An Action Research Study on the Digital Transformation of Concentrated Solar Thermal Plants

Inga Miadowicz[a], Daniel Maldonado Quinto[a], Robert Pitz-Paal[a], Michael Felderer[a]

[a]*Deutsches Zentrum für Luft- und Raumfahrt (DLR), Linder Höhe, Cologne, 51147, North Rhine-Westphalia, Germany*

Abstract

The fourth industrial revolution (I4.0) marks the beginning of a new data-based age in which people, machines, products, and facilities are interconnected to realize smart factories. However, in practice many industrial facilities still rely on conventional automation pyramid system infrastructures according to the third industrial revolution (I3.0) paradigm. To bridge the gap between scientific progress, technological advances, and practical application, this study conducts action research in a concentrated solar thermal (CST) power plant. The goal is to demonstrate the digital transformation of an existing industrial plant into a cyber-physical system according to the principles of I4.0. Thus, the study covers the entire development lifecycle, starting with a requirements specification, followed by design, and ending with the realization and evaluation of the infrastructure in a real-life scenario. As a result, we generate theory from practice and generalize the learnings as a blueprint for the digital transformation of other CST plants and comparable industrial environments.

Keywords: Digital Transformation, Industry 4.0, Concentrated Solar Technologies, Internet of Things,
Cyber-Physical System, IoT ARM
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1. Introduction

Industrial revolutions are transformations in economic, social, work and living conditions that began in the second half of the 18th century [1]. While the third industrial revolution (I3.0) introduced digitization and automation of individual devices in the same physical location based on computers, the fourth industrial revolution (I4.0) marks the beginning of a new data-based age, in which people, machines, products and facilities are interconnected to realize smart factories and enable intelligence across distributed production networks [2]. The main objectives of this shift are to improve efficiency, flexibility, productivity, and sustainability while reducing costs at the same time [1, 3]. The backbone of I4.0 are internet of things (IoT) and cyber-physical systems (CPSs). They allow integrating the physical world with computational entities through networks to monitor, control, and automate systems and processes [4, 5].

Concentrated solar thermal (CST) technologies have the potential to become an important building block on the way to a climate-neutral energy supply for the earth [6]. Due to the good storage capabilities of high temperature heat, they enable a stable and dispatchable electricity generation, leading to a cost reduction in the electricity mix with photovoltaic, wind and other renewables. Moreover, the heat produced cannot only be used for the generation of electrical energy, but also directly used for industrial or thermochemical processes with high levels of efficiency, for example, in hydrogen production, water treatment, or high temperature processes such as drying, sterilizing, or distillation [7]. In recent years CST growth has been slow due to technical difficulties and high costs of investment, operation, and maintenance. An increased level of digitization, automation and intelligence plays a key role in managing operational complexity, improving efficiency, and reducing the overall costs of CST technology [6].

Today, the CST domain heavily relies on the classical automation pyramid model for the operation of plants [8]. Consequently, automation is performed on the basis of a strict hierarchical architecture composed of a field, control, and supervisory level according to the I3.0 paradigm. The field level consists of sensors, actuators, and physical devices that monitor or act on plant components. Programmable logic controllers operate and control field devices at the

Nomenclature

Abbreviations

API	application programming interface
AI	artificial intelligence
AR	action research
BD	big data
CST	concentrated solar thermal
CPPS	cyber-physical production system
CPS	cyber-physical system
COTS	commercial off-the-shelf
FG	functional group
FC	functional component
GE	generic enabler
HMI	human machine interface
HTC	heat transfer cycle
I3.0	third industrial revolution
I4.0	fourth industrial revolution
IAM	identity and access management
IIA	IoT interaction arrangement
IoT	internet of things
IoT-A	IoT architecture
IoT ARM	IoT architecture reference model
IIoT	industrial internet of things
LCoE	levelized cost of electricity
MO	maintenance operator
MMO	mobile maintenance operator
PCS	process control system
SCADA	supervisory control and data acquisition
SPT	solar power tower
VE	virtual entity

control level by receiving data and executing actions. The supervisory level is made up of supervisory control and data acquisition (SCADA) systems and other specialized industrial applications that allow the monitoring and operation of control level devices from a centralized control room by the use of human machine interfaces (HMIs). This method entails several drawbacks, including high costs associated with manual operation and maintenance, reduced effectiveness due to hand-operated controls and reactive maintenance approaches, and shorter component lifespan with possible outages because errors are identified only upon occurrence. In addition, the closed, heterogeneous, and often proprietary nature of industrial control systems imposes constraints on their integration and limits their capacity for enhancement with supplementary hardware and software components, such as third-party sensors or smart services. This reduces the flexibility of the system and the availability of data and software to support data-based decision-making by humans and machines [9]. To overcome the drawbacks, a transformation of the infrastructure is needed that lays the foundation for an effective increase in the level of digitization, automation and intelligence.

Technological advances of the I4.0 era are opening up opportunities in the area of CST. They enable the evolution of traditional hierarchical automation systems into CPSs to break down traditional enterprise data silos and introduce decentralized, data-based and interconnected system architectures. A transformation of the infrastructure into a CPS lays the foundation for improving the degree of digitization, automation and intelligence to increase efficiency, manage operational complexity, and reduce overall costs. It enables a flexible integration of IoT devices and software solutions, extended availability of real-time and historical data, proactive operation and maintenance strategies and improved data-based decision making by humans and smart services. The main challenges in the CST sector are the complexity of the infrastructure and generation processes. There are many interacting legacy and new components, a high degree of heterogeneity, volatile and complex environment conditions, a huge amount of industrial data, and high security, performance, and reliability demands, to name just a few.

From the point of view of the authors, work is needed that shows how industrial plants can take advantage of technological progress and subsequently modernize their technical infrastructures in brownfield scenarios. The central research question of this study is *how CST plants with traditional automation pyramid system architectures can be transformed into CPSs according to the I4.0 paradigm?* To answer the question, an architectural reference model is used to systematically demonstrate the evolution of a CST plant in a holistic way. Inspired by the action research (AR) approach the strategy is to implement a CPS infrastructure in a solar power tower (SPT) plant and generalize the learnings as a blueprint for other CST plants and comparable industrial environments that rely on traditional automation pyramid architectures. Thereby, the study covers the entire development lifecycle, starting with a requirements specification, followed by design and development, and ending with realization and evaluation of the infrastructure in a real-life plant.

The rest of this article is organized as follows. In Section 2 the theoretical background of this work is explained covering SPT plants, IoT and CPS. The methodology of this study and related work are described in Sections 3 and 4. Section 5 presents the results and shows the requirements analysis, CPS design, realization and evaluation. The closing Section 6 summarizes the results and explicitly answers the underlying research question.

2. Background

This chapter gives an introduction to the SPT technology to understand its basic functioning. Afterwards, the concepts of IoT and CPS are explained both in general and in relation to their role in the industrial sector.

2.1. Solar Power Tower Plants

SPT plants are one class of CST technologies that use solar energy for power production. During the past five years SPT plants have been the most common type of newly built CST plants with respect to global CST power capacity additions [6]. From a functional perspective, these types of plant can be logically separated into four parts: the solar field, the heat transfer cycle (HTC), the thermal energy storage and the power block (see Fig. 1). The solar field consists of thousands of dual-axis mirrors that reflect light onto an absorber surface called a receiver at the top of a solar tower [10]. A typical commercial SPT plant producing approximately 100 MW electrical energy has a mirror surface of around 116 m², which corresponds to a number of several 10,000 heliostats [11]. Each heliostat is centrally controlled by a control system for the field and individually tracks to the sun. The second part of the plant is the HTC. The HTC uses a thermal carrier known as heat transfer fluid to absorb the heat from the concentrated solar radiation in the receiver and transfer the heat to the other two units for the subsequent thermal process. Examples for HTCs utilized in SPT plants are air, particles, or salt [12]. The third part of the plant is the thermal energy storage unit that typically uses molten salt to store thermal energy. Depending on the size of the storage unit, the good storability of high-temperature heat enables plants to supply energy whenever needed, day and night. This supports consistent power output, dispatchable energy and improved levelized cost of electricity (LCoE) with respect to the energy price per kwH [6]. The fourth part of the power plant is concerned with power generation and consists of a conventional steam cycle. Here, the generated high-temperature heat of 500 °C to over 1,000 °C is used for efficient thermodynamic conversion of heat into electrical energy based on a steam turbine generator [7].

2.2. (Industrial) Internet of Things

IoT describes an infrastructure of networked objects, people, systems and information resources [13]. Physical and virtual entities called things provide intelligent interfaces accessible over standardized communication protocols so that they can interact on the basis of internet technologies [5]. IoT is not a single technology, but a collection of technologies such as sensors, actuators, gateways, and communication and information solutions that are used to create a smart environment [13, 14]. It is applied in various application domains such as transportation, agriculture,

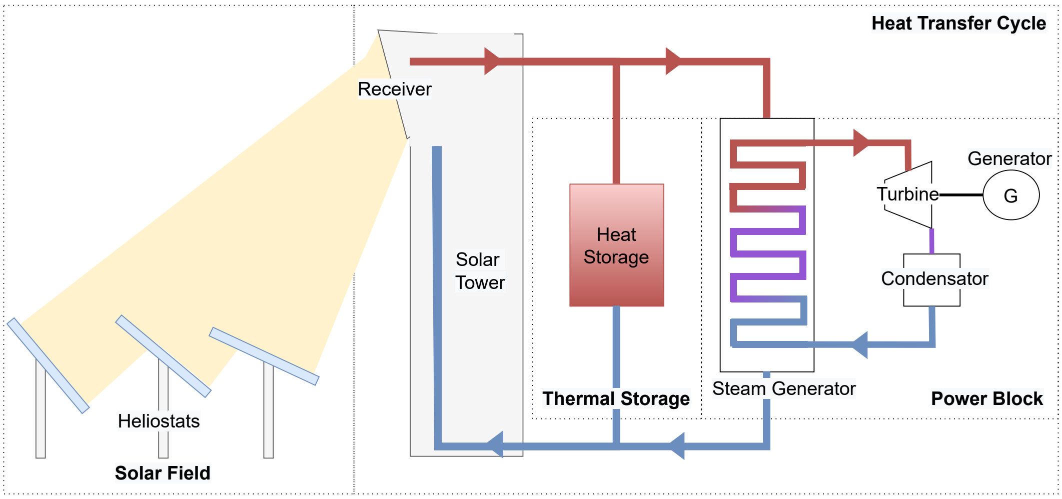

Figure 1: Overview of physical components in a Solar Thermal Power Plant

smart cities, power systems, smart factories, or healthcare [9]. Its benefits include but are not limited to an improved efficiency, productivity, quality, flexibility and transparency across the entire value creation process [9, 15].

