MASIMO – A HYBRID EXPERIMENTAL PLATFORM FOR THE SIMULATION AND EVALUATION OF DATA-DRIVEN MAINTENANCE ENTERPRISES

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Abstract
The development of data-driven maintenance service providers considering “Industrie 4.0” components requires intensive research into the implementation of lifecycle data, advanced processes and their workflows, intelligent communication architectures, and smart interoperable systems with semantic capabilities. To this end, DLR-MO is operating an implementation and test environment that emulates maintenance service providers and supports future investigations, for example, self-determined interacting assets or agent-based execution systems in a cyber-physical-social system (CPSS). This model will be used to develop and improve data-driven process flows and their management, data processing and storage, automation and human-machine interactions.

1. INTRODUCTION

In recent decades, several standards have emerged in the manufacturing industry to design, build and operate efficient enterprises. More recently, these standards have been revised or supplemented to support the realization of a digitalized industry, with activities being summarized under the term “Industrie 4.0”. The paper describes the initial results of a feasibility research on the extent to which Industrie 4.0 architectures and their standards can be applied to MRO service providers, because they were primarily developed for the digital transformation of the manufacturing industry. The question arose because there are significant differences between the two industry sectors: Unlike a manufacturer, an MRO provider's product is mostly intangible, since the product is the MRO service itself, which cannot be stored. Unlike a conventional manufacturer, where the processes are linear and repeatable and the work content is clearly defined, a maintenance service provider must manage variable processes and work contents depending on the input conditions of the maintenance-receiving assets. These agile responses require flexible and adaptable skills as well as tacit knowledge provided by experienced staff, which underlines the importance of humans involved in MRO services.

However, these characteristics of MRO service providers show strong similarities with the capabilities of future manufacturers envisaged in the Industrie 4.0 standards and recommendations, namely flexible production on demand. Applying these standards means transforming established structures, especially from very hierarchical structures (e.g. automation pyramid) to extremely flexible, self-organized levels. The latter is realized by so-called cyber-physical-production systems (CPPS) based on the Internet of Things (IoT). The IoT is „*a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual “things” have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network*” as stated by the European Research Cluster on the Internet of Things (IERC) in [1]. As described in [3] humans and machines as well as other resources should interact just as naturally in CPPS as they do in social networks. Thus, the digital transformation is more than just digitizing analogues processes or systems to increase their efficiency by automation or a seamless communication in a network. It is a comprehensive socio-technical change, a change in the way peoples, machines and systems work together, not in CPPS but in **Cyber-Physical-Social Systems** (CPSS). All these features of CPSS fit well with the requirements of an MRO service provider, namely to be flexible and adaptable to different inputs, considering human skills and tacit knowledge. In this context, standards have been published, such as the "Reference Architectural Model Industrie 4.0 (RAMI 4.0)" [12] for supporting the creation of CPSS and the "Asset Administration Shell for Industrial Applications" [27] as data-driven replications in these CPSS. Since these standards relate to the manufacturing sector, our research focuses mainly on the following questions:

1. **What could a CPSS architecture of data-driven maintenance service providers look like, building on the insights of Industrie 4.0, which has its origins in the manufacturing sector?**
2. **To what extent can the standards and recommendations of Industrie 4.0 be applied to data-driven maintenance service providers, including humans?**
3. **What might an overarching supervisory system look like in a CPSS of a data-driven maintenance service provider, with one focus on tacit-knowledge of humans?**

To answer these questions, a multi-scale hardware maintenance simulation model was developed. The model helps to explore the limitations, opportunities, and requirements for implementing, adapting, and enhancing Industrie 4.0 components for a data-driven MRO service provider. A CPSS network was first derived that considers the specific characteristics of an MRO service provider and draws on

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broad accepted design approaches. Based on this CPSS, Industrie 4.0 components were integrated to handle and supervise the flexible processes and work content of data-driven MRO service providers. Conclusively, the gaps for further research were identified.

2. CYBER-PHYSICAL-SOCIAL SYSTEM

In general, the CPSS *"is about the intersection, not the union, of the physical and the cyber. It is not sufficient to separately understand the physical components and the computational components. We must instead understand their interaction*" [2]. Although there is not yet a standardized design process for CPSS, at least the Open Platform Communication Unified Architecture (OPC UA) is increasingly becoming a common basis for communication in and between these systems. OPC UA is an open standard (IEC 62541) for data exchange and widely accepted as the enabling technology for Industrie 4.0 [4]. It also provides an extensible meta-model (i.e. the base OPC UA information model) that allows the definition/modeling of data structures to describe the semantics of the data exchanged. Due to these characteristics, the broad acceptance, the standardization and above all the industry sector independence, OPC UA was selected here as the central framework for establishing the main communication in the CPSS.

For the creation and investigation of the CPSS, the maintenance simulation model (MaSiMO) was developed. It supports to elaborate and improve the potentials of Industrie 4.0 features, applied to data-driven maintenance service providers. Table 1 lists important characteristics of Industrie 4.0: In summary, digital transformation is based on three core components, namely the CPSS using the internet of things (standardized communication network), semantic interaction (data to information) and data-driven representations of tangible and intangible assets, as also stated in [3]. If one compares these envisaged characteristics with the current requirements for an MRO service provider, strong overlaps can be identified – among other:

- Flexible and adaptable process flows on demand,
- variable work content and systems depending on the input findings and
- applying tacit-knowledge, depending on input conditions, which will be supported e.g. by machine learning approaches.

