Karlsruhe Institute of Technology & University of Stuttgart, 2024

A Gaia-X-based Ecosystem for Manufacturing

Lessons Learned from the Project Gaia-X4ICM

Abstract

Digitalization is the most important driver of innovation and a strategic goal throughout the manufacturing industry. In the context of Industry 4.0, many ideas, concepts, and visions have been developed to make production technology more efficient, flexible, precise, and sustainable through digital added value. Various research activities, such as innovative value streams, product tracing, and carbon footprinting, require an increased level of data exchange and digital service usage. Ecosystems like Gaia-X are seen as key enablers to address these challenges and foster value co-creation between participants. Although great progress has already been made, the current status of Gaia-X falls short of the potential of ecosystems due to a lack of actual implementations and related experiences.

The aim of the project Gaia-X4ICM was to establish the idea of digital ecosystems for manufacturing, to enable the coupling with production systems, and thus to create the basis for a strong scaling innovation platform for the ICM and beyond for research and industry. Research groups and institutes from the University of Stuttgart (ISW, IFSW, HLRS) and the Karlsruhe Institute of Technology (wbk, AIFB, SCC) have formed an interdisciplinary cooperation to achieve these goals. This manuscript summarizes key lessons learned and research findings of applying the principles of Gaia-X-based ecosystems to manufacturing industries.

DOI: 10.5445/IR/1000174929

This manuscript is a collaboration between the Karlsruhe Institute of Technology (KIT) and the University of Stuttgart. It summarizes the key findings of the project Gaia-X4ICM (SdManuX), which is part of the InnovationCampus Future Mobility (ICM) and funded by the Baden-Württemberg Ministry of Science, Research and Arts.

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Citation:

Erb, Y. et al. (2024). *A Gaia-X-based Ecosystem for Manufacturing: Lessons Learned from the Project Gaia-X4ICM* [White paper]. DOI: 10.5445/IR/1000174929

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List of Abbreviations

AIFB	Institute of Applied Informatics and Formal Description Methods (German: Institut für Angewandte Informatik und Formale Beschreibungsverfahren)
AISBL	French: association internationale sans but lucratif, shortened to AISBL. The Gaia-X European Association for Data and Cloud AISBL represents the core of the organizational structure. It is an international non-profit association under Belgian law.
AAS	Asset Administration Shells
CAB	Conformity Assessment Body
DPP	Digital Product Passport
DPUC	Data Product Usage Contract
DUA	Data Usage Agreement
EDC	Eclipse Dataspace Connector
EMP	Easy Metal Printer
GUI	Graphical user interface
GXDCH	Gaia-X Digital Clearing House
GXFS	Gaia-X Federation Services
HLRS	High-Performance Computing Center Stuttgart (German: Höchstleistungsrechenzentrum Stuttgart)
IaaS	Infrastructure-as-a-Service
ICM	InnovationCampus Mobility of the Future
IDSA	International Data Spaces Association
ISW	Institute for Control Engineering of Machine Tools and Manufacturing Units (German: Institut für Steuerungstechnik der Werkzeugmaschinen und Fertigungseinrichtungen)
IFSW	German: Institut für Strahlwerkzeuge
KIT	Karlsruhe Institute of Technology
LAaaS	Laser Analysis as a Service
OAW	Onboarding and Accreditation Workflow
OCT	Optical Coherence Tomography
OPC UA	Open Platform Communications Unified Architecture
OT	Operational Technology
PaaS	Platform-as-a-Service
RUL	Remaining Useful Life
SCC	Scientific Computing Center
SCS	Sovereign Cloud Stack
SD	Self-Descriptions
SDN	Software-defined networking
SELF	Self-Learning Functional Laser Micromachining
SME	Small and medium-sized enterprises
VM	Virtual Machine
WBK	Institute of Production Science (German: Institut für Produktionstechnik)
XFSC	Cross Federation Service Components

1 Introduction

1.1 Digital Transformation of the Manufacturing Industry

Florian Frick

Digitalization is the most important driver of innovation and a strategic goal throughout the manufacturing industry. In the context of Industry 4.0, many ideas, concepts, and visions have been developed to make production technology more efficient, flexible, precise, and sustainable through digital added value. Typically, data from the production environment, such as engineering, product design, or operational technology (OT), is combined with IT methods like data analysis, AI-based processes, or visualizations.

However, many of these new approaches have not yet been transferred to real industrial installations [1]. Methods that require large amounts of OT data and depend on scalable IT platforms are particularly affected. The digitalization of production also often ends at the factory level. Cross-company approaches are barely present since implementations are often complex and the cost exceeds the expected added value. This is caused by the prevailing system architectures, platforms, and communication systems, which are characterized by closed, proprietary, and incompatible solutions. Coupling OT systems with IT often requires considerable effort.

The general IT domain had to overcome similar challenges when transitioning to more connected systems. Open and uniform standards, common data models, and clear abstraction models enabled recent approaches such as edge, fog, and cloud computing.

Using the same approaches and solutions in OT has so far only been possible to a limited extent. The compatibility of architectures and methods is limited, connectivity is complex, and there is a lack of standardized data models and data security.

1.2 Ecosystems as Promising Mean to Support the Digital Transformation

Sebastian Lins

Nowadays, research and practice aim to establish ecosystems to tackle problems of closed, proprietary, and incompatible IT solutions and to drive the digital transformation of industries. It is not surprising that the term “ecosystem” has gained more and more traction in practice and research over the last two decades. Various organizations choose an ecosystem strategy over alternative arrangements to drive value co-creation, value co-production, and value capture [2], [3].

Different categories of ecosystems have emerged, of which business, innovation, platform, and data ecosystems are the most widespread [4], [5]. Business ecosystems typically resonate about identifying and managing an ecosystem around a specific organization, and hence the ecosystem is regarded as a community of interacting organizations, institutions, and individuals that impact the organization and its customers and suppliers [5], [6]. Innovation ecosystems are arrangements between organizations to combine (upstream and downstream) resources and activities to offer innovations for customers [5], [7]. Interdependent but independent organizations seek to create and commercialize innovations that benefit the customers [7]. Platform ecosystems are typically more technology-driven and emerge because platform owners integrate complementors to make the platform more valuable to customers [5], [8]. Finally, data ecosystems refer to "socio-technical complex networks in which actors interact and collaborate with each other to find, archive, publish, consume, or reuse data as well as to foster innovation, create value, and support new business" [9, p. 589]. Ecosystems can be open or closed: While open ecosystems are free for everyone to join, closed ecosystems often enforce technical or legal entry barriers [10].

These different categories have in common that ecosystems involve independent organizations and (IT) artifacts, which might even belong to different industries but engage in relationships and alignment to create individual and/or ecosystem-wide value, such as complementary innovations, products, or services [5], [11]. These relationships between organizations do not need formal, contractual agreements or hierarchical governance but require some degree of coordination, orchestration, and management, as well as agreement on standards and a set of basic requirements to enable interaction and the creation of products or services for customers. "The strength of ecosystems, and their distinctive feature, is that they provide a structure within which complementarities (of all types) in production and/or consumption can be contained and coordinated without the need for vertical integration." [5, p. 2263].

Several initiatives have formed seeking to conceptualize, develop, and implement ecosystems in practice, bringing organizations, institutions, and individual actors together. Value creation is, however, not the only objective of these ecosystems. In recent years, ecosystems have emerged with the primary goal to promote digital sovereignty. In general, the concept of digital sovereignty describes forms of independence, control, and autonomy over digital infrastructures, technologies, data, and digital content [10], [12]. Since the term digital sovereignty is similar confusing and complex like ecosystems, various forms and antecedents of digital sovereignty have been discussed, such as technological, data, or cyber sovereignty [13].

One of the most important and well-known initiative to foster digital sovereignty through ecosystems is Gaia-X. Launched in 2019, Gaia-X was introduced as a "federated, open data infrastructure based on European values" [14]. Its core objective was to increase industrial competitiveness and to reduce European dependence on non-European companies by creating an "open, federated, secure and trustworthy data and cloud infrastructure for Europe as the basis for a digital ecosystem" [15]. To foster its establishment, the international, non-profit "Gaia-X foundation AISBL" was founded in Belgium in 2020, and regional hubs emerged across the world, building a network of many organizations, institutions, and individuals, that are further backed by a community of volunteering contributors.