Industrial internet of things (IIoT) describes the expansion of IoT technologies to the industrial domain [9]. It can be seen as a subset of IoT that describes a network of intelligent and highly connected industrial components that are deployed to achieve an effective production with reduced operational costs on the basis of real-time monitoring, automated controlling and an improved maintenance operation [15]. Thereby, industrial environments face special challenges including a lot of components, a high degree of heterogeneity, huge amounts of data with an increased variety, and mission-critical industrial processes. Compared to many IoT scenarios, IIoT therefore has high demands on safety, security, reliability and latency that need to meet the demands of industrial environments [9].

2.3. Cyber Physical (Production) System

A CPS describes the integration of computation and physical resources and processes through networks [16]. It is a new generation of systems that makes use of IoT, big data (BD) and artificial intelligence (AI) technologies to bridge the gap between the virtual and physical world in an intelligent way [17]. In this sense, physical components affect cyber components and vice versa on the basis of feedback and control loops. The type of system can typically be described as a distributed system that monitors, automates, and controls complex physical subsystems and processes. It is often defined as a system of systems that consists of multiple embedded systems and provides interfaces for human users to the overall system infrastructure [5].

A CPS is described as a backbone for the I4.0 where the CPS is applied in an industrial environment throughout the product and service life cycle [2, 18]. In this context, the term cyber-physical production system (CPPS) has been coined to indicate the usage of a CPS in a production context. Hence, special interest is paid to adaptive factory processes and the concept of a digital twin as a basis to enable advanced automation in complex industrial settings [19]. Its design challenges include the integration of industrial standards for interoperability of heterogeneous system components, a highly flexible system infrastructure that adapts to business needs, technical and environmental changes, large amounts of data, and the fulfillment of requirements with respect to the performance, security, and reliability of the infrastructure [20].

3. Method

This section outlines the research objectives. Furthermore, the research design and process are described as the foundational methodology of the study.

3.1. Research Objectives

As outlined in the introduction, an increased level of digitization, automation, and intelligence plays a key role in managing operational complexity, improving efficiency, and reducing the overall costs of CST technology. However, the degree of digitization, automation, and intelligence in the CST domain is quite low compared to other domains, mainly due to the complexities of the infrastructures involved and the scale of investment for holistic infrastructure changes [21, 6, 22]. From the viewpoint of the authors work has to be done that shows how existing plants that typically rely on classical automation pyramid architectures can subsequently modernize their digital infrastructures to establish a basis for effective data-driven decision-making by both human operators and intelligent services.

Therefore, the study authors investigate the incorporation of I4.0 technologies like IoT, BD, and AI into a CPS tailored for next generation CST plants. Unlike most research that centers on I4.0 architectures and technologies for completely new system infrastructures, our focus is on exploring digital transformation journeys for existing setups, known as brownfield scenarios [23]. This implication poses some additional challenges, such as the integration of existing legacy systems with new technologies for a cost-effective transformation with minimal operational disturbances [24]. Rather than developing a fully new architecture from scratch, our approach is to extend an existing automation pyramid architecture with a middleware layer to seamlessly retrofit existing facilities and make the overall system I4.0 compliant (see Fig. 2). On the one hand, heterogeneous devices from the field, control, and supervisory levels of the existing facility should be integrated into the new CPS architecture as well as possibly future IoT devices such as sensors or actuators to provide unified access to plant data and automation capabilities. On the other hand, the new middleware layer should lay the foundation for higher-level services to efficiently improve the level of digitization, automation, and intelligence.

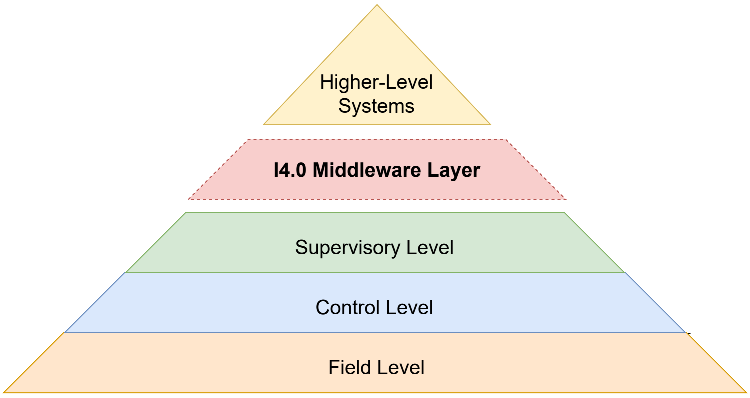

Figure 2: CPS Middleware Layer to retrofit existing industrial facilities

From a functional perspective, the middleware layer is not supposed to realize a special use case but to lay the foundation for the improvement of different kinds of use cases, such as condition monitoring, predictive maintenance, operation optimization or energy forecasts [25]. Independent from the general automation level of the plant, the role of human users and smart services should be supported at the same time. Thereby, the role of human users should be supported based on live and historical data visualization, personalized dashboards, and automated alerting services that support decision-making during operation and maintenance. Moreover, the development and deployment of smart services should be enabled based on unified access to complex industrial infrastructures, interconnection of heterogeneous subsystems, consolidation and harmonization of data from different sources, availability and provisioning of historical and real-time data, management of large amount of industrial data, and provisioning of a basis infrastructure that allows the operation of digital services in a secure, reliable, and flexible manner.

Because brownfield scenarios do not start from scratch, they are generally tied to a particular research environment that establishes the initial conditions, possibly imposes specific requirements for infrastructure modifications, and allows the evaluation of their effectiveness exclusively within that specific research context [26]. Organizations that plan a digital transformation of existing plants especially need methods that guide them on their digital transformation journey from planning to realization to find technical infrastructure concepts that are beneficial and applicable to their specific scenario in a cost-effective way. Therefore, the study is generally concerned with the demonstration of a subsequent transformation process of an existing traditional plant into a CPS on the basis of an architectural reference model and the generalization of the lessons learned for the research community. The further development of the digital plant infrastructure in the course of this study can be seen as a constructive empirical research approach that aims to bridge the gap between scientific progress, technological advances, and its practical application [27].

In summary, the research objectives of the study are to digitally transform existing industrial facilities based on the introduction of a I4.0 middleware layer. The middleware layer is integrated into classical automation pyramid plant architecture to lay the foundation for improved data-based decision-making by humans and machines. In this sense, an end-to-end transformation process is conducted in an real-life industrial plant in a systematic way to generate theory from practice.

3.2. Research Design

As outlined in the previous section, a suitable CPS infrastructure can only be developed and evaluated in the application context itself to understand the complex social-organizational problem, the challenges of the real world domain and the effectiveness of the solution approach. Based on this assumptions action research (AR) has been chosen as an underlying research method for the study. AR is a problem-oriented research strategy that attempts to understand a phenomenon in its context. The objectives are to study the complex nature of the information system domain to generate theory from practice [26]. Thus, the idea is to impose a theoretical framework in a concrete research context, take action to solve a problem, observe the effect of change, and generalize experience and solution approaches for similar problem domains. It is originally rooted in social sciences, but has gained increasing attention in the research area of information systems and software development [28].

In the context of this study, the IoT architecture reference model (IoT ARM) serves as a theoretical framework for the systematic elicitation of requirements, the design and implementation of the CPS infrastructure. The IoT ARM has been developed in the IoT architecture (IoT-A) project with more than 20 large industrial companies and research institutes between 2010 and 2013 [29]. It comprises reference models, a reference architecture, guidelines, and domain-independent support for the realization of IoT projects [30]. The main reasons for choosing IoT ARM are its domain-independent scope that offers a transfer of the design approach to a wide range of domains and its extensive support for the requirements analysis phase which is crucial for the design and evaluation of the solution [29]. The core of the methodology is based on architectural views that take into account stakeholder concerns and support the development process throughout the study. The architectural views address single aspects of the overall system and divide the complex task of designing an IoT system into smaller, more manageable subtasks [30].

As a first step of AR studies, a research context should be defined as a basis for the research questions and possible generalizations to be made. For our purpose, a research SPT plant in the German city of Jülich has been chosen, because it offers a unique, critical and revelatory case [26]. First, SPT plants in general have a higher complexity in plant design, operation, and maintenance compared to other types of CST plants [6]. This makes SPT plants a critical case that allows exploration of possible CPS infrastructures in an advanced scenario. It encompasses different challenges that can also be found in other types of CST plants and other types of industrial systems to allow a transfer of experiences to other possibly simpler types of plants. Second, the SPT plant in Jülich is a special research plant, which has the same technical conditions as commercial power plants. It can be described as a revelatory site that is usually inaccessible for scientific investigation due to the risks, legal restrictions, and financial burden of a holistic infrastructure transformation of commercial plants. Third, the SPT plant in Jülich is a unique case that offers an increased degree of automation and intelligence compared to actual commercial CST plants. Some intelligent applications have already been implemented for the plant, but so far without an underlying CPS architecture. In this way, the effect of the transformation of the infrastructure can be observed and the support of automation and smart application development can be assessed compared to the initial situation.

In summary, AR has been chosen as a research method to study the digital transformation in the area of CST plants and industrial systems. Thus, research is conducted in a SPT plant in Germany on the basis of IoT ARM as a theoretical framework to study the effect of change and generate theory from practice.

3.3. Research Process

The AR research process is based on the client-system structure defined by Susman and Evered [31]. The model describes an iterative process that includes the working phases diagnosis, action planning, action taking, evaluation, and specification of learning. In the course of this study, only one iteration is conducted, but lessons learned and possible actions to improve the solution are outlined at the end of the study as a baseline for a next iteration in a subsequent research study.

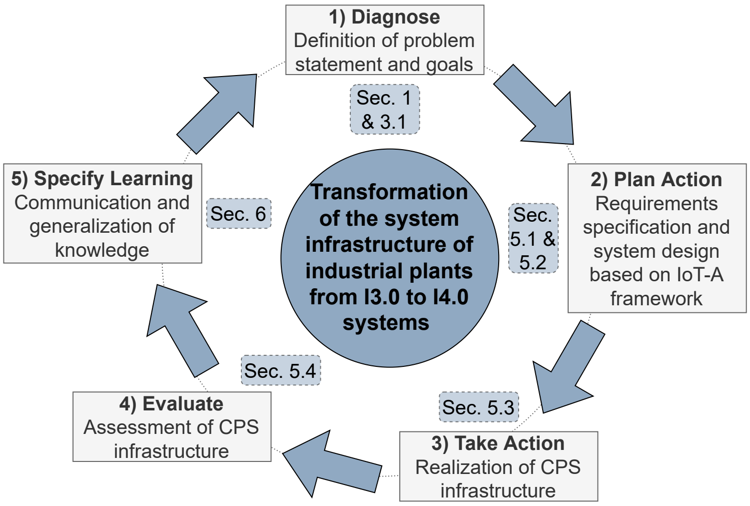

Figure 3: AR Research process on the basis of client-system structure methodology of Susman and Evered [31]

The concrete research process of this study is shown in Fig. 3. The process starts with a diagnosis step that identifies the primary problems as underlying causes of the organization's desire for change [28]. This includes the definition of the problem statement and the research objectives described in the beginning of the study (see Sections 1 and 3.1). The next step is the planning of actions to specify the organizational activity that might help to solve the research problem [31]. This step is guided by the IoT ARM to systematically understand the target domain, identify requirements, and design an appropriate solution (see Sections 5.1 and 5.2).