Domain	Industrie 4.0
Architecture	CPSS: IIoT, agent-based MES
Asset	Individual products or services
Processes	Variable on demand
Work content	Variable on demand
Configuration	Automatic reconfiguration at run-time and continuously over lifetime
Information	Information and semantic models in integrated runtime system (digital twin)
Connection	IEEE-TSN- based, time sensitive and scalable networks, wireless com
Optimization	Data-driven, e.g. with machine learning

Table 1: Features of Industrie 4.0

Taking these requirements into account, MaSiMO must be able to simulate maintenance process flows that are as complete, flexible and adaptable as possible and that correspond to real maintenance processes and environments at shop floor up to the entire enterprise level. These replicated process flows will be equipped with use-case specific and advanced maintenance technologies such as robotics, industrial internet of things (IIoT), maintenance data analysis, human-machine interfaces and interactions, and various supporting software applications. The design flexibility of the process flows is achieved through an adaptable default structure of the simulation model. One of the most important technical features of MaSiMO is its hybrid scaling (Figure 1): it integrates scaled-down and life-size environments into an expandable/flexible cyber-physical-social system. In general, the more detailed the processes to be described, the more life-size the associated elements of the simulation environment will be. Furthermore, the model combines virtual and physical applications that complement each other in the constructed CPSS. With the integration of virtual or tangible, scaled or real-size applications in the simulation platform, the research strategic goal is to capture complex processes as comprehensively as possible across the MRO service providers. Using CPSS as a framework for the overall architecture is a promising solution for implementing such a hybrid approach. It connects everything from small virtual plants or model-based surrogates to real MRO workshops, humans with tacit knowledge and the maintenance-receiving assets such as aircraft, engines, drones, wind turbines, trains etc.

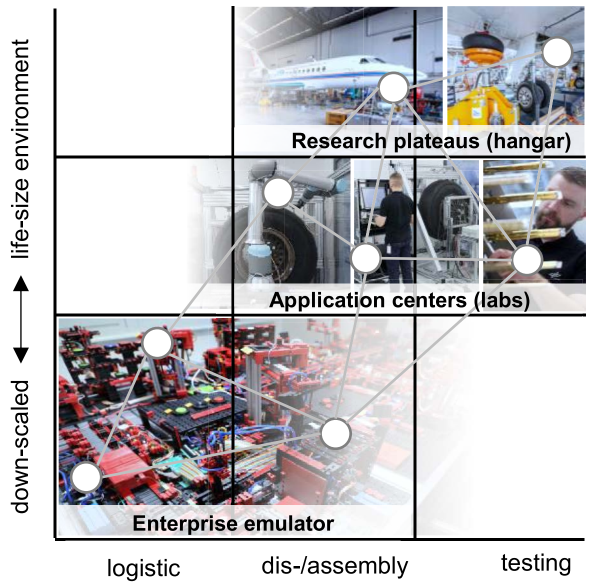


Figure 1: Interaction of non-scaled and scaled elements at the different MRO enterprise levels in MaSiMO's CPSS

2.1. Network Architecture of the CPSS

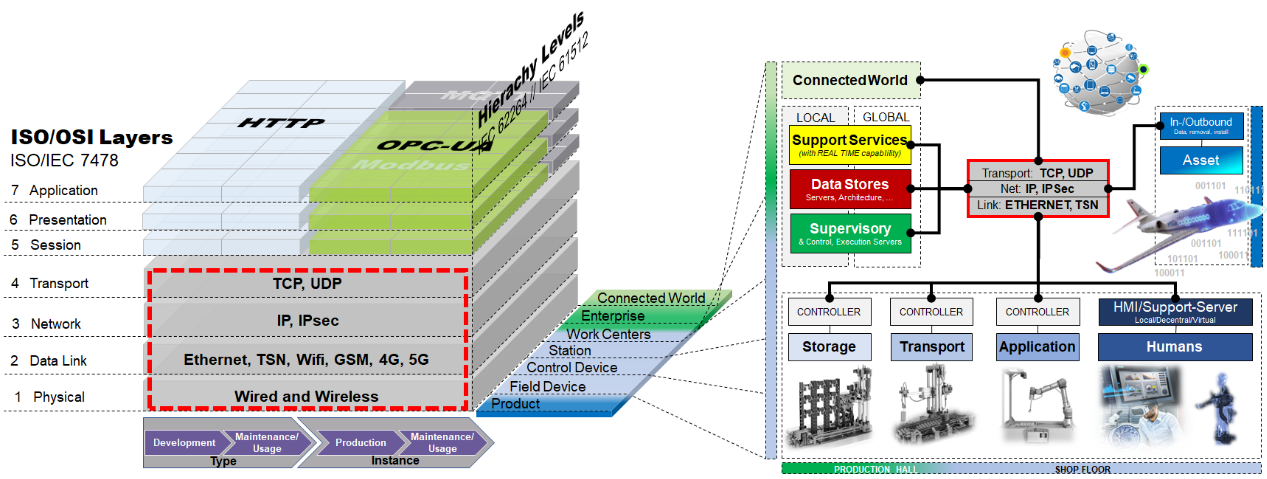
According to the German Standardization Roadmap on Industrie 4.0 [18], "*technically, industry 4.0 represents the fusion of IT (Information Technology) and OT (Operational Technology)*" and "*[…] will require an unprecedented degree of system integration across domain borders, hierarchy borders and life cycle phases.*" Referred to this, in a fully connected maintenance environment, all the OT- and IT-systems across the levels shop floor, enterprise and supply chain, need to be integrated into automated, interoperable, and flexible networks that enable seamless data exchange, analysis and decision making.