Consolidating and reflecting the promises and statements of Gaia-X over the last years (e.g., [14], [16]), we summarize that Gaia-X seeks to support the emergence of trustworthy ecosystems, controlled not by one but shared by many to fulfill European values and principles. Trustworthiness relates to an open, transparent, and secure digital ecosystem where data and services can be made available, compiled, and shared in an environment of trustworthy actors and

IT artifacts. The basic architecture of Gaia-X is based on the principle of decentralization through federations to counteract the prevalent centralization of digital service offerings. Federations based on Gaia-X result from many individual data owners and technology providers that agree to share data and services. These actors adopt a standardized set of rules and control mechanisms to foster European values of openness, transparency, security, data protection, sovereignty, and interoperability, as well as to create trust among all ecosystem participants.

These promises of Gaia-X have led to tremendous investments from EU governments and organizations alike, spanning various industries and the public sector, including aerospace, agriculture, tourism, education, energy, finance, geoinformation, health, manufacturing, media, mobility, smart cities, smart living, construction and logistics [17]. So-called 'Lighthouse Projects' are the front-runners implementing the Gaia-X framework, aiming to create data exchange platforms and service ecosystems built on transparency, trust, and openness [18].

1.3 The Project Gaia-X4ICM

Florian Frick

Significant progress has already been made in the context of Gaia-X: A basic architecture is available and the first services are taking shape. Nevertheless, science and industry have hardly benefited from this when the project started. Moreover, research and further development of the architectures and components developed to date are challenging, as there is a lack of real implementation and experience on top of the barriers to start being very high. The potential of ecosystems and the current status of Gaia-X are therefore highly disproportionate.

Digital solutions play a central role in the InnovationCampus Mobility of the Future (ICM). Various research activities, such as innovative value streams, product tracing, and carbon footprinting, require an increased level of data and service exchange. Ecosystems like Gaia-X are seen as key enablers for related challenges. Therefore, the aim of the project Gaia-X4ICM is to establish the idea of digital ecosystems for manufacturing, to enable the coupling with production systems, and thus to create the basis for a strong scalable innovation platform for the ICM and beyond for research and industry.

Research groups and institutes from the University of Stuttgart (ISW, IFSW, HLRS) and the Karlsruhe Institute of Technology (wbk, AIFB, SCC) have formed an interdisciplinary cooperation with complementary skills to achieve these goals.

The project is divided into three sub-projects: setting up the basic infrastructure, conceptualizing the ecosystem, and implementing applications for manufacturing. The basic infrastructure includes hardware resources and the necessary software stacks. Another integral component is converged communication technology, which plays a decisive role in connecting IT to OT. In addition to basic services and data spaces, the focus is on suitable processes, including a secure and systematic onboarding of new services and participants. Building on this, various exemplary software services for manufacturing are implemented at the application level, which combine innovative, digital approaches with real production scenarios. The implementation takes place at several locations and includes the integration of the infrastructure in data centers, as well as the coupling with real production systems in research and learning factories.

2 The Vision of Future Factories and Converged Infrastructure

Florian Frick

The digital transformation of manufacturing is an ongoing process. Production technology is increasingly being digitalized, often using or adapting technologies from IT. IT-OT convergence pushes the idea to the next level with the goals of seamless integration and interoperability. A cross-vendor ecosystem must fit this changing and future converged architecture while significantly being enabled by it. Even though there is not a single and clear vision of the factory of the future, many trends and technologies are accepted across the industry.

2.1 Digitalization of Production Technology

Solutions from IT have been adopted for the digitalization of production for years, from PCs to Ethernet. Typically, these are adapted to the established OT solutions and integrated into the processes. As a result, although proven technologies from the IT sector are increasingly being used, production systems are still mostly closed, customized, and monolithic. Ecosystems from a single manufacturer are typical, from cables and control software to the cloud.

The increasing complexity of the IT-OT convergence not only presents companies with major challenges but slows down innovations. To raise innovation to the IT level and its dynamics, other aspects must be adopted in addition to the technologies: Clear layers and levels of abstraction, a separation of hardware and software, open standards and a common infrastructure.

A key trend in digitalization is the modularization of hardware and software components. This is a prerequisite for the scalability, maintainability, and flexibility of many services. The use of innovative platforms, from CPU-based systems to reconfigurable hardware, offers the opportunity to implement complex control algorithms while complying with real-time requirements.

Cloud technologies are attracting increasing interest in the context of digitalization, both as a data and control platform [19]. This opens up new possibilities in terms of scalability and computing power. In addition to value-added services, such as the use of artificial intelligence for process optimization [20], complete machine control systems can also be outsourced to the cloud [21]. Other research topics in this area also deal with the possibility of ensuring operational reliability from the cloud. Novel edge and fog services are also entering the markets, providing computational capabilities in close vicinity to the production [22], [23], [24].

2.2 Connectivity and Communication Technology

The exchange of information and data is the basis for the digital transformation and, therefore, also for the successful integration with larger digital ecosystems. This applies between services but in particular to the data sources and sinks. In production environments, sources and sinks are state-of-the-art devices and software functions, as well as new ones that are being added as part of digitalization. Examples include production planning systems, industrial control systems, and sensors at the field level, directly interfacing the physical process.

In the IT environment, connectivity is largely guaranteed by standardized communication architectures. The familiar protocols along the Open Systems Interconnection layers, such as Ethernet and TCP/IP, dominate. The communication infrastructure is implemented using interoperable devices from different manufacturers, such as switches, routers, network cards, and firewalls. An important trend in the environment of larger installations is the increasing use of software-defined networking (SDN).

In contrast, in the production environment, communication technology is characterized by a large number of incompatible, sometimes proprietary technologies, referred to as fieldbuses [25]. These are typically used to create isolated networks between a controller and field components. A key feature of fieldbuses is their real-time capability.

With emerging technologies like Time-Sensitive Networking [26], DetNet [27], or deterministic 5G, multiple key enablers are potentially overcoming the previous dilemma between standard solution or determinism [28]. These technologies enable converged real-time networks, which are considered the communication infrastructure for the factory of the future.

2.3 Virtualized Platforms

A trend towards the separation of hardware and functions in the IT environment is virtualization using containers or virtual machines [29]. Obstacles to the use of these methods for OT applications are the lack of determinism, the integration of real-time communication, and suitable engineering processes.

Current trends like Time-Coordinated Computing, hardened runtimes, and advanced management mechanisms increasingly allow to use these technologies for industrial applications. Local platforms to consolidate multiple real-time workloads are seen as key enablers for virtualized control systems, for instance, Virtualized Programmable Logic Controllers.

Beyond local systems, cloud integration is another key topic [30]. Traditional cloud infrastructures rely on virtual machines, although the focus is increasingly shifting to container technologies. Utilizing these technologies for services or applications which are directly connected to industrial applications is, to date, highly proprietary and state of research. A key challenge is data sovereignty, which is the ability of an institution, organization, or individual to restrict the location of a set of data and enforce these restrictions [31]. Data sovereignty has two main components. First, effective systems for data storage must be created that allow users to express their intents. Second is the verification/auditing of the data itself. The first task is largely solved by commercial providers. The second area is an active area of research, with proposals ranging from encryption to Internet geolocation.

2.4 Future Factory as Part of a Digital Ecosystem

Future factories will be based on a novel communication and compute infrastructure. While the challenges within a factory are mainly related to determinism, solutions for data exchange are required when multiple companies are involved. These must be solved by an appropriate digital ecosystem, which will benefit from the local infrastructure but also must be aligned with it.

3 Key Elements of the Gaia-X4ICM Ecosystem

Yannick Erb, Heiner Teigeler, Sebastian Lins, Ali Sunyaev

3.1 General Ecosystem Design and Principles

Gaia-X seeks to enable trusted, decentralized digital ecosystems by proposing architectures and mechanisms to deploy federated and secure data infrastructure and service ecosystems [16]. In its essence, Gaia-X, therefore, comprises two (interdependent) elements: (1) data ecosystems to foster data sovereignty and ensure data exchange and (2) service infrastructure ecosystems enabling the creation of value and innovations through harnessing cutting-edge technologies and platforms and their underlying infrastructures. These two elements are frequently illustrated by an X, as shown in Figure 1.