The third and fourth steps of the AR process are concerned with the realization of the solution to take action (see Section 5.3) and the evaluation of the effectiveness of the system design with respect to the study problem (see Section 5.4). These steps encompass the implementation of the system design in the research context guided by further IoT ARM architectural views and the testing of the fulfillment of the requirements as a basis for evaluation. The last step is to generalize the knowledge from the concrete implementation project. Thereby, the success or failure of the study is communicated to the scientific community with special emphasize on the IoT ARM methodology that guides the transformation process, the resulting system design, and the evaluation results of its concrete realization (see Section 6).

4. Related Work

Work that can be related to the study can be logically separated into two blocks: CPS infrastructures in the area of CST and studies that use the IoT ARM framework as an underlying methodology for the development of solutions independent of the domain.

The first group of related work concentrates on CPS infrastructures in the area of CST. Although the potential of IoT, BD, AI and other emerging technologies is being promoted in many articles [6, 7, 11], the main focus of the research community in CST domain is concerned with the application of AI. However, AI in the area of CST has been applied mainly in scientific research rather than real-life industrial plants due to the complexities of the infrastructures involved and the holistic infrastructure changes [21]. Studies that discuss suitable infrastructures as a baseline for automation and smart application development are rare. We have only been able to identify two articles that address possible infrastructures for smart CST environments from a high-level perspective [8, 22].

The second group of related work realizes CPS systems on the basis of the IoT ARM methodology. Here, we identify some studies that use IoT ARM as a baseline for architecture construction. For example, Verdouw et al.

use the functional IoT ARM model to propose a technical model for the implementation of digital twins in a smart agriculture scenario [32]. Three other papers from Sotiriadis et al., Preventis et al., and Fortino et al. assess or compare concrete implementation platforms based on the IoT ARM [33, 34, 35].

In general, there is great interest in suitable CPS infrastructure solutions in the area of CST, but digitization in the sector is progressing more slowly compared to other domains [21]. Research on technical infrastructures that support digitization, automation, and intelligent service development in the area of CST is rare. The few examples that we identified focus on a conceptual level and discuss technical possibilities rather than holistic transformation processes, architectural concepts and concrete implementation options. In addition, there are some studies that partially use IoT ARM to compare technological platforms or develop generic architectures in other domains. They have in common that they only use single parts of the IoT ARM and do not rely on the framework for the digital transformation process of an industrial plant. To the best of our knowledge, there are no studies that attempt to close the gap between scientific progress, technological advances, and its practical application in a AR project by making use of IoT ARM for the digital transformation of a CST plant in the era of I4.0.

5. Results

The results of the study describe the stepwise development of the CPS infrastructure. Thus, the following chapters address the requirements analysis, architecture, realization, and evaluation of the solution.

5.1. Requirements

Following the process of the IoT ARM to generate architectures, the first step towards a concrete architecture is to understand the target domain. Based on that, the requirements can be specified as a baseline for the subsequent architectural process.

5.1.1. Understanding the Target Domain

For the purpose of understanding the target domain, we begin with the creation of three architectural views according to the IoT ARM framework [30]:

- *Physical entity view:* Identifies physical objects from the real-world scenario that are relevant from a user or an application perspective.
- *IoT Context view:* Describes the relationships, dependencies, and interactions between the system and its environment. This view has an external perspective on the scenario to define what the system does and how the system interacts with the outside world and its actors.
- *Domain model:* Expansion of the IoT context view to model the internal perspective on the system with an expanded level of detail to understand the elements and interactions that make up the target application.

We start with the definition of the physical entity view. It is made up of all the physical components of the SPT plant that are relevant for the application scenario. Using the conceptual scheme for SPT plants described in Section 2.1 the heliostats, receiver, HTC, heat storage, and components of the power block unit can easily be identified as physical entities. As there are more than 50 entities that are part of the power block when looking at the details of the plant, they are summarized as power block components in the view. Moreover, the physical entity view is extended by relevant sources from the environment. Special attention is typically paid to the weather conditions and cloud movement, so both are taken into account as additional physical entities. Overall, seven physical entities have been identified that are summarized in Table 1.

Next, we define the context view of the scenario. Fig. 4 shows the resulting model, which is composed of existing (solid black lines) and planned (blue dashed lines) infrastructure components and their relations. Part of the existing infrastructure are all physical elements listed in the physical entity view. The heat storage, receiver, HTC, and components of the power block unit that are controlled by a control station for the CST. Furthermore, the heliostats are controlled by a second control station for the solar field. The plant is operated by two types of human users. First, there is the maintenance operator (MO) who is responsible for the operation of the control station of the CST and the control station for the field. In addition, the role is supported by a weather app that is connected to sensors in the

Nr	Name	Description
1	Heliostats	Mirrors to reflect solar radiation onto the receiver
2	Receiver	Heat absorber on top of the solar tower
3	Heat transfer cycle	Thermal carrier that is used to absorb and transfer heat for the thermal process
4	Heat Storage	Storage unit that stores thermal heat for continuous power generation if no solar radiation is available
5	Power Block Components	Components that are used for a conversion of heat into power such as steam generator, turbine or condensator among others
6	Weather	Weather conditions that need to be considered for operation such as solar radiation or wind speed
7	Clouds	Clouds that move over the heliostat field and influence the available solar energy for production

Table 1: Physical entity view of the SPT plant

field, such as wind or solar irradiation sensors. Moreover, the MO role has various cameras at its disposal, such as cloud or target cameras that monitor the movement of the clouds or assess the accuracy of the heliostats for calibration purposes. Second, there is a mobile maintenance operator (MMO) who is responsible for the maintenance of heliostats in the field. To support the role, the MMO has a tablet that is connected to the field control station, to get information on single heliostats and move them in positions that allow their maintenance. Additional planned components are future smart services that a data analyst deploys or implements and the CPS middleware layer. The CPS middleware layer is supposed to integrate all available data sources, including environment sensors, camera streams, and data from control systems. Furthermore, all three roles MO, MMO and the data analyst should be supported by the CPS infrastructure with data and CPS services to support data-based operation, maintenance, and service development.

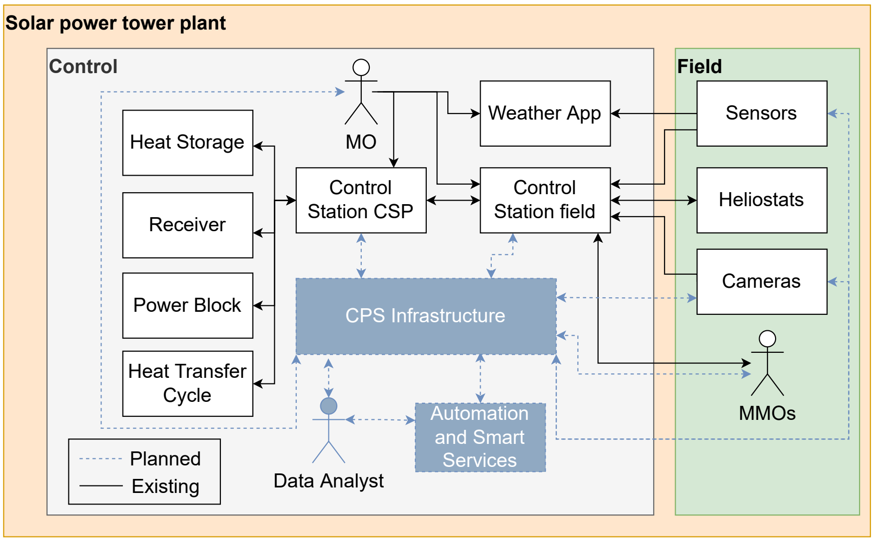

Figure 4: Context view of the SPT plant

Finally, the domain model can be derived from the context view, as shown in Appendix A. In our scenario, the domain model is separated into components of the control plane, field, and the CPS infrastructure. It is made up of human users (yellow), physical entities (orange), devices (blue), and software entities (green) following the official IoT ARM domain model notation [36]. Devices can be sensors or cameras that monitor a physical entity or a hardware controller that monitors and acts on a physical entity. Software entities can be further distinguished into resources (dark green) and services (light green). Resources implement certain functionalities and give access to information on or actuation capabilities to real-world objects and are therefore typically hosted on a device. Services expose resources through common interfaces and make them available for applications and other services.

Compared to the context view, the domain model provides a detailed description of the internal components and their relations. The model shows that each of the physical entities is monitored and / or actuated by a device that hosts the related entity resource. In the field, the receiver is monitored by a flux density camera and an infrared camera, the clouds in the sky are monitored by a cloud camera, and the weather is monitored by a bunch of sensors in a weather station. A heliostat controller is locally attached to each heliostat to provide information on heliostat status, adopt its configuration, and move its axis. The MMO works in the field using a tablet that is connected to the field control station to provide information on the heliostats and bring them to maintenance positions. In the control plane, the power block components, HTC, heat storage and the receiver are monitored and controlled by a process control system (PCS) which hosts all of their resources. The control station for CST is a SCADA system that has access to the PCS and provides a HMI with monitor and control functions. To distribute PCS information to the related control station of the field, an OPC UA server is used to expose the data. The field control station additionally gets information from the weather station using an OPC DA server, cloud predictions from a service connected to the cloud camera, and flux density and heat distribution information provided via another OPC UA server. The MO is located in the centralized control room and operates the control system for the field and the SCADA-based control system for the CST while getting additional insights from a weather app.

The scenario is planned to be extended by the CPS middleware layer. Thus, a data acquisition service obtains all camera streams, heliostat data, weather data, PCS data, cloud predictions, and calculated flux density and infrared matrices and passes them to a data management service. The data management component is responsible for storing the information in the data store, providing an application programming interface (API) for data access, or directly streaming the data to smart services. In addition, a service must be provided that can visualize live and historical data from the data store and send alerts to MO and MMO for proactive support in case of danger to support the human role.