The above goal of IT-OT convergence will be achieved through the merging of IoT and CPSS affecting all industrial levels and processes. In this context, a challenge is to develop a reference architectural model to provide descriptions and standards for integration and implementation on a common ground. As a comprehensive literature review in [11] shows, “*[…] many studies have been carried out from the CPS perspective in the scope of I4.0, standardizing ideal frameworks for its use in the industry*”. Finally, the authors identified three main architectural concepts based on their frequency of use, namely the Reference Architectural Model Industrie 4.0 (RAMI 4.0, DIN SPEC 91345 [12]), Industrial Internet Reference Architecture (IIRA) and 5C Architecture. These reference models are neither blueprints nor a substitute for a CPSS construction manual [20], and some authors also criticize inconsistencies or unclear definitions [5]. Nevertheless, here they provide valuable guidelines for its initialization, setup and design on a common basis between different stakeholders.

The IIRA has been developed by the “Industrial Internet Consortium” (IIC)[1], “*the world’s leading organization that serves to transform business and society by accelerating the adoption of IIoT*” [13], RAMI 4.0 has been introduced by the German industrial network “Plattform Industrie 4.0” (PI4.0)[2]. Although the goal of both is the guided convergence of IT and OT, the scopes, objectives and approaches differ: While the IIC addresses the application of the industrial internet of things (IIoT) across industrial sectors (Energy, Transport, Manufacturing, Health Care, Public) and emphasizes cross-sector commonalities and interoperability, the PI4.0 focuses primarily on production in detail. Thus, both architectural models have complementary and similar elements or perspectives that are worth combining by enabling “*interoperability among IoT systems that are built based on these reference architectures*” [13]. Unlike IIRA, RAMI 4.0 provides a service-oriented architecture (SOA) that combines data and services through a *“horizontal integration among factory networks and plants”* and through a “*vertical integration within a factory, with products at one end and the Cloud at another*” [11]. In parallel “*lifecycle management, end-to-end engineering and human beings orchestrating the value stream*” [13] are considered. In contrast to the IIRA, RAMI 4.0 framework includes specific recommendations for standards and technologies to design the IIoT. In this context, RAMI 4.0 offers a structured description of the main elements of an asset using a layer model consisting of three axes, as shown in *Figure 2* (a).

Applying these reference architectures to data-driven MRO service providers requires some consideration of integration, as they target manufacturing companies. The main differences concern the product and the process flow. In contrast to the manufacturer, the product here is an intangible service with an asset as input, which is also the output of the process. By comparison, manufacturers use several components as inputs to their processes and receive a product as output. Transferred to MRO service providers, one can assume that these multiple inputs are different services on an asset in order to check and improve its condition. However, these reference architectural models describe the structure of future, fully digitized manufacturers whose intended capabilities are non-linear, variable process flows to quickly adapt production, including content, to customer demand. Furthermore, RAMI 4.0 is based on a service-oriented system architecture, but focuses less on the functionalities and more on the communication and data-driven interoperability between the different layers - this is described in an industry-independent way. **These features are strongly related to the requirements of data-driven MRO service providers, which suggests the use of the reference architecture models.**

A standardized communication architecture enables the central capability of CPSS, namely seamless interoperability between all embedded systems, elements and humans. The comparison of both reference architectures shows that the layer structure of RAMI 4.0 has the greatest similarities to the domains in the "Functional View" of IIRA. Here also the communication capabilities are located such as the “communication layer”, the “information layer” and the “connectivity cross-function” respectively. In this context, both reference models rely on the Open Systems Interconnection model (ISO/OSI model; ISO/IEC 7498 1:1994) to describe their communication architecture in more detail. For example, *Figure 2* (a) shows the decomposition of the communication layer of RAMI 4.0 through its extension to the ISO/OSI layers. So, the vertical and horizontal communication is ensured by applying standardized protocols. Conclusively, for setting up a network of CPSS there are several communication standards available. However, there is a convergent picture between the major industry and research initiatives of IIoT, as they recommend, for example,



(a) (b)

Figure 2: (a) RAMI 4.0 hierarchy levels (based on [18]), (b) Core IT-network infrastructure of MaSiMO, linked to (a)

[1] https://www.iiconsortium.org (accessed on 21.08.2022)

[2] https://www.plattform-i40.de (accessed on 21.08.2022)

composing the **"Transport"** layer of **TCP** and **UDP**, while **IP** and **IPsec** are proposed for the **"Network"** layer. Furthermore, there is a more or less common understanding regarding the upstream layers, emphasizing **Ethernet** and the emerging **Time Sensitive Networking** (TSN) for the "**Link**" layer and the opportunities of **wired** and **wireless communications** in the "**Physical**" layer. More complex seems to be the standardization of the downstream network architectures with some diverging proposals. Finally, in the present work, **OPC UA has been selected** as the main communication framework in the concerned network layers and above-mentioned areas of application, since it is considered as core standard for both the PI4.0 and the IIC reference architectures and essential for CPSSs on I4.0 context, as jointly stated in [13].

Not to be neglected are other **global initiatives** such as the "Connected Industry 4.0" in Spain, the "La nouvelle France industrielle" in France, the "Smart Manufacturing Leadership Coalition (SMLC)" in the USA, "China Manufacturing 2025" in China or the Japanese "Robot Revolution Initiative" [17]. However, skimming through their strategies, these initiatives have either agreed to cooperate with or refer to the German initiative in the area of IoT/Industry 4.0. This, the "Reference Architecture Model 4.0" and the introduction of the "Industry 4.0 Component" justify the use of the **fundamentals of the "Platform Industry 4.0" for the design of MaSiMO's CPSS**.