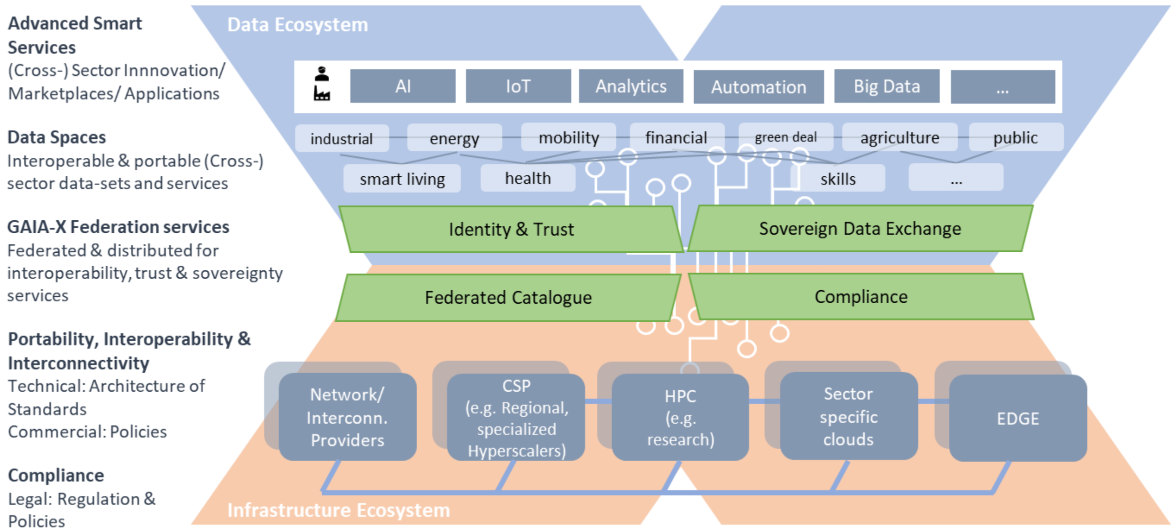

Figure 1. Illustration of Gaia-X Ecosystems, adapted from on [32]

Data ecosystems comprise all data spaces, data assets, and related software services. “At the core of data ecosystems are the capabilities of each party to contribute to data sharing by either receiving it (data users), sending it (data provider), or facilitating the process (data intermediary)” [4, p. 4]. In Gaia-X4ICM, we developed four important applications that span up data spaces and provide corresponding software services (Section 4.1-4.4). In contrast, the infrastructure ecosystem comprises all computing nodes, hardware, and networks to operate data services. In our ecosystem, cloud infrastructures are offered to operate the use case applications (Section 4.5). Both ecosystems cannot be viewed separately as they build upon each other, i.e., they are complementary.

According to Gaia-X, data spaces and infrastructure services are grouped together to build federations. Generally, a federation is a group of participants who work together [33]. Following the principles of decentralization, a federation is not owned by a single organization, but participants cooperate as equals and determine, for instance, common rules collectively. Gaia-X federations are orchestrated according to different sectors and can consist of participants from the same or different industries.

To ease the understanding of this whitepaper, we align with the Gaia-X conceptual model that describes important terms, corresponding concepts, and their relationships [34]. Most importantly, the Gaia-X conceptual model describes three participants and their generic roles that can join data space and service ecosystems [34]. Participants are entities that are onboarded to the ecosystem (and have a Gaia-X participant credential). They can have several roles: service provider, service consumer (also named users), or federators (also named operators). Service providers and service consumers are key in business-to-business relationships, while federators enable them to interact with each other. Service providers own resources and offer them as services to other ecosystem participants by defining the service offering and providing service instances. Resources can be cloud, fog, and edge services, and data products, among others. Service consumers can search for service offerings and consume service instances.

Finally, Gaia-X foresees federators that host so-called Gaia-X Federation Services (GXFS) [34] (e.g., the Gaia-X digital clearing house services [35]). These services link data spaces and infrastructure services by representing the minimum technical requirements and services needed to operate federated Gaia-X ecosystems. Hence, GXFS support participants to operate and orchestrate federations individually. GXFS leverage existing standards and open technologies, particularly freely accessible and open-source software. To support the development of the Gaia-X-based ecosystems, the so-called "Cross Federation Service Components (XFSC) toolbox" was developed as part of a GXFS project funded by the German government (refer to [36]). Gaia-X proposes five key GXFS to operate each federation: (1) Identity and trust based on a Self-Sovereign Identity, (2) a federated catalog as a repository of offerings, (3) data sovereignty services to have full self-determination of data exchange, (4) compliance services handling ecosystem onboarding and accreditation workflows, and (5) a portal providing user-friendly access to all services. These GXFS will be summarized in the following sections because they form the foundation for the Gaia-X4ICM ecosystem.

3.2 Identity & Trust Management

In the Gaia-X4ICM ecosystem, identity and trust management increases sovereignty and trust among the participants.[1] We propose that the federation services "Authentication & Authorization Service," "Organization Credential Manager," "Personal Credential Manager," and "Trust Services" are important GXFS to enable and support efficient identity and trust management in the ecosystem [33].

A core concept used to set up Gaia-X-based ecosystems is using credentials, previously referred to as Self-Descriptions (SD) [34]. Gaia-X credentials are cryptographically signed attestations describing ecosystem entities in a machine-interpretable format. The Gaia-X credentials are central to the GXFS because they form the building blocks of a decentralized machine-

[1] Note that identity and trust management was not the focus but was nevertheless considered in the conceptual design based on the existing Gaia-X solutions.

readable knowledge graph of claims since each credential carries a tamper-proof and authenticable part of the information about an entity. By using credentials, participants in an ecosystem can rely on verifiable information and build trust in participants' claims and offerings.

SD, in the form of credentials, serve as user profiles for participants in a federation, providing detailed information about themselves and the services or data assets they offer [37]. Such profiles help all participants understand who they interact with within the federation. Additionally, they specify which provider offers each service or data asset, along with the associated assurances. Federation participants validate SD according to self-determined rules. They may rely on automated processes and software components using cryptography to verify the credibility of participants' statements and claims automatically. All participants in a federation can exchange and validate credentials and other information directly with each other. The advantage of this is that (self-sovereign) identities do not have to be managed or checked centrally. Participants can check each other's verifiable credentials to ensure their identity. This allows participants also to maintain control over which data and details are shared with others during the verification process. This identity and trust management approach is called a decentralized and self-sovereign trust system in Gaia-X ecosystems [38].

3.3 Compliance Management: Onboarding & Accreditation of Participants & Services

The onboarding and accreditation workflow's (OAW) objective is to foster secure and reliable participation in the Gaia-X ecosystem and achieve transparency for consumers and providers [39]. Each federation should designate an (external) onboarding authority and conformity assessment bodies (CABs) that perform and are responsible for accreditation workflows.

Before a provider can join the ecosystem and offer its services, it has to undergo an OAW to prove that it is authentic, trustworthy, and reliable. The provider onboarding workflow manages the gathering of information relevant to the accreditation, such as information stored in SD and corresponding credentials, signed terms and conditions, and further relevant assurance information. Figure 2 summarizes the workflow. The consumer onboarding workflow is similar to the provider workflow, except that the workflow ends after the identity has been verified (i.e., marked in blue at the end of the process in Figure 2).

