plant manufacturers may provide these tasks as a service that can be acquired together with the physical plant. Or third party companies providing operation and maintenance service could provide and use the digital twins to extend their range of services. Both stakeholders could benefit from scaling the development to many individual units.

5.2 Security aspects

A detailed description of how the implementation of a digital twin could be protected against (cybercriminal) attacks is beyond the scope of this report. A few general remarks worth to consider are summarized in the following, based on the security framework published by the industrial internet consortium [13].

The deployment of digital twins is closely related to the development of the internet of thing (IoT), where the different part of the system are communicating via the internet and are connected extensively to other parts of the business. Historically, industrial systems were secured by physical separation and network isolation. This is however not possible, if the advantages of IoT technology are to be exploited, i.e. scalability, flexibility and scope of the services that can be cost-efficiently supplied based on the IoT infrastructure. However, as the IoT infrastructure includes many elements that communicate via the internet, there are many potential targets for attacks on the network, namely, the connected devices, the network and the back-end platforms. Successful attacks on IoT infrastructure in energy utilities (and other systems) can have severe consequences.

When implementing digital twins based on IoT infrastructure, the operational technology used to control and monitor the plant is combined with informational technology. While operational technology is focused on safety, resilience and reliability to ensure the correct operation of the controlled systems, securing information technology focuses on reliability, security and privacy.

Table 2 Definition of characteristics of a trustworthy IIOT (Industrial internet of things) infrastructure

Security	Being protected against unintended or unauthorized access, change or destruction.
Safety	Operating without the risk of causing damage to the health of people, the environment or property.
Resilience	Ability of a system to fulfill its task despite dynamic adversarial conditions and to restore the operational capabilities if needed.
Reliability	Capability of a system to fulfill the intended task with the desired quality in the specified time.
Privacy	Right of an individual or a group to control what information to them may be collected, processed and stored and by whom, and to whom that information may be disclosed.

That means a trustworthy IoT system includes all of these characteristics. Thereby, the system is protected against attacks, but also against disruptions in the environment, faults within the physical or IoT systems and human errors.

In order to secure an IoT system all parts of the system need to be protected, i.e. the endpoints (devices), the communication (network) and the back-end platform. This also includes managing and controlling policies and updates, and using analytics and remote access to manage and monitor the entire security process. A challenge that needs to be taken into account for energy conversion units, such as heat pumps and refrigeration units, is there long lifetime, which possibly results in an increased effort to integrate the existing operational technology with the IoT system, while still assuring that all characteristics of a trustworthy system are met.

6 Discussion and open questions

The implementation framework for a digital twin proposed in this report is based on the specific characteristics of large-scale heat pumps and refrigeration units. It was chosen to integrate with the already existing SCADA systems and possibly existing data exchange infrastructure. The lumped approach will be demonstrated for the large-scale heat pump case and the distributed digital twin is mainly discussed with regard to large-scale refrigeration plants.

We expect that digital twins for large-scale heat pumps and refrigeration plants will mainly provide services to the individual plants (e.g. fault detection, set-point optimization) and to a lesser extend to an agglomeration of large-scale units (e.g. aggregation services for participation in the power regulation market). Digital twins are expected to deliver valuable information on the current state of the system and improvement potential of the operation to the operators. This information may be automatically transferred into control actions in future. At the current state (research and demonstration project), it is however estimated that the digital twin services will still be supervised by human operators to not compromise security and safety of operation.

Within the current project, digital twins are developed for existing heat pumps and refrigeration plants. In future, the digital twins may ideally be developed during the development phase of the plant and be delivered together with the plant (or its components). This would allow exploiting the resources used for modelling and design during development also during the operational phase of the plant. Implementing the digital twin at an early development stage may result in other communication architectures then the ones proposed here, which was built on top of the existing system. However, the intention to design an architecture that does not locally restrict the access and is scalable to many units will be relevant for alternative architectures, too, as this is feasible for both local operators as well as remote maintenance service providers that are interested in using the digital twin services.

For other applications, such as small-scale heat pumps, the proposed implementation would differ, as the existing control system is different (less complex, less available data, etc.) and the provided services will rely on automation to a larger extend. This means that the communication network may be expected to include many individual units, connected to central server providing smart data services and the functionalities of the digital twin.

At this point of the project, there are still some uncertainties regarding the details of the implementation of the service modules and the information exchange, e.g. how real-time data will be handled within the different modules of the digital twin. The development and detailed description of the developed models and service modules, including practical issues concerning the implementation is in focus in the following work packages of the project and will be reported in the respective deliverables.

7 Conclusion

In order to develop an demonstrate digital twins for large-scale heat pumps and refrigeration units within the EUDP project “Digital twins for large-scale heat pumps and refrigeration units” a framework for the digital twin based on the general digital twin architecture by Steindl et al. was proposed. The framework is focused on the communication infrastructure for information exchange between the physical assets, data containers and the virtual space and on the model set-up within the virtual space. It is proposed to build the communication infrastructure on top of existing SCADA systems and (possibly existing) data cloud infrastructure. The virtual space contains both a detailed representation (simulation models) of the physical system and service modules. It is proposed that the service modules are written in Python, and the simulation model implemented in Modelica /Dymola are interfaced using FMI standard. Other applications (e.g. R) may be interfaced using FMI, too or direct Python interfaces where applicable. A lumped implementation, where the digital representation is gathered in one place, external to the physical system is found to be the most suitable approach during the development of the digital representation and to retrofit existing systems. For future applications a distributed digital twin is proposed, where different service modules are implemented directly at the control level, where there information is needed. This allows for short response times and less data transmission, but requires that suitable hardware is in place.

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