2.1.1. Network applied

In a first step, the institute environment, consisting of offices and laboratories in different buildings, was organized in an experimental IT network in such a way that it comes as close as possible to real company architectures as described with the hierarchy levels of RAMI 4.0 (*Figure 2* (a)). Thus, the structure also corresponds to international standards like the IEC62264 and IEC61512. Table 2 describes the company hierarchy levels and the Institute's research facilities assigned to them. These are interconnected with the experimental IT network to form the overarching IoT of MaSiMO (compare *Figure 2* (b)), this core network is the backbone of the top-level (parent) CPSS. As mentioned, the simulation platform works with different levels: At a glance, the upper level handles digitized requests and responses, generated by or given to airlines or aircraft for example. The intermediate levels cope with the execution and the data exchanges within the logistic, e.g. part's receiving or deliverable, storage, company-internal transport. The lower levels cover operation and the data exchanges between workshops and the detailed level works with data exchanges between machines or between humans and

RAMI 4.0 | DIN/IEC62264	EQUIVALENT RESEARCH FACILITIES
Enterprise	**DLR-ZAL-OFFICES**
Site Office floors (Management, R&D and design)	*The office wing houses **MES/MOM** systems and **SCADA**, as well as the research, development and implementation of them and other digital solutions: from microservices to the entire CPSS.*
Site-Area (Production floor)	**Hangar + shop floor logistic** *A fischertechnik model reproduces all processes relating to **goods receipt**, **delivery**, **storage** and **logistics** on site. It maps the entire MRO company on a scaled-down environment.*
>>> NON-LINEAR PROCESS FLOWS <<<	
Work Centers	**Shop floor** | DLR-ZAL-RD-AREAS
A work center groups one or more stations. Work centers represent the highest-level element that performs maintenance functions and is regarded in production planning and scheduling. They have well-defined process capabilities and throughput capacities.	*The work centers are emulated on research plateaus or with the scaled surrogates by **replicating the interactions of the different stations** (e.g. work cells for production processes) that compose the work centers.*
>>> NON-LINEAR PROCESS FLOWS <<<	
Stations, control and field devices	**Stations** | DLR-ZAL-LABS
Stations are subdivisions of work centers and have discrete manufacturing/ maintenance capabilities and capacities. They are composed of lower level equipment units that are not regarded directly in production planning and scheduling.	*In the labs, the **MRO processes** are replicated **in detail** and in real size at stations. In order to connect the systems used to the CPSS, they must be I4.0-compatible, whereby Asset Administration Shell encapsulation is preferred.*
Product	
Maintenance-providing assets (services)	Maintenance-providing assets (services); use of **real** and **surrogates**

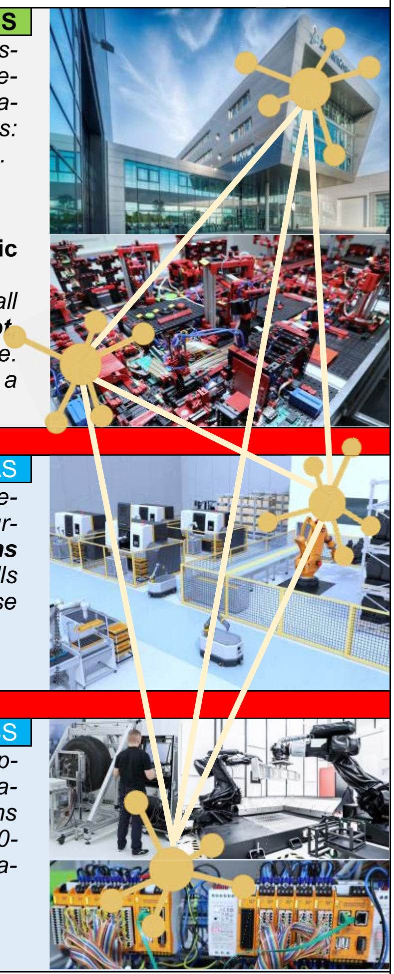


Table 2: IoT-networked company levels and the Institute's research facilities assigned to them

machines respectively. These complex interactions and operative intercorrelations are investigated by applying a hybrid solution:

On the one side the whole enterprise level is simulated by a down scaled model-based hardware (Table 2: top picture); on the other side the work center levels are implemented in laboratories or hangars (Table 2: middle/bottom picture), which are digitally interconnected with the before-mentioned enterprise level. The latter receives requests and manages the logistics as well as the commands to the different workshops, receives their responses and acts properly. Thus, developing and testing suitable communication formats as well as command algorithms to execute all digital requests and responses between the stations and process steps, is one essential task. With the experimental platform scaled data, resembling a real company, can be experimentally generated and forwarded to other optimization tools (e.g. ERP, MES) or researchers. The results of these tools or the researcher's knowledge can be returned. Thus, an iteration is possible.