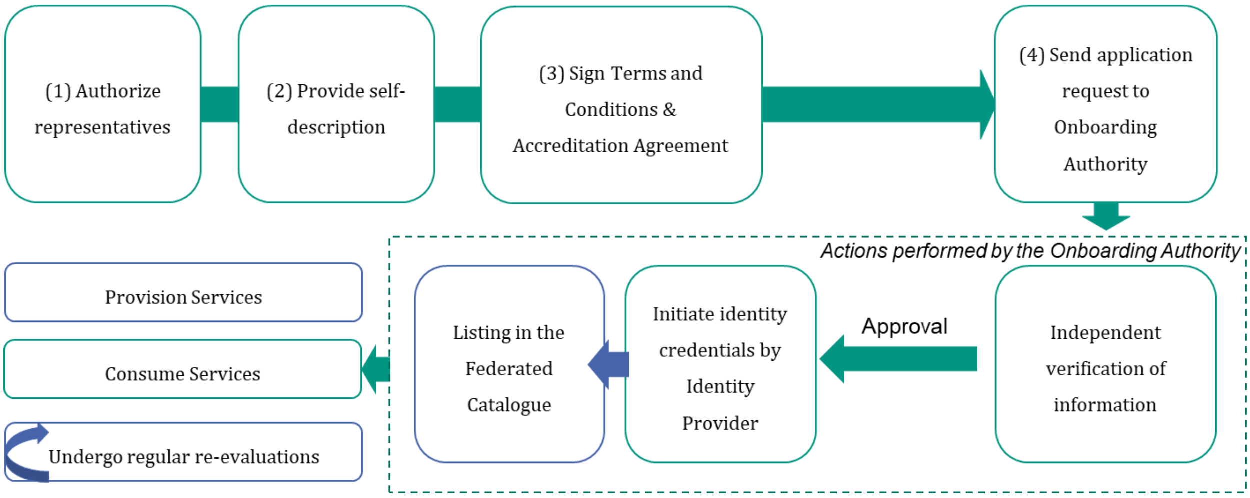

Figure 2. Provider and consumer OAW

Providers can offer a service in the ecosystem. Services refer to a composition of resources. The service OAW manages the gathering of information relevant to the service accreditation, such as the SD, signed declaration of adherence, and further relevant assurance information. Figure 3 summarizes the OAW of services.

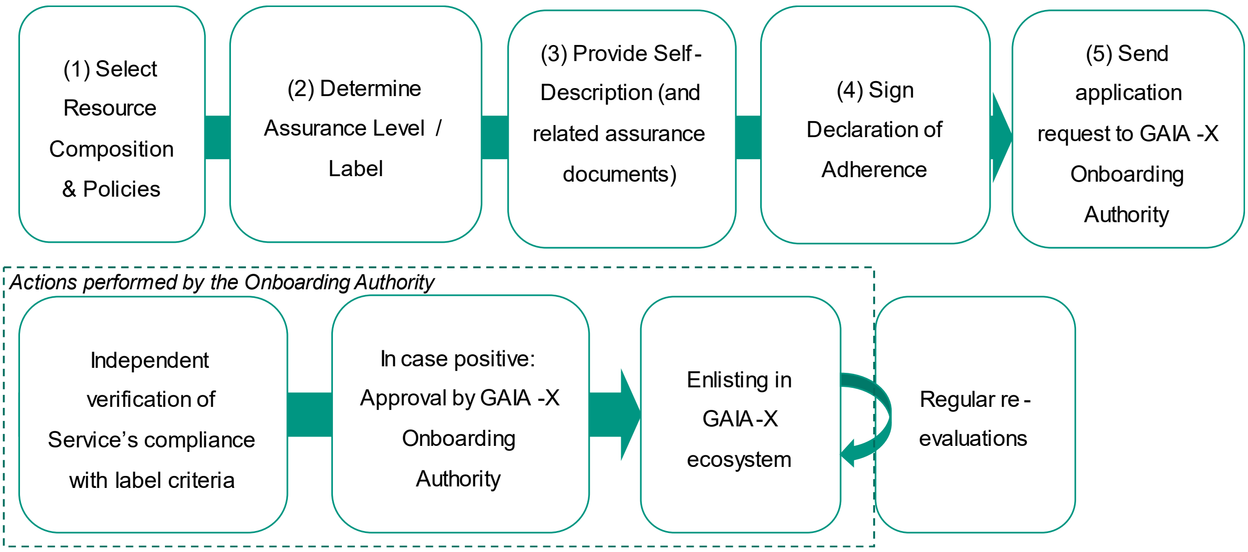

Figure 3. Service OAW

The onboarding process and especially the initial credential issuance can be supported by the Gaia-X Digital Clearing House (GXDCH), which can be incorporated into the Gaia-X4ICM ecosystem's onboarding process via the GXDCH wizard [40]. The GXDCH is an essential element and federation service of Gaia-X [40]. It is a network of distributed and decentralized execution nodes offering services to obtain Gaia-X compliance. The nodes are operated by several AISBL-approved market federators (i.e., Gaia-X Lab, Aruba, T-Systems, Aire Networks, *as of October 2024*) that act as operators of federation services. The services offered comprise the mandatory (i.e., Gaia-X registry, Gaia-X compliance, Gaia-X notarization service for the registration number) and optional (i.e., wizard, wallet, catalog) software components of the Gaia-X Framework.

Thus, the GXDCH provides Gaia-X clearance as a minimum by verifying the Gaia-X rules, obtaining Gaia-X compliance, and becoming a part of the Gaia-X ecosystem.

3.4 Federated Catalog & Portal

The federated catalog is a repository of SD that facilitates searching and selecting participants, providers, and their service offerings within a federation [34]. The catalog is designed to help participants—whether they are consumers, providers, or federators—find the best matching service offerings and stay informed about relevant changes [34]. SD are utilized to search for and select service offerings within a catalog. They also facilitate tool-assisted evaluation, selection, integration, and orchestration of services. Additionally, they support the enforcement of common rules, continuous validation, monitoring of usage policies, and negotiation of contractual terms between providers and users of these service offerings.

The Gaia-X portal acts as the client interface for Gaia-X federations, and each federation can develop and maintain its own unique portal [34]. In the case of the Gaia-X4ICM ecosystem, the portal displays all use cases as a usable service. The portal provides detailed information on each service and is the main point of access for all participants in the ecosystem. The portal offers a business web client that facilitates data sharing and helps users find the right infrastructure, aligning with Gaia-X's goal of creating a sovereign data ecosystem. The integrated federation services needed to interact with one or multiple Gaia-X federations enable Gaia-X members to browse the catalog for infrastructure services, access information about data offerings, and utilize editing and orchestration functionalities.

3.5 Self-Sovereign Data Exchange

Within the Gaia-X4ICM ecosystem, data is exchanged either as part of a service offering (e.g., an upload of image or feature data for wear and tear analysis of tools, Section 4.2) or data exchange itself is the service offering (i.e., data exchange along the value chain for digital product passport, Section 4.1). To uphold the ecosystem principles and values, data exchange within the ecosystem must be self-sovereign and adhere to European regulations in each case. To implement data exchange services, such as the digital product passport, Gaia-X provides the concepts of a data product, data usage agreement (DUA), data product usage contract (DPUC), and data intermediaries, which will be summarized in the following [34]. Figure 4 shows the conceptual model for data products proposed by the Gaia-X AISBL [34].