In summary, the target domain of the planned CPS infrastructure is described on the basis of the physical entity view, context view, and the domain model. Thereby, all physical entities are listed and an external and internal system perspective is given.

5.1.2. Requirements Specification

The next step towards the development of a concrete architecture is the requirements specification. IoT-A does not suggest a specific requirement engineering process. It only provides a set of aids for requirement election and translation of requirements into architecture features. Thereby, a set of general unique requirements has been published together with IoT-A that can be used as a basis to determine and specify individual requirements [37]. On the one hand, they can help inspire the gathering of concrete IoT demands for the specific scenario. On the other hand, they propose a structure for requirements specification that helps to track system functions back to project needs, support the assessment of the completeness of the requirements specification, and guide the architectural composition [30].

To be able to easily integrate the requirements from the unified requirements list and for the sake of traceability to the IoT ARM architectural views, the structure of the IoT-A unified requirements list is used to specify the requirements in this study. The structure uses three types of requirements: Functional requirements that describe system functions or behavior, non-functional requirements that define quality aspects, and design constraints that guide architectural decisions according to individual framework conditions. Each requirement is then specified by a unique ID, its type, description, rationale, functionality group, functionality components, and a reference to the domain model view, architectural view, and quality perspective. As IoT-A does not propose a concrete methodology for the requirements specification process, this work integrates a systematic requirements engineering process for IoT systems from Silva et al. into the IoT ARM approach [38]. Basically, Silva et al. suggest performing requirements engineering for IoT systems in three steps named project scope, IoT system definition and IoT system requirements specification. From the viewpoint of the authors it can perfectly be combined with the IoT ARM framework that supports each definition step based on architectural views.

The purpose of the first step of Silva et al. is to define the problem or opportunity of the project and to identify stakeholders and their needs [38]. This step can be integrated with IoT ARM by making use of the context view and is in line with the IoT ARM task to define the business goals of the undertaking. The high-level scope and goals of the project have already been outlined in Sections 1 and 3.1. In this section, further details on stakeholder needs for the CPS infrastructure are discussed on the basis of user interviews. For this purpose, representatives of the MO, MMO and data analyst role have been interviewed as direct system users and the plant owner and system administrator as additional indirect stakeholders. In summary, the MO and MMO roles have the main objective of improving the operation, monitoring, and maintenance of the plant. The roles can benefit from data-based support and share the same needs to flexibly visualize live data and get warnings and alerts to be informed of issues that exist or may arise. The data analyst has the job of deploying and developing smart applications based on different data sources. Their needs compromise the provisioning of live and historical plant data from possibly all sources, flexible integration of new IoT devices to have more data available, and interfaces to plant control systems to increase the level of automation. The plant owner has to decide on investments and strategies for the further development of the plant and is responsible for a secure and safe plant operation. Therefore, the plant owner has the interest to reduce the overall cost, improve the flexibility of the plant to meet changing business needs, and ensure operational safety and security. Moreover, the role formulates design constraints for the transformation process, for example, the integration of high-cost legacy subcomponents, use of standard-based open-source software and a non-disruptive transformation process with respect to the daily business. The system administrator must take care of the technical infrastructure, enable its further development, and make it qualitatively available to all system users. Therefore, the administrator prefers to use industrial standards for an increased level of interoperability and easy integration of new components. Moreover, the role can also be supported by data for system infrastructure administration, including monitoring capabilities and alerts in case of malfunctions.

The second step of the requirements specification process compromises a definition of IoT scenarios and the identification of IoT components and actions [38]. The components of the system, their relations and actions can be easily read from the domain model on the basis of the device and software entities and the type of their relations. For scenario specification, Silva et al. refer to a method from Da Silva to specify the behavior of the system based on scenarios [39]. To guide the process, Da Silva identified seven IoT interaction arrangements (IIAs) that help to systematically identify all types of IoT behaviors on the basis of standardized interaction patterns. The study authors used the approach but needed to add more interaction patterns for the application in the industrial domain, because there are many involved non-IoT devices that lead to additional types of IIA patterns. In general, the authors have defined 22 scenarios for the CPS system. In summary, there are scenarios for alphanumerical data exhibition of IoT- and non-IoT devices, non-IoT actuations triggered by individuals based on warnings and alerts from IoT and non-IoT data, and non-IoT actuations triggered by smart services based on IoT and non-IoT data. An example of each type of scenario can be found in Appendix B.

The last step aims to describe the use cases of the system and specify the requirements for the device and software components [38]. This step is based on the results of the first two steps and can once again make use of the domain model for graphical support. In addition, the functional groups (FGs) of the IoT ARM framework can be used to categorize requirements into building blocks that make up the system. The FGs can be summarized as follows:

- *IoT Service:* The first FG encompasses interface requirements that are related to the data acquisition services. These services have to provide functionality to integrate resources into the CPS infrastructure on the basis of different interface protocols and make them accessible to other services. In our case the existing IoT and Non-IoT devices of the plant should be integrated into the CPS infrastructure and the integration of future not yet specified IoT devices should be possible for the further development of the plant according to the needs of stakeholders.

- *Application:* The second FG describes functionalities for direct user interactions and smart applications. These are the functional stakeholder needs of MO, MMO, and data analyst identified in step one, such as live data visualization or alerting services.

- *Virtual Entity:* The needs of the data analyst also cover requirements for data access by machines for the deployment and development of smart services. These types of requirement belong to the virtual entity (VE) functional group and describe the functionality for the seamless integration of physical and virtual entities. They encompass needs such as an API for receiving live and historical data, control of plant components based on virtual counterparts, or a semantic layer to describe entities and their services.

- *Security:* Next, security services must be added to secure plant operation and meet the needs of the plant owner. Therefore, qualitative requirements such as confidentiality, integrity, and availability are specified. Moreover, functional requirements such as authentication, authorization or role management services are added.

- *Management:* Finally, the system infrastructure needs to be managed by the system administrator. The role is supported by functionalities of the management FG that includes administrative features such as the ability to have an overview of all components that are involved in the system or scale the services dynamically at runtime according to the system load.

The use case diagram in Fig. 5 summarizes the FGs and related use cases of the stakeholder. For the sake of simplicity, the use cases are grouped by functional blocks, and the requirements necessary to enable the primary use cases are not visualized but specified in the requirements list. These are mainly basic technical requirements related to the functional groups IoT service or VE such as retrieving or storing the SPT plant data.

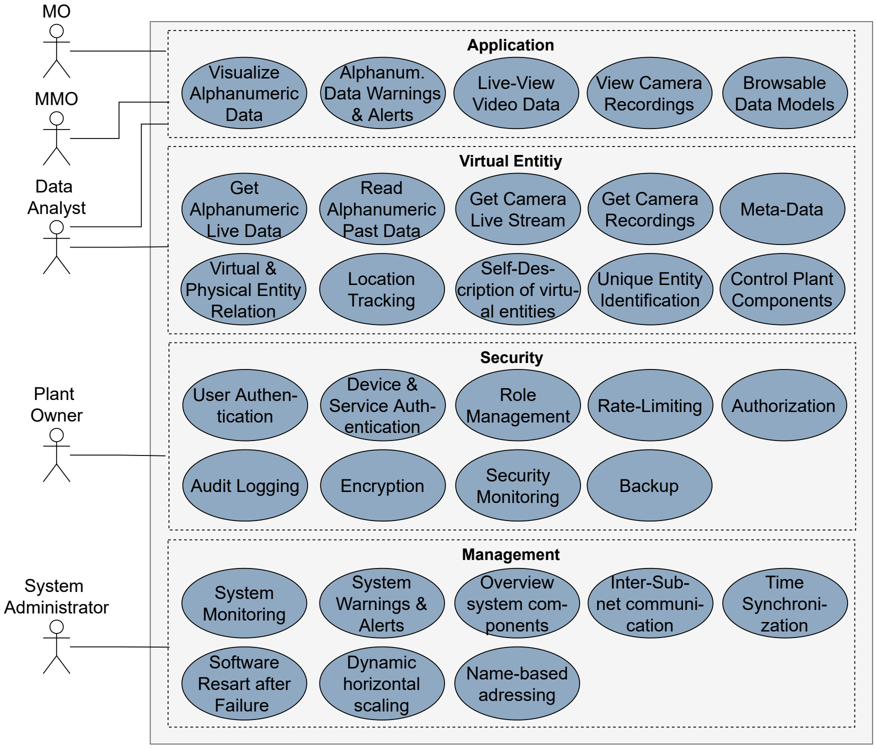

Figure 5: Use case diagram for the CPS infrastructure of the SPT plant

Overall, we rely on the methodology of Silva et al. and Da Silva for the requirement specification process and combined the approach with IoT ARM architectural views and the IoT-A unified requirements list. Based on this, we specify 66 design constraints and functional and non-functional requirements for the realization of a CPS infrastructure in the SPT plant. The full list of requirements can be found in the referenced data repository[1].

5.2. *Cyber-Physical System Architecture*

In general, a technical architecture describes the components of a system, their intercommunication and the interactions of the whole system with its environment [32]. This study in particular emphasizes the analysis from the informational and functional perspectives according to IoT ARM, which will be addressed in the following subsections.

5.2.1. *Information View*

The IoT ARM information view defines the structure of the managed information in the system. Basically, it captures the digital representation of the physical world based on VEs and its associated services. VEs model physical entities and typically have a name, attributes, attribute types, and values to which metadata can be related. Services

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[1] Link to data repository of the journal

are associated with VEs on the basis of attributes so that the model shows which attributes can be read or set using the service [30].

Following a widespread trend in the industrial domain [40], the requirements specified for the SPT plant scenario describe the need to virtually represent plant components, provide interfaces to automatically control parts of the plant, and synchronize virtual representations with their physical counterparts. To put it differently, what is being highlighted is the requirement for a bidirectional digital representation of the actual world, commonly referred to as a digital twin [41]. The idea is to shadow the structure of the SPT plant in the virtual world and provide a unified access layer to heterogeneous plant data and control systems for humans and smart services [42].

The environment of the SPT plant is a heterogeneous, large-scale, and dynamic environment with many hardware and software assets that could be interrelated statically or dynamically. To digitally represent the complex environment of the SPT plant into the virtual world, our information model is supposed to provide flexible digital representations of physical entities together with their relation to other physical assets or virtual representations to additionally receive information on their context in the overall SPT plant. This should be achieved with the help of a knowledge graph that stores VE data together with information about their related context and their source of information with respect to the services and devices that provide the data. Consequently, virtually every physical asset of interest is represented, encompassing all recognized physical entities, along with devices and services that monitor, interact with, or offer access to a resource in the overall system [32].