2.2. Asset Administration Shell in the CPSS

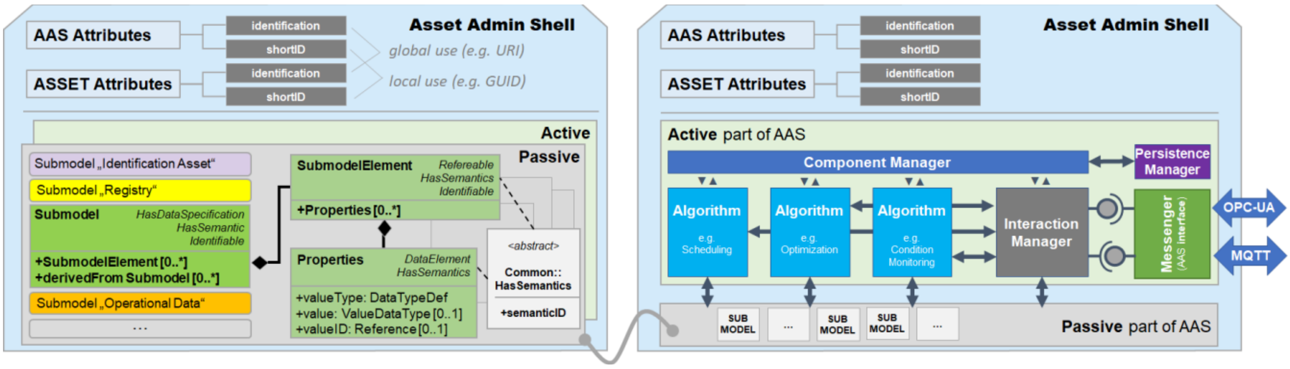
Before assets can be considered in the CPSS of a data-driven maintenance service provider (e.g. in MaSiMO), they have to be connected to it. Therefore, both suitable physical interfaces and a comprehensive digital description of the properties or functions of the assets over the lifecycle are required – available and accessible everywhere in the IoT, at real-time or historically. In this context, the Plattform Industrie 4.0 (PI4.0) consortium introduced the concept of the Asset Administration Shell (AAS) as a cornerstone of interoperability in its reference architecture of IoT. An AAS is a data-driven representation of an asset that has emerged in an industrial context. The AAS contains information about the asset, including documents, properties, parameters and functionalities, embedded in a 2022 standardized architecture (DIN EN IEC 63278-1, 2022, [27]). Together with the asset, they form a so-called Industry 4.0 component. In its most advanced form, it interacts self-determined with other AAS in the network, creating smart CPSS. The information provided by an AAS is updated throughout the lifecycle of the asset, from its development to its disposal. **The question is to what extent these Industrie 4.0 components are suitable for use in the CPSS of MRO service providers?**

An important feature of data-driven MRO is the implementation of humans interacting with all other system components in the CPSS by providing their "services" in the form of tacit knowledge and other skills. The draft IEC 63278-1 [28] explicitly emphasizes the use of **AAS to embed humans in a data-driven environment**. In [28] it is highlighted that in a "*data-driven economy, the potential for value creation can be fully exploited* […]" if, above all, the vertical and horizontal interactions in the networks, with digital consistency and the "***human being as a conductor for added value***" are understood. Thus, the AAS gives humans a virtual identity with individual skills that allow them to interact with other intangible or tangible assets involved in the CPSS.

As shown in Figure 3 (a), the AAS structure follows a standardized information model defined by the top-level AAS attributes, followed by the definition of their associated submodels, which are further characterized by elements such as collections, operation and property instances, which refer to individual information and functions. "Details of the Asset Administration Shell – Part 1" [14] introduces this information model in UML and thus provides a practical approach for the implementation in various formats, including XML, JSON, AutomationML, RDF and OPC UA.

One of the most important aspects of the information model is the proper identification of the AAS elements by giving them an identifier (ID) in order to uniquely recognize them. The explicitness of the elements results from a chain of identifiers. An important feature of the identification concept is that it takes **semantic identifications** into account, which are **essential for data-driven communications with a correct data interpretation**. In this context and as shown in Figure 3 (a), so-called "semanticIDs" refer to documents or other sources that are linked in the abstract class "HasSemantics". These sources provide a unique description of the meaning of the submodels and their elements or properties, especially designed for machine-based clear interpretations. For an exclusive semantic, the usage of comprehensive and **standardized dictionaries like ECLASS**, "*the only worldwide ISO/IEC-compliant data standard for goods and services*", or IEC 61360 is strongly recommended whenever possible. Otherwise individual semantic content with ID can be defined.

In Figure 3 (b) a concept is shown, how the design of such a pro-active AAS and thus a simplified server architecture could look like. In the present work, the drawn concept is a merged result of different proposals on this topic, in particular by [21][23][24]. In general, and as introduced in [16][18][19], a **component manager** realizes the overall administration of the datasets and considers, if available, algorithms for AAS internal data processing. For that, the component manager links the data and functional elements and triggers further process steps, for example in response to the algorithm results or other requests (external/internal). To store documents, objects, time series, or other AAS's



(a) (b)

Figure 3: Structure of passive (a) and active (b) administration shell → AAS Server

elements, a **persistence manager** is suggested in e.g. [23] and [24] that is responsible for bidirectional data exchange to one or more databases. The databases can either be part of the AAS server environment or be connected externally. In the suggested approach shown in Figure 3 (b), the data are collected or even pre-processed in the component manager before being sent to the persistence manager and vice versa. For the interoperation between multiple AASs in the CPSS – one of the most important features of an I4.0 network – an **interaction manager** of each AAS, recommended in [21], is responsible for establishing a communication by following common interaction patterns. The goal is an autonomous interoperation of all assets involved in the use case, from the self-initiated requests to the final delivery, which requires a certain degree of standardization of communication. "*The interaction manager uses state machines to implement various semantic interaction protocols for calling up the necessary decision algorithms*" [22]. According to VDI/VDE 2193:2020 part 1 and 2 [25][27], these flows are not linear, but include feedback loops of negotiations, clarifications, withdrawals, or rejections. As interface and responsible for the message transport a **messenger service** is implemented into the AAS Server.

For initial tests of the Asset Administration Shell concept in the data-driven maintenance environment, some components in the simulation platform were already equipped with AAS. From the preliminary findings, it follows that the concept of the AAS provides the necessary flexibility, communication capability and intelligent response behavior required for a data-driven maintenance system. While the DIN EN IEC 63278-1, 2022 [27] focuses on the manufacturing perspective, the standard provides a quite open format to apply the concept to service providers as well. In particular, [28] states that AAS consist of assets that "*may be material or immaterial, and of various natures such as:*

- *services,*
- *physical objects,*
- *information,*
- *humans,*
- *documents,*
- *software […]."*

In addition, as described above, an AAS has mechanisms to uniquely identify all descriptive elements and to replace, delete, or add these elements during the lifecycle of the asset. Both unique identification and modifiability are essential for a successful implementation in an MRO environment for both the MRO provider and customer assets. Furthermore, a customized AAS data storage system ensures that data are preserved throughout its lifetime.