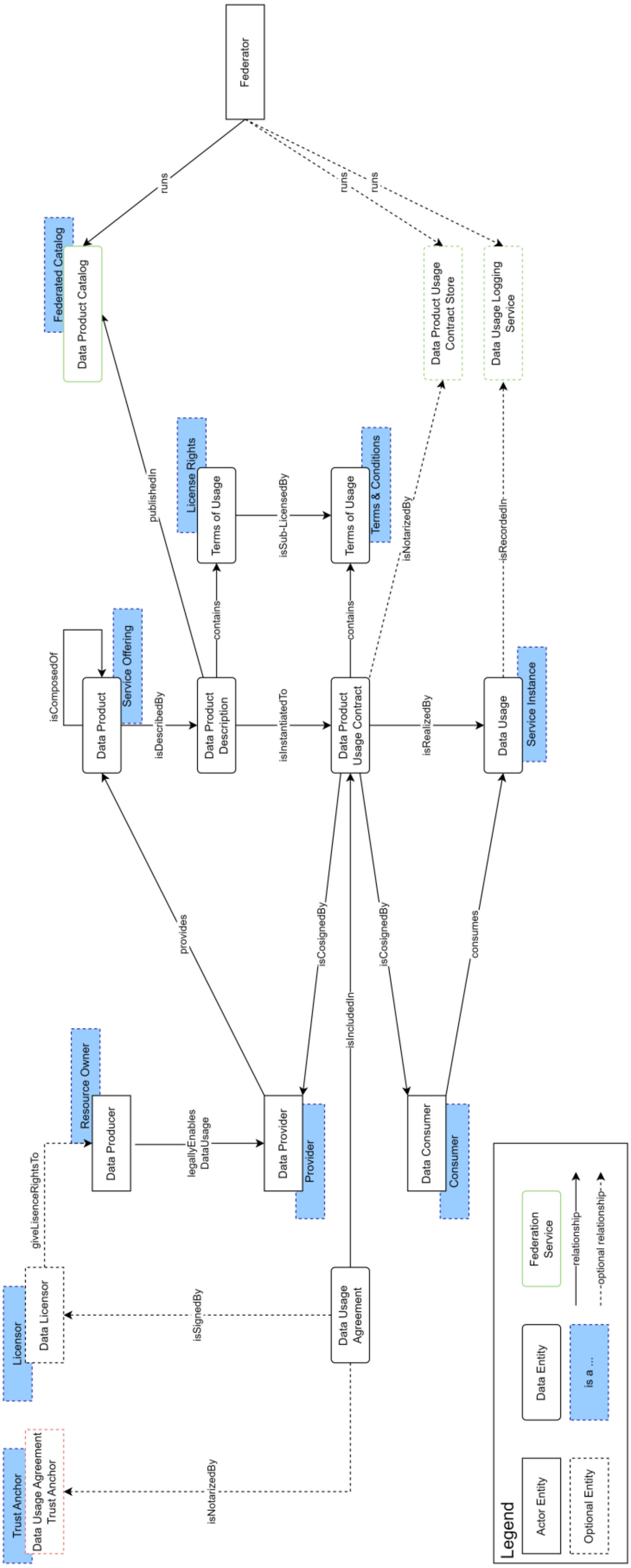

Figure 4. Data product conceptual model, adapted from the Gaia-X AISBL [34]

Data product providers offer data as a service, namely the data products, to data consumers [34]. Data products have a valid Gaia-X credential in the form of a data product description stored in a data product catalog, which represents a federation service and is run by a federator. The data product catalog can, but must not necessarily, be searchable for data consumers. Before the data consumer can consume a data product, a DPUC, including enforceable terms of usage and the sublicensed data license granted, must be negotiated between the data consumer and the data product provider. The DPUC is a so-called Ricardian contract[2] and can be notarized in a federated DPUC store.

Before data can be included in data products, data producers, being the resource owners or data holders, must legally enable the data product provider to provide the data as part of a data product [34]. Sometimes, the data may only be licensed to the data producer by a data licensor (e.g., data subject as per GDPR, data owner as per copyright, etc.). Then, the data licensor needs to sign a DUA, which includes the terms and conditions associated with the data. This DUA must adhere to regulations for the type of licensed data (e.g., GDPR for personal data) and allows the data producer to distribute the data (to the data provider), as well as the data consumer to use the data under specified constraints. The DUA is, therefore, included in the DPUC. To increase trust, a DUA is notarized by a DUA Trust Anchor, a party mutually trusted to oversee and manage DUAs within the ecosystem. A data licensor may revoke a DUA at any time.

Several roles can be combined to enable data exchange as a service in the form of data intermediaries that shall support participants in establishing a commercial relation on the basis of data products. The Gaia-X AISBL [34] proposes that data providers, the federator running the data catalog, and the DUA Trust Anchor can act as an intermediary. However, as data intermediaries are a higher-level concept, the concrete concept definition will differ for the project's use cases.

We draw upon these concepts for data exchange services and, more generally, data exchange within ecosystems. The use case 'Digital Product Passport' describes data exchange as a service offering having a data intermediary facilitating the data exchange between the parties of a value chain. Tailoring the higher-level concept of a data intermediary to the needs of our ecosystem, we propose to combine the roles of the data provider, as a proxy between data producers and data consumers, and the federator running a data catalog. However, we do not want to integrate the role of the DUA Trust Anchor. This is due to the high likelihood of having an important and strong participant in the value chain running the digital product passport on behalf of the whole value chain. In this case, we do not want to grant this party the power to control the DUAs negotiated, as this is not necessary for the service offering and would result in this party dominating the value chain data. A trusted other party operating as a DUA trust anchor helps ensure that data licensors remain self-sovereign.

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[2] "Ricardian contract: a contract at law that is both human-readable and machine-readable, cryptographically signed and rendered tamper-proof, verifiable in a decentralized fashion, and electronically linked to the subject of the contract, i.e., the data" [34, p. 21].

The remaining manufacturing use cases depict service offerings that have other purposes than exchanging data. However, for the service providers to fulfill their service offering, data must be exchanged between the service consumer and the service provider and vice versa. To comply with the principle of self-sovereignty, postulated by Gaia-X, we deem it important that the concepts of a DUA and DPUC are transferred to any data exchange between two parties within the Gaia-X4ICM ecosystem. This means that no data is allowed to be exchanged as part of a service offering if there are license rights attached to that data and no consent (in the sense of a DUA) is obtained from the data licensor. The DUA can either be obtained on behalf of the service consumer or the service provider. Furthermore, the service consumer and the service provider must mutually agree upon any data exchange. Drawing on the concept of a DPUC, it must be clear to any of these parties what data is exchanged for what purposes and under which terms of usage. Moreover, the data exchange must adhere to the license rights granted in the consent by the data licensor, if there are any.

Further details on the data exchange (services) within the Gaia-X4ICM ecosystem are described as part of the use case descriptions in Section 4.

Research and practice propose various technologies to support sovereign data exchanges. In Gaia-X4ICM, we propose to rely on the Eclipse Dataspace Connector (EDC) Connector and the Open Platform Communications Unified Architecture (OPC UA).

Eclipse Dataspace Connector. The Eclipse Data Space Connector (EDC) is governed by the Eclipse Foundation and aligns with the specifications of the Gaia-X AISBL Trust Framework and the International Data Spaces Association (IDSA) Dataspace protocol. The EDC aims to enable decentralized, secure, and sovereign data exchange between organizations. The EDC architecture distinguishes between metadata and the actual data transfer, which is enabled by channel extensions for flexible and scalable protocols such as HTTPS, S3, and REST. The EDC is divided into a control layer, which handles contract management and API interactions, and a data layer, which handles data transfer. All transfers are contractually bound and automatically managed, preserving data sovereignty. The EDC uses standards, such as Gaia-X and International Data Spaces, and can be extended to other protocols and ecosystems. Future developments include self-sovereign identity and new channel extensions for streaming protocols. An important aspect is the integration of the Industry 4.0 Asset Administration Shells (AAS), which provides a standardized API for the transparent use of data from backend systems, enabling the EDC to be optimized for Industry 4.0 applications [41].

OPC Unified Architecture. OPC UA is a standard for platform-independent data exchange based on a service-oriented architecture. In addition to the ability to transport data, it has an integrated semantic description of the data. OPC UA has been established as best practice for data exchange in the industrial context. A wide range of open data models, so-called companion specifications, create an interoperable ecosystem. These data models can be extended for specific applications by companies' specifications and are uniformly mapped in the OPC UA data space. On top of the classic communication based on the client-server principle, new parts of the OPC UA specification introduce the transmission via publish-subscribe mechanisms.

4 Manufacturing-Related Services within the Gaia-X4ICM Ecosystem

The Gaia-X4ICM ecosystem comprises four manufacturing-related services and the underlying infrastructure that together build the Gaia-X4ICM ecosystem (Figure 5):

1) **Digital Product Passport** (Section 4.1): provides essential product information, such as legal documents and carbon footprint, and includes details from all phases of the product lifecycle, such as design, materials, and transportation.
2) **Wear & Tear-Aware Components as a Service** (Section 4.2): monitors and analyzes machine components to predict their remaining useful life.
3) **Tool Wear & Tear Recognition as a Service** (Section 4.3): offers on-machine tool condition monitoring and provides in-line tool condition assessment to maximize tool life and optimize machining parameters.
4) **Laser Analysis as a Service** (Section 4.4): optimizes laser-based manufacturing processes using real-time data and machine learning.
5) **Cloud Infrastructure Services** (Section 4.5): provides the required cloud infrastructure for the Gaia-X4ICM ecosystem through an OpenStack-based platform to ensure secure, federated data management.