In the CPS scenario, the information relations can be observed based on the domain model. First we can distinguish into different information classes that can be defined as devices, services, and information resources. A device produces data on a physical entity, and a service provides access to an information resource. An information resource represents physical assets from the physical entity view as a VE and is bidirectionally synchronized with the real world based on the related device and service entities. Information resources can be differentiated into two types. Primary data is directly produced by devices from real-world and exposed via software services. Secondary data is created based on primary data to provide additional insights for other services. Examples for primary data include sensor, camera or control system data and examples for secondary data include but are not limited to predictions or calculations such as cloud movement predictions or calculated flux density matrices based on video streams.

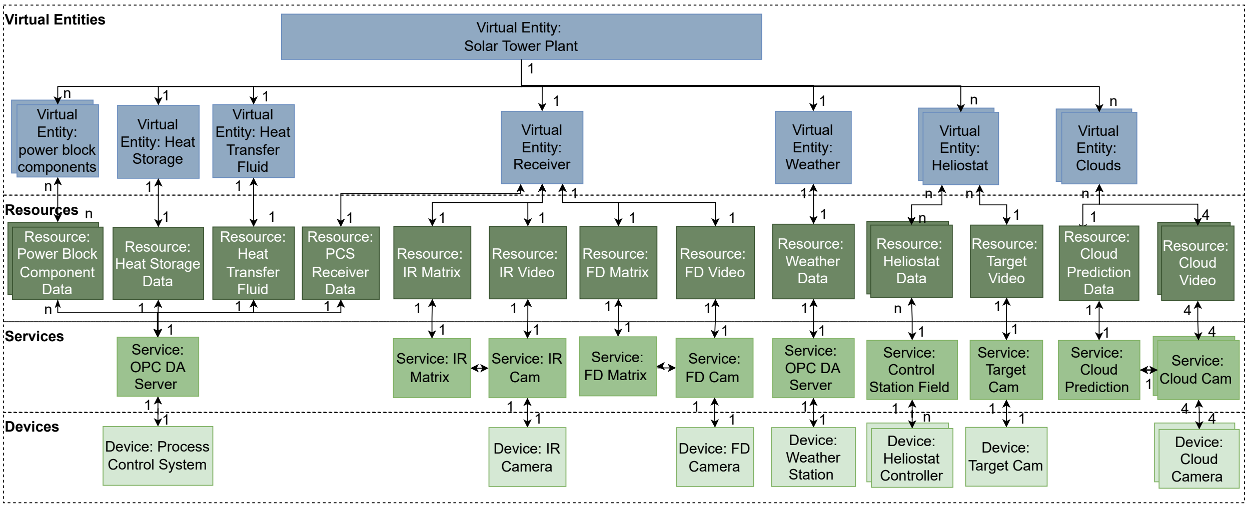

Figure 6: Information View for the CPS infrastructure of the SPT plant

To capture diverse representations and relationships of entities in a common information model for the SPT scenario, we created a layered information tree model that captures the actual data for the digital representation of physical entities together with information about their related context in the SPT plant and their source of information with respect to the services and devices that provide the data (see Fig. 6). The layers correspond to the observed information classes devices, services, resources, and virtual entities. The first layer captures data on virtual entities of a SPT plant. It is made up of a root entity *SPT plant* that represents a specific CST facility. The root entity is linked to all virtual entities that represent physical entities of the plant such as *receiver*, *weather*, or *clouds*. In this way, a user or service can quickly grasp an overview of all components of the SPT plant by examining the connections with the root entity, and conversely, physical entities can always be linked to a particular physical location represented by the root entity. The second layer includes the actual primary and secondary information resources. Each information resource digitally represents a physical entity and is therefore related to a VE. Thereby, a VE can have multiple resource representations, for example, the VE *clouds* is represented by a *cloud video* resource with live-data and a *cloud movement predictions* resource with forecasts on cloud movements. The third and fourth layer include services and devices. Each information resource is linked to a service in the third layer that exposes the information resource. The service is again linked to another service in the same layer in case of secondary data or a device in case of primary data. Devices produce data and possibly allow to control parts of the plant as part of the fourth layer.

Overall, we modeled the digital representation of the SPT plant by creating VEs for all physical entities, devices, and services that are part of the SPT plant. Thereby, the VEs are bidirectionally synchronized digital twins that can be interrelated to other VEs in a layered manner. In this sense, the structure of the information model of the SPT plant is captured based on a knowledge graph so that the information provided by the CPS are synchronized with the physical world, adds additional context details to components of the plant, allows trace back information to its source, and makes the overall structure of the plant transparent to humans and machines.

5.2.2. Functional View

The functional view describes the functional decomposition of the system to break down the total complexity of the system into manageable parts. It is based on the IoT-A functional model that describes the underlying FGs of the overall system and their interactions in a layered approach [32]. The functional view specifies application runtime functional components (FCs) that belong to a certain FG as functional building blocks of IoT applications [30].

Following a microservice approach, we decompose the system tasks into independent services that are deployed within containers and act together on the basis of standards to realize functional and non-functional requirements of the CPS infrastructure. The approach is increasingly used for the transition from centralized system infrastructures towards highly decentralized systems in large-scale system environments [43]. The approach enables the creation of an open, modular, and flexible system design that allows the use of automated deployment tools and enables scalability, reliability, and portability as a baseline for a reliable and real-time application environment in the industrial scenario [44].

In the requirement specification, we have already assigned a FG to each functional requirement to organize the requirements collected according to the IoT-A functional model. As a next step, the scenario-specific functional view for the CPS infrastructure is described. The resulting functional view can be found in Fig. 7. It shows a decomposition of the requirements of each FG into software and hardware FCs (green and orange) and relates them with generic IoT ARM FCs (gray).

First, the *device FG* provides hardware components that are attached to physical entities to monitor or act on them [30]. The devices are scenario-specific and can be defined as the already identified device entities of the SPT plant such as the weather station or the flux density camera (see Section 5.1.2). Second, the *communication FG* manages interactions between different components and enables communication between devices and the IoT service FG [32]. In the context of the SPT plant, all components are connected in a local LAN that supports network and end-to-end communication between physical nodes in the CPS infrastructure.

Third, the *IoT service FG* is composed of IoT and resolution services. It provides functionalities to obtain resources from devices, send commands to actuators, and discover, lookup, and resolute names of IoT services [33]. For each device that is planned to be integrated into the CPS infrastructure we identified a certain interface protocol that allows access to the resource such as OPC DA or ZeroMQ. Following the IoT ARM guidelines, the idea is to create a generic IoT wrapper service for each interface protocol that can be configured to integrate seamlessly with the specific device [30]. Using wrapper services, communication to heterogeneous devices can be abstracted from the CPS infrastructure. New devices can be easily integrated either by using an already existing type of IoT service or by developing a new IoT service that supports a new type of interface protocol. Moreover, a CPS portal service is aware of all services in the system and provides functionality to discover, lookup, and resolve the names of CPS services for humans and machines.

Fourth, the IoT ARM *virtual entity FG* is structured into the FCs VE resolution, VE service, and monitoring of VE and IoT services [30]. The VE resolution FC provides functionalities to retrieve associations between VEs and

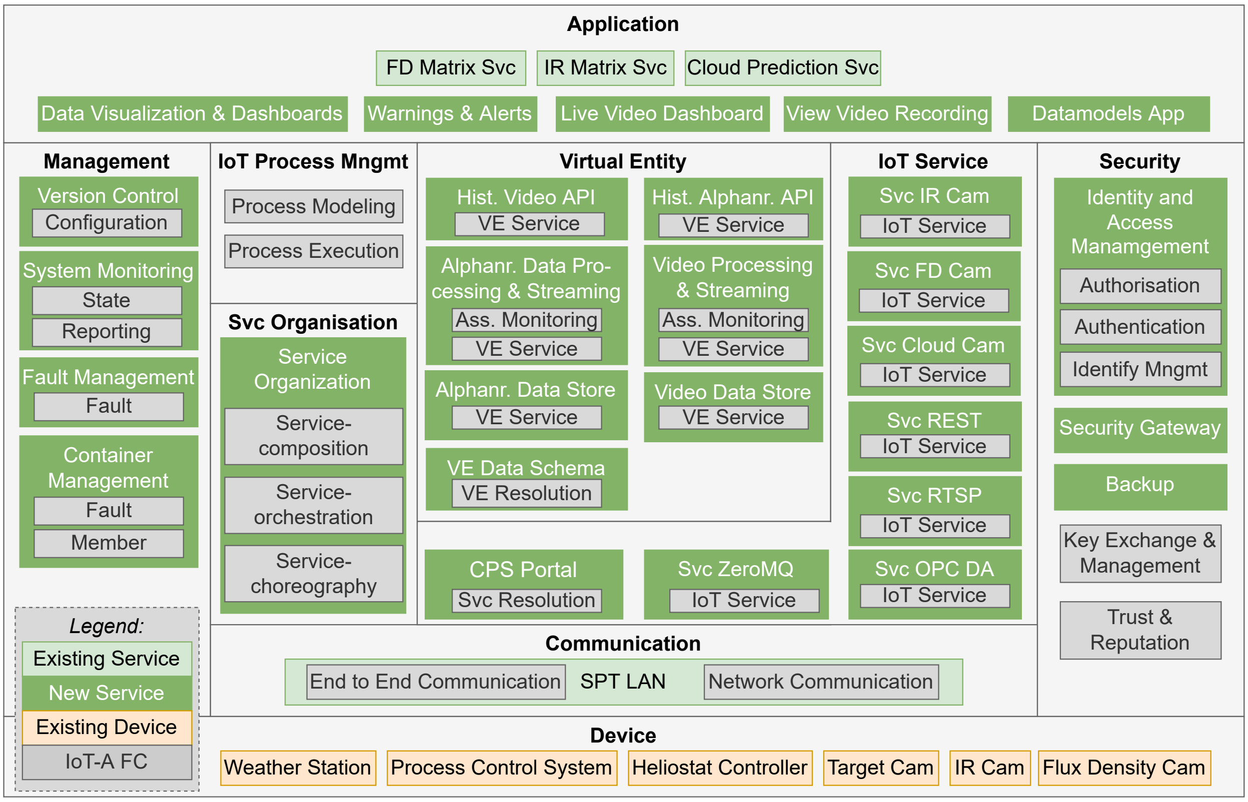

Figure 7: Functional View for the CPS infrastructure of the SPT plant

IoT services. In the SPT plant scenario each VE is linked to its information source as part of the data model so that associations of VEs and IoT services can be queried (see Section 5.2.1). Next, there is the VE service that provides read and write access to VEs. In our scenario, this is achieved by using data processing and streaming FCs that retrieve information from the IoT services and either directly stream it to interested data consumers or store it in the data store. To access historical data, there is a historical data API that allows to read data from the data store. Because the handling of video and alphanumerical data is different in terms of retrieval, storage, processing, and provisioning, there are FCs that are concerned with alphanumerical data and separate FCs that are responsible for the management of video data. Finally, there is a IoT ARM FC for VE and IoT service monitoring that is responsible for automatically finding and sending notifications on association changes between VEs and services. As associations of IoT services and VEs are part of the information model, this functionality is also located in the data processing and streaming FC in case of the CPS infrastructure. They are supposed to notify data consumers in the event of changing relations or other changes in the data model if needed.