In RAMI 4.0, the AAS is also referred to as a digital twin of industry. A comparison of the AAS of PI4.0 with the digital twin concept of US-IIC led to the joint conclusion of both consortia that *"the Asset Administration Shell provides a comprehensive support to the key requirements for digital twins as described and characterized by the IIC"* [15] and that the *"suitability of the Asset Administration Shell to support digital twins is **<u>not limited to manufacturing</u>** use cases"* [15].

The reviewed characteristics of the AAS and the fact that it is standardized (DIN EN IEC 63278 [27], VDI/VDE 2193 [25][26]) allow the following conclusion: It is proposed that the CPSS of data-driven MRO service providers consisting of tangible and intangible assets, such as maintenance-receiving objects or -providing services by humans and supporting infrastructures, are equipped with AAS as data-driven representations. **The question of the compatibility of Industrie 4.0 components for data-driven service providers can thus be answered positively at the current research stage.**

2.3. Supervision of the CPSS

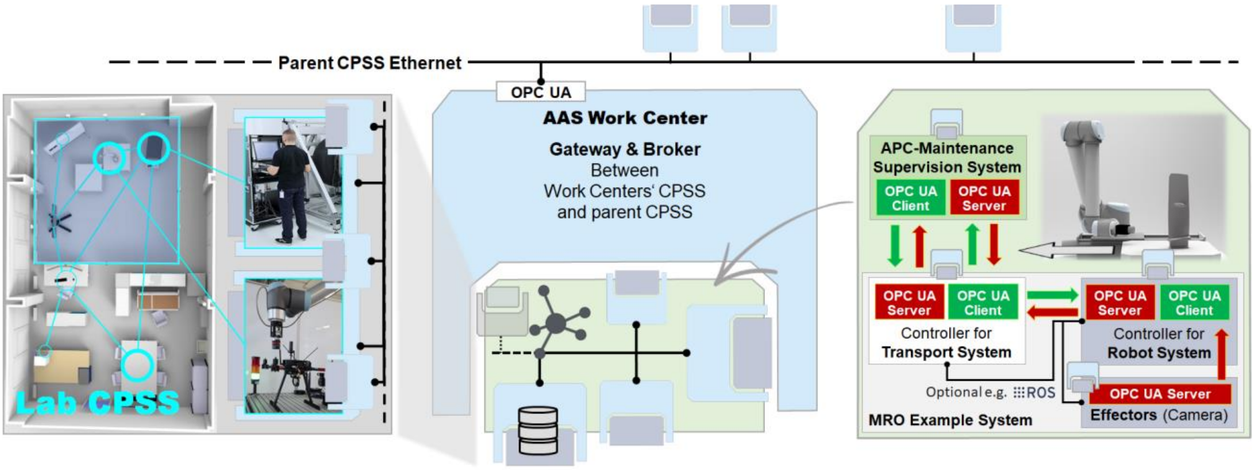
Even with a decentralized architecture of networked humans, self-managed maintenance units or other data-driven services in the MRO CPSS, controlling and to some extent coordinating services are required, like execution systems provide. They receive the orders, in the simplest case trigger the start and return the results, between the different levels of the CPSS. The enterprise's operations are thus based on a hybrid execution of self-organized systems and superior units that control and supervise the MRO process flows both in the overarching CPSS and in its sub-segments according to maintenance tasks and requirements. A module that meets these requirements is realized in the manufacturing industry as a Manufacturing Execution System (MES). According to the VDI 5600:

"*Traditionally, MES are used to plan, control, and monitor all manufacturing processes and thus support important tasks such as order management, detailed scheduling and process control of production, equipment management, materials, energy and human resources management as well as data acquisition and performance analysis*."

The question is to what extent these MES are suitable for use in the CPSS of data-driven MRO service providers as an execution system?

To approach this question, the tasks of such an execution system is first outlined if it is to be used by an MRO service provider: The upper level and the logical operational flows in the CPSS depend strongly on the process flows, how the assets are processed outside and especially inside the MRO enterprise. At this top level, it's about guiding, tracking and monitoring both assets and their data-driven counterparts as AAS along a path of task-dependent, flexible process flows and corresponding locations such as hangars, shop floors (work centers) and stations. It is about taking the shop floors or stations skills, capacities, availabilities and overall efficiencies into account, while allowing the shop floors and their stations themselves to work independently (see Figure 5: sub-CPSS connected to parent CPSS): **Each of these shop floors and stations can be its own CPSS composed of other CPSS and so on** (Figure 5 (b))**.** Although the floors and stations in the CPSS operate independently, each participant needs to know the general flowchart of the overall task in order to (e.g. automatically) initiate a push or pull of the next process step(s). The top process flow and the associated top-level sequences are provided, monitored, and partially controlled and optimized by a parent execution system. In addition, shop floors or stations can have their own and, to a certain extent, self-determined execution systems that are subordinate to the parent system. However, the basic structure and functionality is more or less identical in all of them, they differ mainly in content and scope.