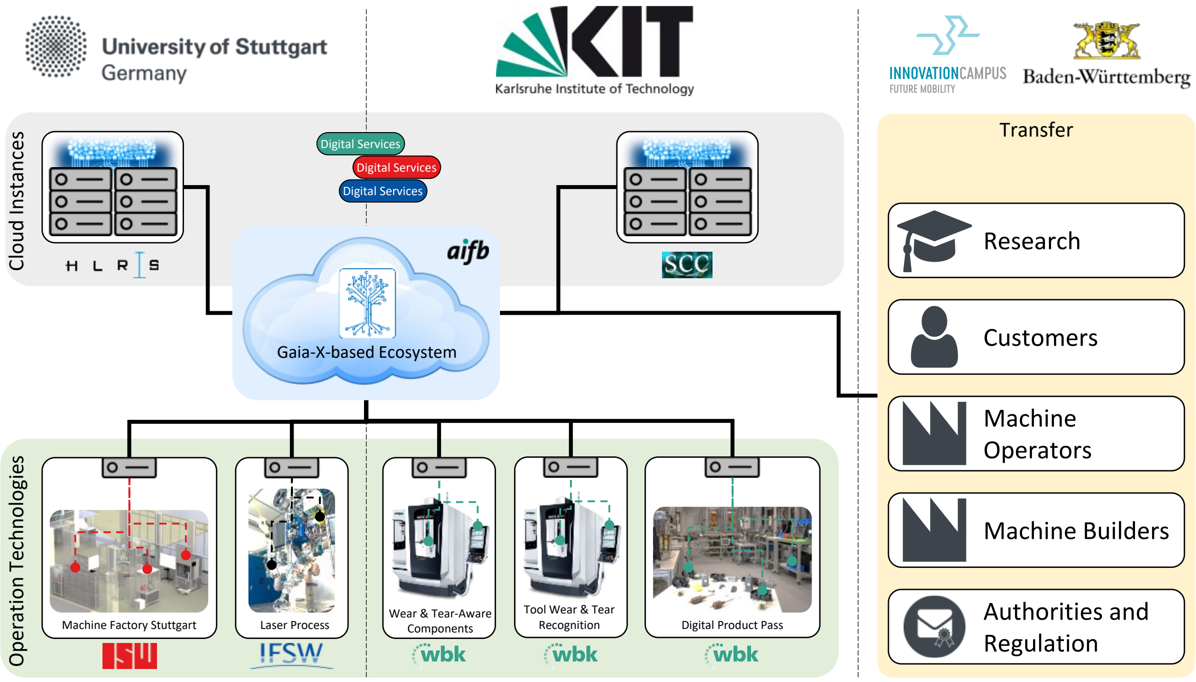

Figure 5. Illustration of the Gaia-X4ICM ecosystem

4.1 Digital Product Passport: Self-Sovereign Data Exchange Along Value Chains as a Service

Kevin Gleich, Sebastian Behrendt, Gisela Lanza

4.1.1 The Digital Product Passport in the Gaia-X4ICM Ecosystem

The Digital Product Passport (DPP) provides general product information, such as legally required documents or the product's carbon footprint. This information can be made publicly available through the Gaia-X4ICM ecosystem. For dedicated and certified roles, specialized information such as repair or disassembly instructions or the contained materials are available after onboarding into the Gaia-X ecosystem. The DPP is based on AAS with high interoperability and connectivity to different communication protocols and domains. This also promotes data sovereignty and compliance by enabling decentralized data exchange via Gaia-X.

As described in [42], the data exchange for the generation of the DPP is organized in a decentralized way, where the information for the DPP is stored in the respective companies (Figure 6). When a DPP is requested, the data is exchanged between the companies and the DPP service in the ecosystem via the EDC and REST. The EDC ensures that only the necessary information is transferred, payments are executed, and the identity of the participants is verified.

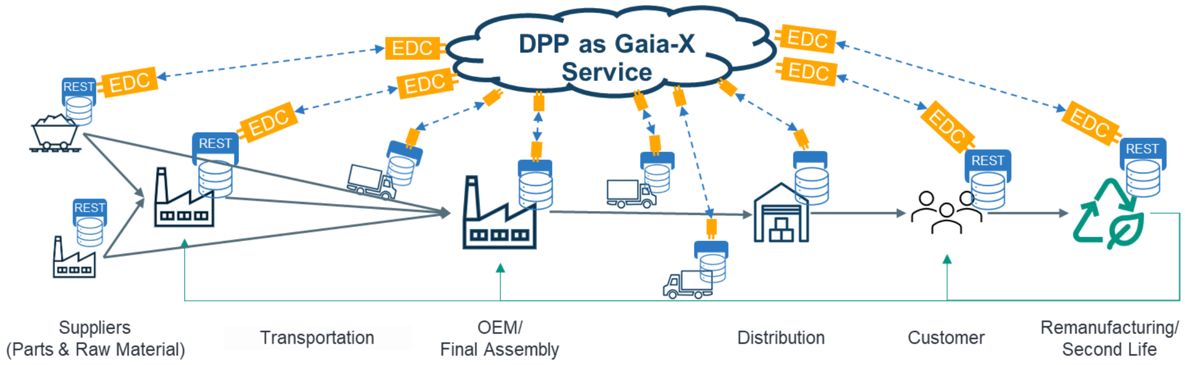

Figure 6. Data exchange along value chain from local AAS-servers to Gaia-X and the DPP and vice versa via EDC and REST [42]

This decentralized data exchange, controlled by EDC and Gaia-X, ensures higher data security and sovereignty, resulting in higher acceptance of the DPP service. This is necessary because the DPP contains critical product information. The DPP itself contains information from all phases of the product lifecycle, including:

1. Design data,
2. Material data,
3. Production process data,
4. Transportation data,
5. Life cycle and usage data,
6. General product data, and
7. Carbon Footprint.

4.1.2 Integration into the Ecosystem: Roles and Business Models

Since the data for the DPP comes from all participants along the value chain and is integrated into the ecosystem, several clearly defined roles are needed to provide the service. The roles describe the data handling and access rights of the participants in the context of the DPP. A distinction is made between service providers and users who host the DPP service or just use the DPP and the data it contains. Furthermore, the role of the data provider is also considered since it is possible to only provide data for the DPP, e.g., as an external company, without using the underlying service. Because most DPPs are required by some regulations, e.g. the battery legislation in the EU, and driven by the manufacturer of the end products, a specific business model for the DPP service is not necessary for most participants. Even for the manufacturer, there is usually no need for a data-driven business model behind the DPP, and the only case where a business model is required is when an external company hosts the DPP. Therefore, for the service provider role, a separate participant, the external service provider, is considered, and only for this role business models are discussed. This results in eight possible roles for the DPP service within the ecosystem:

1. **Manufacturer of the final product:** Produces the products and sells them to customers
    - **Service Provider:** The manufacturer can act as a service provider. In this case, the manufacturer hosts the DPP and organizes the necessary infrastructure. Whether the manufacturer provides the DPP service itself or not, it is responsible for integrating the value chain partners. The manufacturer must ensure and coordinate that each value chain partner provides the necessary data for the DPP.
    - **Service User:** In addition to providing the DPP service or at least ensuring data availability among the partners, the manufacturer also acts as a service user. Thus, the DPP contains various data, such as the origin of parts and materials or certificates, which can be used in production or final assembly. More advanced use cases for the DPP data of materials and components, such as the pairing of out-of-tolerance parts, are also possible (e.g., [43]) but are not considered here.
    - **Data Provider:** Since the manufacturer produces the final product, consisting of the final assembly and the possible in-house production of individual parts and components, it also generates data for the DPP. This data consists of the final bill of materials, the place and time of production, the carbon footprint, and additional information and documentation such as manuals. Therefore, the manufacturer also acts as a data provider for the DPP.
2. **External service provider:** If the manufacturer is unable or unwilling to host the DPP service itself, an external party can be hired to host the service.
    - **Service Provider:** The external service provider organizes the infrastructure and is responsible for the availability and delivery of the DPP service. It provides the functionalities and interfaces of the DPP in a generic and adaptable way. It is also responsible for the technical integration of the value chain partners. However, the legal integration of the partners and the responsibility for data

availability remain with the manufacturer of the product for which the DPP service is used.
   - **Business Model:** Since the external service provider offers the DPP service to one or more companies, it has its own specific business model. Different options and combinations are possible, such as a fixed monthly price or a usage fee for each DPP accessed or generated. However, the specific business model has to be adapted to the specific use case, e.g. small and medium-sized enterprises (SMEs) or large international enterprises, and also depends on additional functionalities and requirements of the use case for the DPP service.
3. **Material and Component Suppliers:** They provide the final manufacturer with raw materials or (semi) finished assemblies, components, or parts. The roles of the Gaia-X ecosystem do not distinguish between the different types of delivered goods.
   - **Service User:** In the case of the production of single parts, components, or subassemblies, the supplier acts as a manufacturer. For the corresponding stage in the value chain, he has the same role as the final manufacturer and can act as a service user. Suppliers can be part of the Gaia-X ecosystem. In this case, they can use the service. If they are not part of the ecosystem, they cannot use the service or they can only access publicly available information and act only as data providers.
   - **Data Provider:** In terms of the end product, the main role of data providers is to provide data for the DPP. The data includes information on the materials used, the origin, the certification of the processes, and the carbon footprint. The data is integrated into the DPP for the corresponding material or component and is processed in the DPP for the end product.
4. **Transportation and Distribution Companies:** They transport or distribute the products, materials, and components between the companies in the value chain and to the customer.
   - **Service User:** In general, transportation and distribution companies do not use the DPP. However, some products may have special transport requirements or transport documentation, such as cold chains. In such a case, the transportation and distribution companies may need to access the DPP to verify the requirements or previous transportation steps. In this case, they need to be part of the Gaia-X ecosystem and become service users.
   - **Data Provider:** Provides data about the delivery time as well as the carbon footprint of the transport, or the average of the transport and the distance, so that a carbon footprint calculation is possible.
5. **Customers:** Who use the end product until resale or disposal.
   - **Service User:** Customers use the publicly available information of the DPP. It can be accessed in different ways, e.g. a direct web link via QR code or a web interface where the product ID can be searched. However, the end customer is not part of the ecosystem and, therefore, only a limited service user with respect to the whole Gaia-X ecosystem.

   - **Data Provider:** During the use of the product, various repair or maintenance activities may be performed on the product. These activities can be reported by the customer or by the service provider. Since customers are not considered a registered part of the Gaia-X ecosystem, the data is provided through a publicly accessible interface.
6. **End-of-Life Companies:** Companies that collect and process the product at the end of its life, such as recyclers or remanufacturers.
   - **Service User:** Since information about the product history is essential for optimal end-of-life management, recyclers and remanufacturers access the information within the DPP. In particular, information on product variants, materials contained, and disassembly instructions are relevant.
   - **Data Provider:** When the product is recycled or remanufactured, the first life cycle of the product ends. Therefore, the product passport is no longer needed for the product. However, since the materials or complete components are reused, the recyclers and remanufacturers provide information about them for the next product, based on the previous DPP.
7. **Infrastructure-as-a-Service (IaaS) Providers:** If the manufacturer or external service provider does not have the necessary infrastructure to host the DPP service, IaaS providers can provide it.
   - **Service Provider:** The IaaS provider operates the server and storage infrastructure needed for the DPP as a service. This service can be accessed via the Gaia-X ecosystem, where different interchangeable alternatives, e.g. SCC or HLRS, are possible for the DPP.
   - **Service User:** The IaaS provider does not use the DPP service.
   - **Data Provider:** Since they only provide the infrastructure, the only data they can provide is information about where the information is stored and the resulting carbon footprint.

While collaborating through the DPP, each participant has specific terms and conditions that govern collaboration, data exchange and storage, and communication while using the service. Especially with regard to data, clear agreements are necessary. For example, data providers may agree to store and archive the data provided to the DPP for at least five years from the date of provision. However, the specific terms and conditions of the DPP service need to be defined on a use case basis since, for example, data of different criticality and products with different life spans may be considered, resulting in different agreements.

4.1.3 Participant Onboarding and Service Usage

Many participants will need to go through OAW because they want to use the DPP service or part of it. For this, the normal OAW has to be carried out, where, depending on the product, special additions or contracts may be possible. However, for the sake of simplicity, also with regard to the Gaia-X4ICM ecosystem, this will not be considered further here. Therefore, for the DPP service in the Gaia-X4ICM ecosystem, all participants or companies that want to use the DPP have to follow the standard OAW (Section 3.3).

However, especially for SMEs, e.g. small suppliers or service and transport companies, the complete onboarding process is not valid, as it is too complex and time-consuming. Therefore, the DPP service offers the possibility of external or associated partners. These partners have limited access so that only the specific information they generate can be transferred to the DPP, but they are not assigned a specific role in the ecosystem. As a result, they are only data providers and not service users. Therefore, these partners can only access the publicly available information within the DPP via the available interfaces.

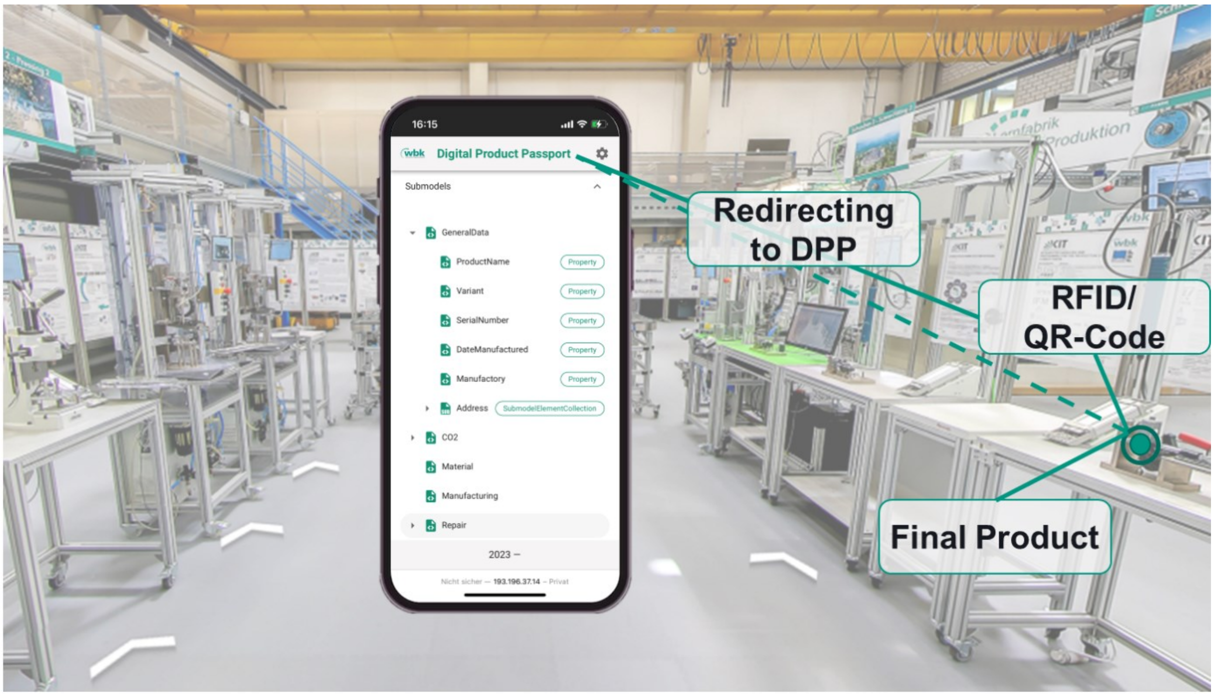

Figure 7. Demonstrative implementation of the DPP service in the Learning Factory Global Production at the wbk [44]

There are different ways to access the DPP of a specific product, which can vary within the value chain, e.g. from complete batches for materials to the individual product at the end. However, since the DPP contains seamless information for the entire value chain along the entire product lifecycle, a traceability system is required. The design of such a system is a complex task with a high degree of freedom [45]. Therefore, it is assumed that traceability can be ensured for the Gaia-X4ICM ecosystem. For example, the DPP will be accessible via a QR code, redirecting the product user to the publicly available interface (Figure 7). If users want to use specific information, e.g., for recycling, they can log in to the DPP with their Gaia-X account to get full access to the data available for their assigned role, e.g., the recycler.