Fifth, the *process management FG* integrates the IoT system with traditional business processes on the basis of modeling and execution FCs [33]. In our case, the actual management and execution of the process can, on the one hand, still be performed manually by operators based on a SCADA-based HMIs and additionally supported with data-based insights from CPS infrastructure services. On the other hand, tasks can be automated by integrating loosely coupled smart services into the application layer so that the degree of automation of plant processes can be improved in a stepwise manner. The idea is that the CPS platform performs basic services in terms of interconnection, data management and provisioning of data-based services, while the actual business process is driven by higher-level systems that benefit from the existing service layer. Therefore the functional view of the CPS middleware layer of the SPT plant does not contain FCs from this FG.

Sixth, the *service organization FG* provides FCs with orchestration, composition and choreography functionality [34]. As the CPS infrastructure is composed of many services that work together to achieve an overall goal, it is necessary to organize the services and create compositions based on orchestration or choreography patterns. Therefore, it is desirable to have a service organization FC that provides the functionality as an underlying management service.

Seventh, the *security FG* is responsible for the security and privacy of the system and its users. It includes the FCs authorization, authentication, identity management, key exchange and management, and trust and reputation [30]. In our scenario, there is an identity and access management (IAM) FC that is responsible for authorization, authentication, and identity management. Furthermore, there is a backup FG that copies data and the service configuration to a secure remote location. In addition, there is a security gateway FC that acts as an entry point to the CPS infrastructure. Because all traffic passes through the security gateway, it can be used to protect against unauthorized access or threats to availability on the basis of security services such as rate-limiting or audit-logging. The two IoT ARM FCs trust and reputation, and key exchange and management are not part of the SPT security FG yet, because there are no related requirements specified.

Eighth, the *management FG* is composed of the FCs configuration, fault, reporting, member, and state. The configuration FC is responsible for the configuration management of other FCs, services and devices. In the CPS infrastructure, a version control system is used that allows to centrally store all configurations in the system, track changes and deploy configuration updates. The objective of the fault FC is to identify, correct, and record faults of the IoT system. For provisioning of this functionality, a fault management FC is used that monitors logs, analyzes warnings and errors, and takes corrective intervention or sends alerts. In addition, the use of containerization technology allows simple health checks and automatic restarts in case of failure. The member FC is responsible for the management of the membership and information of any entity of the IoT system including VEs, services, devices, applications, and users. In our case, this functionality is distributed across several FCs. The containerized deployment allows to provide information on all services of the CPS infrastructure, the data model provides information on virtual entities and related services, and registered users are managed in the IAM functional component of the security functional group. The goal of the reporting FC is to assess the performance and health of the system and generate reports. It is closely related to the remaining state FC that monitors and predicts the state of the IoT system. Both FCs are assigned to the system monitoring FC in the scenario of the SPT plant.

Finally, the *application FG* provides services for the monitoring, operation, and maintenance tasks of the SPT plant. In the layer, all data-based services can be found that make use of the CPS infrastructure to provide value-added services for thermal energy production. These are all existing services and all future smart services for operational optimization and automation, such as cloud prediction, energy forecast, or predictive maintenance services. Moreover, the building blocks from the application FG of the requirements specification that especially support the human role, such as data visualization services, alert and warning services, or a camera dashboard, can be found in the application FG.

Overall, the functional view for the SPT plant introduces 28 new services as functional building blocks of the CPS infrastructure that are organized into the 9 FGs of the IoT-A functional model. In general, we introduced a layered microservice architecture for the CPS middleware that interconnects heterogeneous plant components with smart services and human users and provides basic services for different concerns such as security, administration, or data management.

5.3. Cyber-Physical System Realization

Based on the abstract architecture, the next step in the development process is the concrete implementation of the CPS infrastructure. IoT ARM guides this steps on the basis of additional views and a set of guidelines that support design choices for implementation [30]. In the following, we demonstrate how the actual system can be realized on the basis of the IoT ARM operational view, examine the selection of the technology platform and discuss the on-premise or cloud deployment options.

The first step for the implementation of the architecture is to select the technology platform [33]. In our case, we have two design constraints that guide the step. First, we are supposed to integrate existing legacy devices and services and be flexible for future device and service integration, so that there are high demands on evolution and interoperability. Second, we are supposed to rely on open-source software to create a flexible solution that is made up of exchangeable standard-based building blocks, prevent possible vendor lock-ins, profit from a large user community, and reduce license costs. Therefore, we compared different open-source software solutions that can be used to create a CPS infrastructure according to our requirements [45].

Having compared different solutions, we finally decided to choose FIWARE as the underlying technological platform together with a bunch of additional open-source tools. FIWARE is an open-source IoT platform that is supported by the European Union for more than a decade with several successful implementation projects in many domains [46]. It is supported by a large community, partnerships with industrial companies, and research institutes that drive the further development of the platform [47]. Therefore, FIWARE offers many information resources, community support, reference architectures, software modules, and different deployment options, including bare metal and container-based deployments on-premise or in the cloud [33, 46]. The core of FIWARE are open-source services called generic enablers (GEs) that are published in a FIWARE catalog[2] and can be used to flexibly realize different scenarios according to individual requirements. One of the key features of FIWARE is that it is built on the basis of standards that allow a flexible integration of the solution with many devices and software components. Especially the heavy use of the NGSI-LD linked data model and API that have been standardized by ETSI [48] allow us to mirror the SPT plant structure into the virtual world and realize our planned information model. Moreover, the standard is focused on interoperability, enriches data with meta-data, and offers predefined standard-based data models that simplify the design of the schema for VEs. Furthermore, FIWARE provides support for the IoT service wrappers on the basis of so-called IoT Agents that enable a seamless integration of different types of device protocols [47].

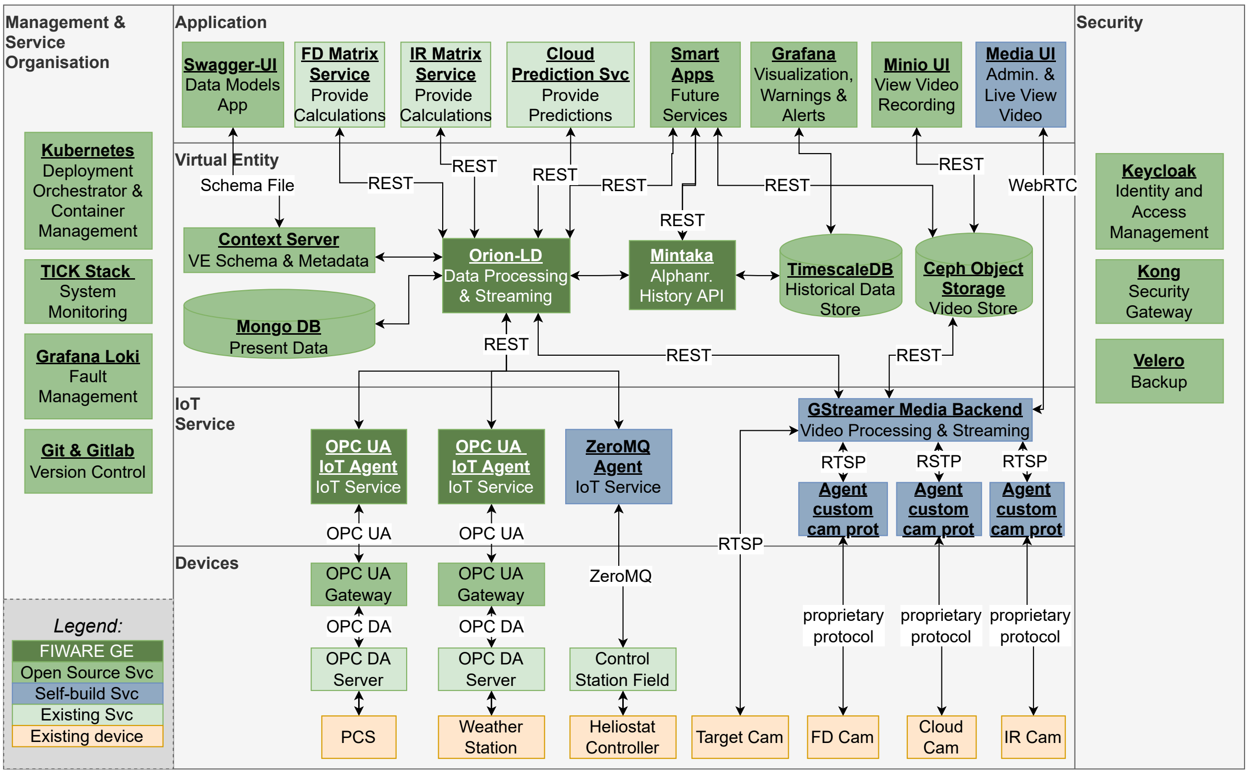

Figure 8: Operational View for the CPS infrastructure of the SPT plant

Based on a concrete platform selection, we can now choose software solutions for the realization of FCs of our functional view. Fig. 8 shows the resulting IoT ARM operational view and describes the interplay of FIWARE GEs (dark green), other open-source software components (medium green), existing SPT plant software components (light green), existing SPT plant devices (orange), and new software components (blue) that have to be developed to realize the CPS infrastructure at the SPT plant. Overall, there are four FIWARE GEs that are used at the heart of the CPS infrastructure for alphanumerical data processing and streaming (Orion-LD), provisioning a historical alphanumeric API (Mintaka) and integration of the OPC UA interface protocol (OPC UA IoT Agent). These solutions are integrated

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[2] Link to FIWARE catalog: `https://www.fiware.org/catalogue/`

with popular open-source tools to store live and historic alphanumerical and video data (MongoDB, TimescaleDB, Ceph Object Storage), orchestrate and manage the containerized deployment (Kubernetes), monitor the infrastructure (TICK Stack), detect and analyze faults (Grafana Loki), and provide version control capabilities for deployment and configuration files (Git, Gitlab). Further open-source tools are used to visualize data and send warnings and alerts (Grafana), manage the schema and make it understandable by humans (NGINX Webserver, Swagger-UI) and secure the solution on the basis of a IAM service (Keycloak), security gateway (Kong) and backup software (Velero). Finally, there are some FCs that can not directly be realized on the basis of existing FIWARE GEs and open-source software solutions. First, this is the IoT service for the integration of heliostat data based on the ZeroMQ interface protocol. Currently, FIWARE does not offer such an IoT agent, so we have to develop our own agent. This can be done on the basis of a template IoT agent provided by FIWARE that simplifies the integration of additional protocols. Second, there is no open-source solution for the retrieval, processing, and streaming of video data. To realize our own media infrastructure, we rely on GStreamer as a framework to develop media pipelines. The media infrastructure consists of a back-end component for video processing and streaming and a front-end component for video live view and administration of the media pipelines. The back-end consumes media on the basis of the RTSP protocol that is broadly supported by many camera vendors. In our case, we have a lot of special industrial cameras that make it necessary to create wrapper agents that support the proprietary protocols of the cameras and send the video to the media back-end afterward.