However, unlike classic command-and-control structures, such as a classic MES, execution systems in CPSS cannot be a central monolithic application, but a system of distributed microservices in the CPSS. An execution system in a CPSS architecture will be more a system of networked agents – a holon of microservices. The VDI 5600-7:2021 defines that the "*MES as a monolithic software application will in future disintegrate into individual independent applications/apps and will also use and integrate external*



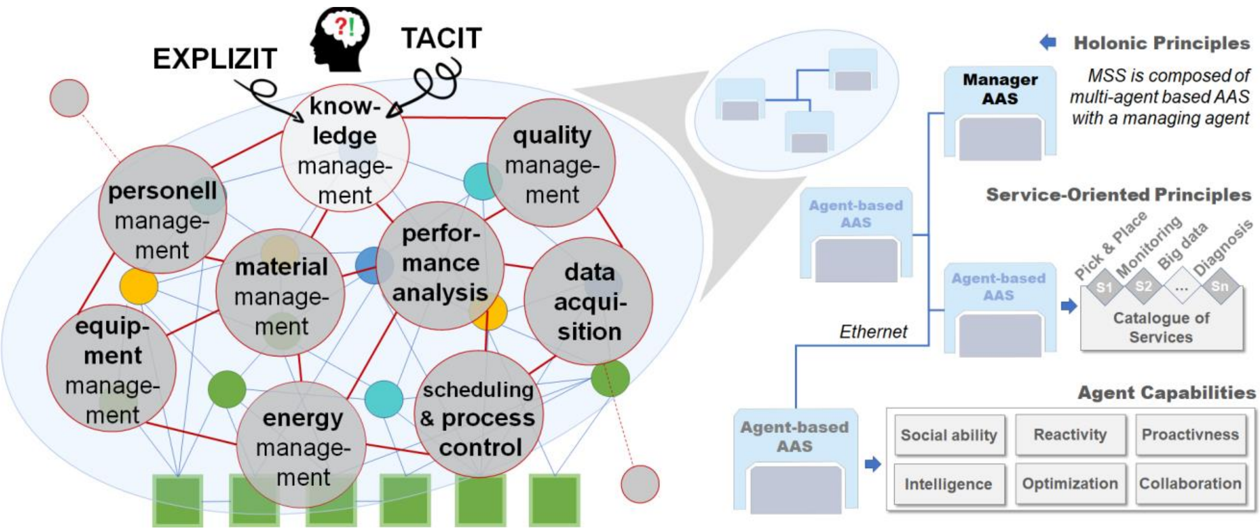
(a) (b) (c)

Figure 5 (a) Exemplary replication of a work center consisting of several stations, based on a real laboratory. (b) Connecting the work center to the enterprise CPSS with a suggested proactive AAS "Work Center Broker" which implements (c) stations and an (sub-)execution system

services. These will be interconnected and communicate with each other decentral via standardized interfaces" [30]. Basically, it is a continuation of the definition of the above architecture of interconnected, independently operating AAS in the CPSS that solve an upstream task as agents (micro-services). According to [32], the "*automation pyramid is dissolving and manufacturing IT is moving towards service-orientation and app-orientation*", which corresponds to the description of VDI 5600 quoted at the beginning. In this context, the authors of [33] note that the research literature on this topic often refers to the multi-agent system (MAS) approach as a promising solution. "*The multi-agent system (MAS) can be regarded as a set of agents that play different roles, but work (act) together in order to reach the common goal*" [34].

Although there is no standardized definition [36], agents are software programs that can be considered intelligent entities ("intelligent agents") if they behave (1.) autonomously, (2.) reactively and (3.) proactively and possess (4.) social and (5.) learning capabilities [38][39]. With other words, an intelligent agent (IA) works autonomously by initiating its own actions and adapting to its environment, interoperates with other agents and using its growing knowledge in decision-making.

The proactive AASs, described in chapter 2.2, have similar features to intelligent agents, namely the intended capabilities for autonomous decision-making, interoperability, reactivity or persistence management. In [33], [36], [37] , [41] and [42], current approaches to building agent-based Asset Administration Shells are presented with the general intent of improving the intelligence of AASs in the areas of decision making, coordination, and collaboration to prepare them for their integration as entities in a MAS. More or less similar is the idea to design the AAS component manager (compare Figure 3 (b), page 5) as an industrial agent based on the three subagents: Process Agent (PA), Resource Agent (RA), Communication Agent (CA). While [42] mainly presents "*a generic and reusable approach for the implementation of AASs for the production phase based on industrial agents*", [41] extends the framework by also considering the design of MAS patterns with an Agent Management System (AMS). Just as the VDI 5600 standard emphasizes "services" as an essential feature of future MES, the above approaches consider a service-oriented architecture (SOA). These services are offered in the CPSS and



(a) (b)

Figure 4. (a) Distributed execution and supervisory system with traditional and advanced tasks, (b) solved by supervised service agents in a CPSS with multi-services (agents) architecture; pictures based on (a): [30], (b): [37]

"*can be reached using discovery services mechanisms by other entities, e.g., other agent-based AASs or external users*" [37], which is similar to the discovery process between proactive AASs (e.g. in "Plug & Produce" systems [29]).

Besides their traditional functions, future MES will have to cover several advanced tasks provided by specialized services, whose domains are partially shown in Figure 4 (a). Related to the demands of data-driven MRO service providers, these are in particular the comprehensive management of improving, applying and conserving tacit-knowledge of both involved humans and artificial systems. Consequently, microservices which collect, manage and provide knowledge across the CPSS are mandatory. For implementation, the authors of [37] propose to build agent-based AASs as systems of microservices, like Figure 4 (b) shows, in which the different services are executed individually or collectively, depending on the task and features of the AAS, e.g., for data acquisition, analysis, control, or monitoring.