From an information view perspective, we realize the information model based on the NGSI-LD standard. The standard allows us to make use of the linked data concept to shadow the structure of our plant in the digital world in a layered model. Additionally, community data models from the FIWARE smart data models program help to design data models in accordance with domain-dependent or independent standards and improve the reusability of data models across domains. We tried to rely on community models for the energy domain wherever possible. While some models from the smart data model program can be reused such as WeatherObserved[3] or ACMMeasurement[4], we also need to define custom ones for the use case of the SPT plant for example to represent heliostats or specific power block components. Following the open-source approach, we published parts of our schemata for the digital entity representation in the CST domain in the smart data model program of the FIWARE community[5]. The digital representation of the PCS systems with about 50 subentitites such as duct systems, receiver, or generator are bound to custom PCS variables that typically differ between SPT plants. In our case, these variables follow a naming system called identification system for power stations that systematically structures the 4000 variable names to semantically express their meaning in the context of the tower [49]. As there are many variables that are retrieved for the receiver, power block components, HTC and heat storage, modeling each subentity and creating configuration and schema files manually is a time-consuming and error-prone task. We therefore created a tool that helps to automatically create schema and configuration files based on the identification system for power stations, so that the configuration and schema files for the PCS subentities are generated [6].

Next, the deployment options are discussed. The first question is how the services are deployed. As described, we have decided to deploy the services in a containerized deployment orchestrated by Kubernetes. That has the advantage that configuration files can be scripted and stored in the version control system, and the service deployment can be centrally managed, monitored, and easily integrated with basic error handling procedures. In addition, each service can be dynamically replicated and distributed to different physical machines to improve the performance and availability of the service. Moreover, the use of virtual overlay networks allows to use cluster-internal ports for all services besides the security gateway, so that the service acts as an entry point to the CPS that safeguards the infrastructure. Each request has to pass through the security gateway, so that security mechanisms such as authentication checks, rate-limiting, or audit logging can be applied.

Another central question for deployment is where to deploy the CPS infrastructure. In consultation with the plant owner, we decided to deploy the CPS system on-premise in a cluster of commercial off-the-shelf (COTS) servers. The advantages of the solutions are full control on hardware and software solutions, increased availability due to the distribution of the applications on several hardware nodes, improved performance on the basis of dynamic load

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[3] `https://github.com/smart-data-models/dataModel.Weather/tree/master/WeatherObserved`

[4] `https://github.com/smart-data-models/dataModel.Energy/tree/master/ACMeasurement`

[5] `https://github.com/smart-data-models/dataModel.GreenEnergy/tree/master`

[6] `https://github.com/DLR-SF/FiwareResourcesKKS`

balancing, and expandability by the possibility of buying additional hardware nodes or resources for the cluster. Depending on the guidelines and strategy of the business the planned CPS infrastructure can also be flexibly deployed in the cloud on the basis of the same container scripts or by using templates of the FIWARE cloud or other cloud providers. Thereby, it can be fully deployed into the cloud or split up into edge, fog, and cloud components in a flexible way. Depending on individual requirements, especially for performance and availability, it can be an option to deploy time-critical applications on the edge, IoT services on the fog, and the remaining services in the cloud.

In summary, the combination of FIWARE and other open-source tools offers many possibilities for the technical realization of the CPS infrastructure on the basis of standards. After exploring, testing and comparing different deployment options, we have developed an operational view that makes use of FIWARE GEs, other open-source solutions and self-build applications. Moreover, the deployment of the CPS infrastructure is based on a containerized and orchestrated deployment that allows the services to be flexibly deployed on-premise or in the cloud depending on the deployment strategy in the research context.

5.4. *Cyber-Physical System Evaluation*

The goal of the CPS evaluation is to observe the effect of change and assess the effectiveness of the system design with respect to the study problem. Thereby, it is evaluated if the CPS infrastructure implementation in the SPT plant meets the study objectives and the specified requirements.

In general, we demonstrated a successful transformation of a SPT plant from a traditional SCADA-based I3.0 system into a I4.0 system based on the introduction of a CPS middleware infrastructure (see Fig. 9). The CPS infrastructure breaks down data silos by receiving data from heterogeneous data sources, increasing the availability of real-time and historical data, and providing data and services for data-based decisions by human operators and intelligent applications. Thereby, it fully integrates physical and virtual plant entities, enables the flexible integration of additional IoT devices, and manages industrial big data. Overall, it lays the foundation for improved operation and maintenance on the basis of a decentralized, data-based, and interconnected system architecture that allows to efficiently monitor, control, and automate industrial systems and processes.

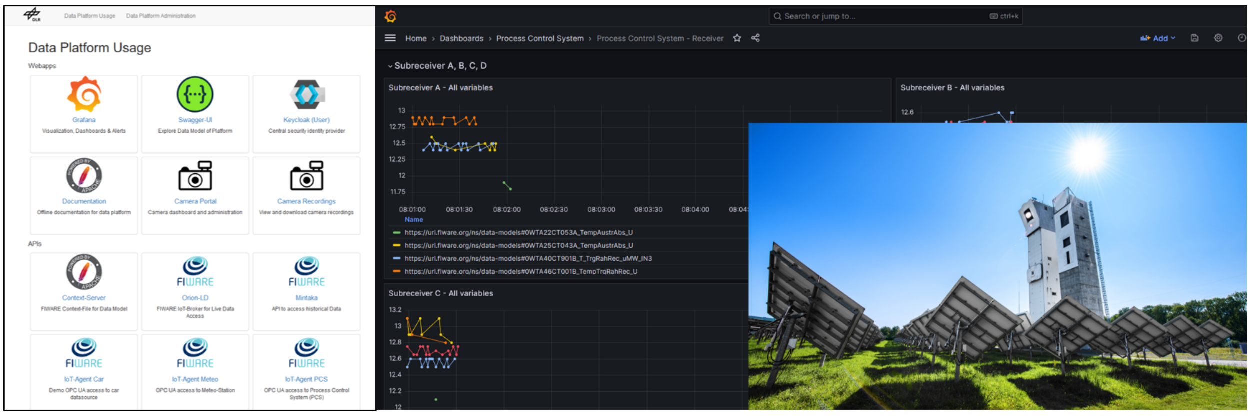


Figure 9: Realization of the CPS in the SPT plant in Jülich

For a more detailed evaluation of the solution, the fulfillment of the specified requirements can be checked. All functional requirements have been met on the basis of FIWARE components, open-source tools, and a few custom developments. Thereby, the design constraints and the non-functional requirements have been taken into account to serve the needs of the SPT plant and its stakeholder. Some non-functional requirements can directly be assessed on the basis of the architecture and the implementation approach such as interoperability, flexibility, scalability, and performance demands. First, the solution provides interoperability and flexibility on the basis of a CPS middleware layer that makes use of standards and generic wrappers to support the integration of different devices and software modules in a flexible way. Second, the distributed, decentralized, and orchestrated container-based deployment allows to operate the solution on an arbitrary number of hosts either on-premise or in the cloud and dynamically replicate services to provide a scalable and reliable solution. Both requirements are especially supported by the use of orchestration software that continuously checks capacity utilization and service health to dynamically balance load and restart services in case of failure. Reliability is further improved by fault management software that continuously observes logs and analyzes malfunctions and failures. Third, the performance of live data provided by CPS infrastructure can be measured with the system monitoring tools. The tools show that live data typically have a latency of about half a second when measuring the time the CPS infrastructure needs from receiving to provisioning data.

The assessment of the other non-functional requirements such as maintainability, security, or usability requires a long-term evaluation and additional tests. Thus, in a next iteration of the AR process concrete use cases for operator support and smart service development can be realized based on the initial release of the CPS infrastructure for a subsequent in-depth assessment. However, first interviews with direct system users revealed simplified data access through central data collection, provisioning of unified interfaces and CPS services. The operation and maintenance conducted by the MO and MMO are supported by flexible visualization of live data and proactive warnings and alerts in case of danger. Moreover, the CPS infrastructure enables data analysts to flexibly integrate new IoT devices and offers a number of features that support the deployment and development of intelligent services. The collection and consolidation of all plant data sources with semantic data models free them in particular from the burden of connecting to heterogeneous information sources, integrate vendor-specific data models, making data machine-readable, and generally care for data acquisition basic tasks prior to smart service development.

In summary, the CPS infrastructure meets the objectives of the study and fulfills functional and basic non-functional requirements. Although further studies on the long-term success of the CPS infrastructure are needed, the study demonstrates a successful transformation of a traditional I3.0 system that follows an hierarchical automation pyramid approach into a fully interconnected, data-based and flexible I4.0 CPS infrastructure.

6. Conclusion

The central research question of this study is how CST plants with strict hierarchical automation pyramid system architectures can be transformed into CPSs according to the I4.0 paradigm. To answer the question, the authors of this paper conducted an AR study and demonstrated the transformation of a traditional SCADA-based SPT plant into a decentralized, data-based, and interconnected CPS infrastructure. The objective of the closing chapter is to summarize the study, discuss the lessons learned, and generalize the results for comparable industrial plants.

In summary, we demonstrated a transformation process of a SPT plant on the basis of IoT ARM and discussed all stages of development, from the analysis of the requirements to the implementation and evaluation of the system. Thus, we started with a domain and requirement analysis to understand the target domain and gather the requirements for the digital transformation of the plant. Here we used the physical entity view, context view, and domain model from the IoT ARM to analyze the structure of the SPT plant and integrated IoT ARM with the approach of Silva et al. for a systematic requirement specification process. Subsequently, we developed an architecture on the basis of the IoT ARM information and functional view that describe the information model and the functional building blocks of the CPS infrastructure in an abstract way. As a last step, we demonstrate the concrete implementation of the architecture on the basis of the IoT ARM operational view and discuss possible deployment options. Thereby, we selected the open-source platform FIWARE and other open-source software modules as concrete technological software solutions and additionally implemented some custom developments to realize our architecture. A first qualitative evaluation of the solution showed a successful implementation that meets the specified requirements and supports operators and smart services in operation and maintenance tasks. Although more in-depth and long-term studies are needed to assess further non-functional requirements, the general objectives of the study have been met.