From this, initial requirements for the design of an execution system in a CPSS of a data-driven MRO service provider or MaSiMO are derived. It follows that a **Maintenance Supervision System** (MSS), as we call it, comprises the following features:

- A Maintenance Supervision Systems in a CPSS will remain responsible for **planning**, **controlling** and **monitoring** all top maintenance processes in the future.
- The future structures are expected to change **from centralized to decentralized** systems, i.e. from a monolithic software suite to a platform. Thus, maintenance supervisory will be realized by distributed but collectively working microservices (agents).
- Microservices can be realized with **agent-based Asset Administration Shells**.

In summary, the currently embedded execution system in the simulation platform's CPSS is a promising **basis for its extension to future multi-agent-based systems**, one of the most current research topics. It initializes a preliminary master instance in a kind of "Maintenance Interoperability Manager", whose idea is oriented towards the concepts of a future MES as "Manufacturing Operations Management" [31] or "Manufacturing Interoperability Manager" of the VDI 5600-7 [30]. It already takes first advantages of the distributed microservices concept. Nevertheless, many improvements and further developments are still necessary to adapt its functionalities and organization to a "MRO Supervision System" (MSS) architecture with agent-based AAS as described above.

3. CONCLUSION

Recently, several standards and guidelines have emerged that support the realization of a data-driven industry. These focus mainly on the manufacturing sector, with activities being grouped under the term Industrie 4.0. The extent to which the findings of Industrie 4.0 can be transferred to MRO service providers, as they differ from manufacturers, is discussed in this paper. Their intangible, non-storable products, their flexible processes and work content dependent on variable input conditions, or the intensive use of tacit knowledge and skills of the humans involved contrast with the production of conventional manufacturers. The latter have clearly defined, repeatable processes with fixed work contents and generate a tangible product as output from several components as input.

However, Industrie 4.0 offers solutions for the transformation of conventional to data-driven manufacturing, with a high degree of flexibility in processes and work contents and the goal of continuously adapting products to customer demands (input). It is a long-term and comprehensive socio-technical transformation, a change in the way humans, machines and systems work together in so-called cyber-physical-social systems (CPSS). Thus, all the features of CPSS fit well with the requirements of an MRO service provider, namely to be very flexible and adaptable to different inputs, considering human skills and tacit knowledge. Standards have been published, e.g., RAMI 4.0 [12] as a guide for creating the CPSS and the complementary Asset Administration Shell (AAS) for creating data-driven replications [27]. Among other things, RAMI 4.0 describes a standardized and sector-independent communication architecture as backbone of a service-oriented CPSS that, together with AAS of humans or other assets, enables seamless interoperability between them. It should be noted that the AAS can be applied to intangible products [27] and that its application is not limited to manufacturing [15], which is a requirement for its use by MRO service providers.

The applicability of the Industrie 4.0 solutions for data-driven MRO service provider is practically demonstrated using a maintenance simulation model (MaSiMO). The reason for using MaSiMO is the limited accessibility to industrial environments and the fact that it is difficult to change or modify running processes in a "brownfield" to test or implement new technologies. MaSiMO consists of a superordinate CPSS level (enterprise logistics) and a subordinate CPSS level with real workshops with stations (including further sublevels). All levels are connected vertically and horizontally via Ethernet and the main communication pattern is standardized by OPC UA, which enables the IoT of the CPSS. To complete the CPSS, simplified AASs were implemented as data-driven representations for a limited number of assets. The application of the standard showed that the AAS includes all the functions required for use in a data-driven MRO service provider: Among other things, AAS can represent humans, services, or tangible products, provide a standardized interface, proactive behaviors, persistence management, scalability, and lifecycle considerations. In summary, the use of the RAMI 4.0 communication architecture and the Industrie 4.0 component (AAS + asset) for building data-driven MRO service providers is recommended.

Finally, the question of how to design an overarching execution and supervisory system of the CPSS was answered: In the CPSS, a distributed system of multi-microservices is recommended. The microservices can be realized with agent-based Asset Administration Shells. Thus, the maintenance execution and supervisory system will be realized by distributed but collectively working agents, responsible for planning, controlling and monitoring all maintenance processes. Besides their traditional functions, the system will have to cover several advanced tasks provided by specialized services. Related to the demands of data-driven MRO service providers, these are in particular the comprehensive management of improving, applying and conserving tacit-knowledge of both involved humans and artificial systems. Consequently, microservices which gather, administer and provide knowledge across the CPSS are mandatory.

The outlook focuses on the implementation of various research and use cases in the experimental platform MaSiMO to enhance MRO I4.0 capabilities in general. Therefore, research and development efforts are needed to establish seamless interoperability between data-driven representations by developing smart applications and integrating them into the CPSS as microservices (agents). For example, lifecycle management tools or intelligent inspection and repair systems will be encapsulated step by step with asset administration shells (AAS) to make them CPSS-integrable. To monitor and orchestrate all these microservices in the CPSS, some kind of agent-based "MRO Supervision System" is required, the development of which is another long-term research activity here.

4. ABBREVIATIONS

AAS	Asset Administration Shell
CPPS	Cyber-Physical-Production System
CPS	Cyber-Physical System
CPSS	Cyber-Physical-Social System
IIC	Industrial Internet Consortium
IIoT	Industrial Internet of Things
IIRA	Industrial Internet Reference Architecture
IoT	Internet of Things
IT	Information Technology
MAS	Multi-Agent System
MES	Manufacturing Execution System
MRO	Maintenance, Repair and Overhaul
MSS	Maintenance Supervision System
OPC UA	Open Platform Communication UA
OT	Operational Technology
PI4.0	Plattform Industrie 4.0
RAMI 4.0	Reference Architectural Model Industrie 4.0
SCADA	Supervisory Control and Data Acquisition
SOA	Service-oriented architecture

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