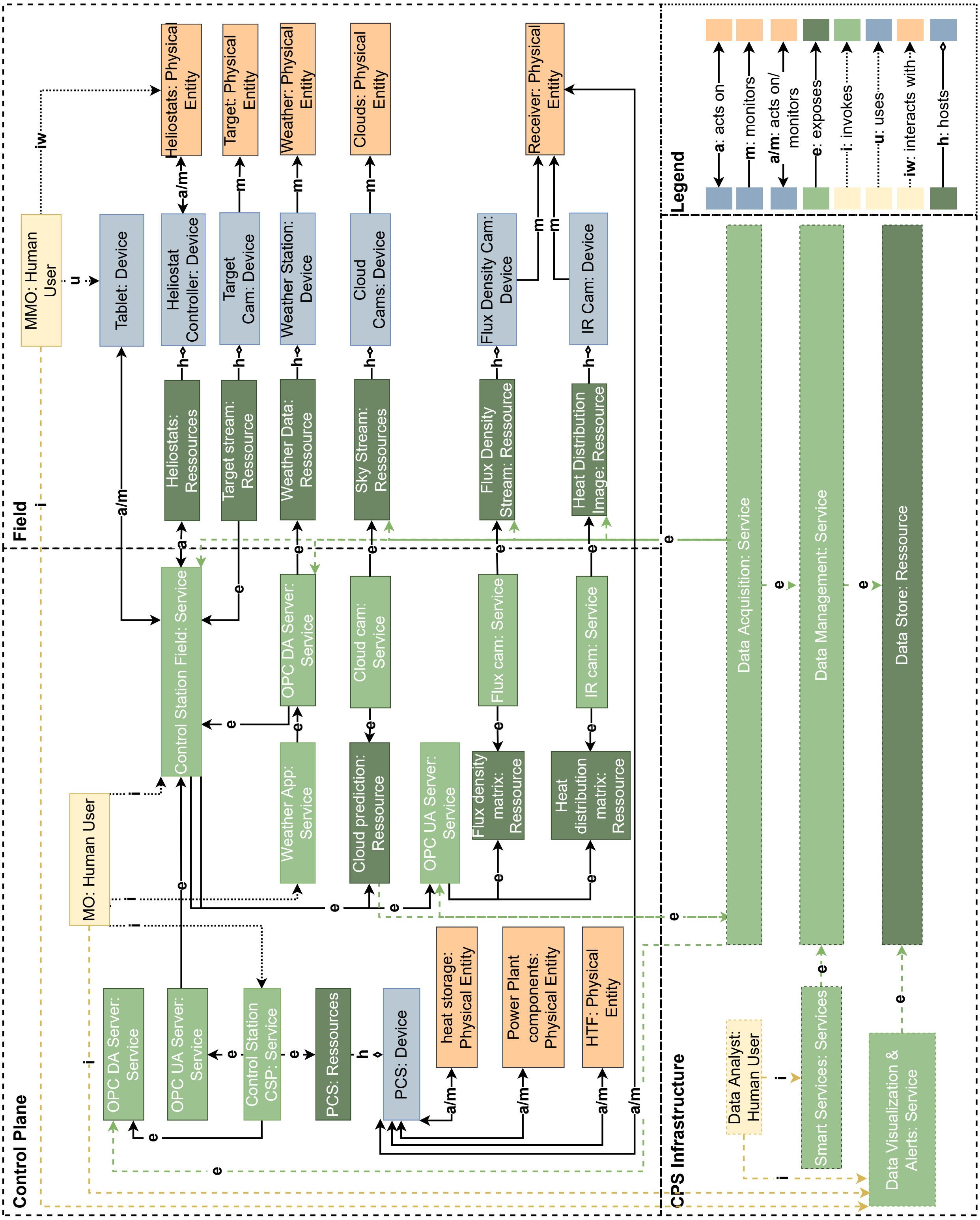
As a result of the study, we learned about the IoT ARM as a methodology for digital transformation projects in the era of I4.0 and the CPS infrastructure development in the research context of a SPT plant. First, the IoT ARM provides extensive support to generate architectures for individual scenarios based on a reference architecture, architectural views, design choices, tactics, and more. From the authors' point of view, especially, the architectural views help decompose the architectural description into more manageable parts, provide models for different stakeholder concerns, and guide the entire development process in a systematic way. In particular, extensive analysis of the target domain has been proven to be helpful for the subsequent requirements analysis and architecture development for plant transformation. The detailed specification of requirements, functional decomposition and the information model supported in turn the selection of technology and the realization of a system that meets the needs of the stakeholder. Second, the realization of the architecture on the basis of FIWARE, other open-source solutions, and self-developed software modules has been proven to be an effective, flexible, and qualitative solution. The standard-based FIWARE framework allows to integrate the solution with a broad range of other open-source software to realize most of the specified requirements with limited time. Only a few modules had to be implemented to support specific industrial protocols and the extensive use of camera systems. Moreover, there are many open-source solutions that can be used as alternative FCs, so that the realization is flexible and modules can be exchanged or extended over time according to the needs of stakeholders. Finding suitable open-source solutions that are able to realize each FC has been the most time-consuming task, because there are many possibilities that need to be tested against the demanding requirements of the SPT plant before the modules can be selected. In particular, the application in the research context created high demands on security, latency, and reliability while imposing extensive challenges such as a large amount of data, extensive data models, and a high degree of heterogeneity.

Finally, the experiences from the AR study can be generalized for other CST plants and comparable industrial environments that rely on traditional hierarchical automation pyramid system architectures. Thereby, we conclude four central statements from our findings:

1. *A CPS infrastructure enables to increase the level of digitization and automation:* The introduction of a CPS infrastructure effectively supports higher levels of digitization and automation in complex industrial environments compared to plants with classical automation pyramid architectures. It can bridge the gap between heterogeneous plant components, consolidate live and historical data from different sources, handle complexities of large industrial infrastructures, and improve the flexibility, interoperability, and scalability of the system landscape. Overall, it lays the foundation for smart service development and optimized decision-making by humans and machines on the basis of a decentralized, data-based, and interconnected system architecture.
2. *A digital transformation of existing plants can be effectively realized based on CPS middleware layer:* A digital transformation in the era of I4.0 can be realized on the basis of an extension of the traditional I3.0 infrastructure rather than an overall system renewal in brownfield scenarios. In this way, the transformation can be done on the basis of a step-by-step approach based on a CPS middleware infrastructure to successively expand the support for data-based operation and maintenance. In this way, operation is not disturbed by change, existing high-cost industrial plant components can be integrated and effort and financial investment in infrastructure transformation can be distributed over time.
3. *IoT ARM can support the infrastructure transformation process:* IoT ARM provides a domain-independent architectural reference model that can be used not only for infrastructure development but also for infrastructure transformation as demonstrated in the course of the study. Thereby, especially architectural views for the analysis of the target domain can help to understand complex industrial environments and identify components that need to be integrated in the transformation process. Overall, the methodology offers extensive support in all CPS infrastructure development phases and has proven to guide the development of a microservice-based CPS middleware layer in an effective way.
4. *Transferability of the results to other environments with traditional automation pyramid architectures:* Overall, we demonstrated a successful approach for the digital infrastructure transformation of a SPT plant. Many of the requirements that we faced while conducting the AR, are described in the literature as common I4.0 needs and challenges (see Section 2). In general, the SPT plant is a complex industrial system with a large number of components, industrial big data, high degree of heterogeneity, and high demands on performance, flexibility, security and reliability of processes. IoT and CPS are opening up the opportunity to interconnect industrial data silos based on a flexible microservice architecture that is realized as a middleware layer to integrate systems, efficiently handle BD and provide data-based services as a baseline for an increased level of digitization, automation and intelligence. Although other SPT plants, types of CST plants and comparable industrial environments might have another collection of devices and services in their plant, the basic methodology, requirement collection, generic architecture, and software solutions of the realization can be transferred to other industrial scenarios with classical automation pyramid architectures from the viewpoint of the authors.

In summary, the study conducted AR to study how existing CST plants and comparable industrial environments can be transformed into CPS infrastructures in the era of I4.0. It demonstrated a methodology, a generic architecture and the realization of a CPS infrastructure in a real-life example to bridge the gap between scientific progress, technological advances and its practical application.

Appendix A. Domain Model of the SPT plant



Appendix B. Example scenarios for the CPS infrastructure of the SPT

No.	Name	Description
1	Weather monitoring (*example for an alphanumerical data exhibition scenario*)	As weather conditions have a significant influence on solar thermal power plants, a weather station continuously monitors important weather parameters such as irradiation, wind speed or temperature. These numerical data should be visualized for MOs, MMOs and data analysts on the basis of a data visualization app, so that they can flexibly get graphical insights on live and historical weather data.
2	Flux density observation (*example for a video exhibition scenario*)	The flux density camera records a video of the receiver to understand the solar energy distribution for optimization purposes regarding power generation and material protection. The CPS infrastructure should retrieve the video data from the camera and provide the live video to MOs, MMOs and data analysts so that they can observe the current solar energy distribution.
3	Heliostat state alerting (*example for an alerts and warnings scenario*)	The control station of the solar field continuously exchanges monitoring and control information with the local heliostat controllers such as motor positions, errors, or states. This alphanumerical data should be continuously evaluated by the data alerting app and warnings and alarms should be sent to the MO if a certain threshold is reached. The MO decides on corrective action, for example, exclude the heliostat from operation or notify the MMO.
4	Automated control with consideration of cloud movements (*example for an automated system control scenario*)	To protect the receiver material, the receiver temperature should be as stable as possible. Because shading by clouds can lead to rapidly increasing or decreasing receiver temperatures, the movement of clouds in the sky is recorded by a cloud camera and predicted by a cloud prediction service based on the sky video stream. Live and historical predictions should be provided to other automation services that execute algorithms and send commands to the control station for the field to reduce or increase the number of heliostats pointing at the receiver.
5	CST control station predictive maintenance (*example for a predictive maintenance scenario*)	The CST control station continuously receives monitoring data from the process control system about the receiver, heat unit, and power block. To support MOs and MMOs, predictive maintenance services should consume live and historical monitoring data, predict malfunctions and send proactive alerts to the MMO on the basis of the data alerting app.

Declaration AI Usage

During the preparation of this work the authors used Writefull for language editing purposes. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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