4.1.4 The Value of Digital Product Passports as Gaia-X Service

The DPP enables a decentralized data exchange along the entire value chain, while the use of Gaia-X and the EDC ensures that data sovereignty remains with the companies. Data exchange is secure and controlled, allowing each company to decide what data to share and under what conditions. This increases data sovereignty, builds trust in the service, and drives adoption and usage. The service is platform-independent, which is especially beneficial for small and medium-sized enterprises, as they can easily use the service for their products and benefit from the advantages of sovereign data exchange. In addition, external partners and data providers can be flexibly integrated, facilitating collaboration between companies and further increasing the use of the DPP service for smaller companies with many small suppliers.

4.2 Wear & Tear-Aware Components as a Service

Alexander Bott

4.2.1 Introduction

In the Gaia X4ICM ecosystem, the "Wear & Tear-Aware Components as a Service" offering is an innovative solution that focuses on continuously monitoring and analyzing machine components to predict their Remaining Useful Life (RUL). This service utilizes sensor technology, edge computing, and cloud-based machine learning models to identify wear characteristics and enable a precise prediction of wear.

Section 3 presented general principles of self-sovereign and privacy-compliant data exchange in the Gaia-X ecosystem. These principles are of central importance for the implementation of a viable "Wear & Tear-Aware Components as a Service" solution. The use of self-sovereign identities and decentralized trust systems enables secure and transparent data transfer between the various participants in the ecosystem, including service providers, consumers, and further intermediaries.

4.2.2 How it Works: The Prediction Pipeline for the Remaining Service Life of Machine Components

The in [46] proposed pipeline for predicting the RUL of machine components consists of three main components, each of which addresses specific challenges in evaluating sensor signals and analyzing them to predict the RUL see Figure 8:

1. Local pre-processing through edge computing: As the sensor signals are typically available at a high sampling rate, a local pre-processing step is required to reduce the amount of data and enable simple anonymization. This pre-processing is carried out using edge computing technologies, which has the advantage that only relevant features need to be extracted and transferred to the (cloud) services in the ecosystem. This not only reduces the data load but also ensures compliance with data protection guidelines by processing sensitive data locally.

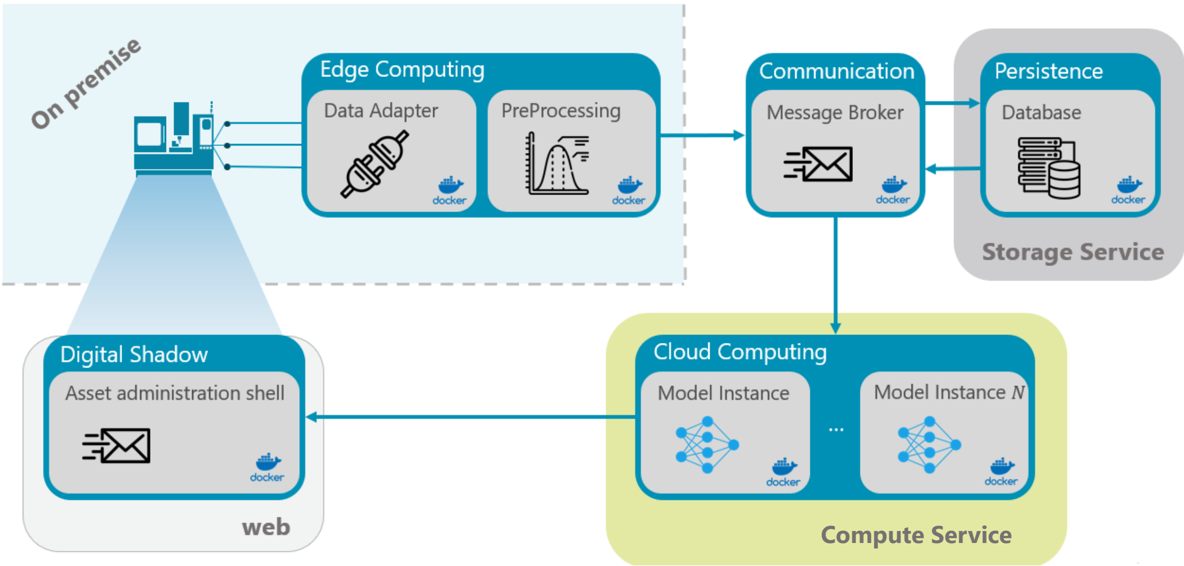

Figure 8. Proposed prediction pipeline for adaptive cloud-based model usage

2. Data transmission via OPC UA: The cleansed and anonymized characteristics are then sent to the (cloud) services via the OPC UA protocol (Section 3.5). OPC UA is a useful technology within the Gaia X4ICM ecosystem because it promotes interoperability between different actors and systems. The use of OPC UA ensures that data transmission is secure and compliant with the Gaia-X principles of self-sovereignty and trust.

3. Cloud-based analysis and model customization: The data is actually analyzed in the cloud using advanced machine learning models that are continuously adapted and improved. The models are fed with a continuous stream of data from production, which leads to a constant increase in the training basis and improves the generalization capability of the models. Approaches such as meta-learning and adaptive model training are used to optimize the prediction quality under varying operating conditions.

4.2.3 Integration into the Ecosystem: Roles and Business Models

The "Wear & Tear-Aware Components as a Service" solution integrates various participants within the Gaia-X ecosystem to enable efficient and data-driven prediction of the RUL of machine components. Each participant takes on specific roles based on their functions and needs. This distribution of roles not only creates synergies but also enables the development of different business models that offer the respective participants new value creation opportunities.

1. **Ball screw manufacturer**: This participant acts as both service provider and service consumer:
    - **Service provider (wear detection service)**: The manufacturer offers wear detection models that are used to predict the wear condition of machine components. This enables the sale of wear prediction models to machine operators or machine manufacturers who can use them to plan or avoid downtimes.

  - **Business models**:
    - *Sale of prediction models*: The ball screw manufacturer can sell wear prediction models directly to end customers or machine manufacturers.
    - *Subscription model for updates and continuous improvement*: The manufacturer could introduce a subscription model that gives customers continuous access to the latest prediction models and improved analyses.
    - *Data-based "pay-per-use" model*: Customers pay according to the scope and frequency of use of the forecast models and access to real-time data.
  - **Service consumer (computational node)**: Utilizes computing resources provided by an IaaS provider to host and operate the models.
2. **Machine operator**: The machine operator is primarily a service consumer:
   - **Service Consumer (wear prediction service, overall machine service)**: Uses remaining component life predictions to optimize machine usage and plan maintenance actions, minimizing unforeseen downtime.
   - **Business models**:
     - *Cost optimization through preventive maintenance*: The operator can save direct costs through optimized maintenance schedules and minimized downtimes.
     - *Pay-per-use for prediction services*: The operator can pay for the use of wear prediction services based on the number of predictions used or the amount of data transmitted.
     - *Performance-based models*: The operator can make agreements with the machine or component manufacturer based on the performance and availability of the machines.
3. **Machine manufacturer**: The machine manufacturer acts as a service provider and service consumer:
   - **Service provider (complete machine service)**: Provides a comprehensive machine service, including integration of wear detection modeling and RUL predictions.
   - **Service consumer (wear prediction service, computational node)**: Uses wear prediction services and computing resources to gain insights into product performance at the end customer and to optimize its own production and services.
   - **Business models**:
     - *Service contracts based on machine performance*: The machine manufacturer can settle service contracts based on machine performance and the prediction of the remaining service life.
     - *After-sales service offers*: Additional services such as training, extended warranties, or maintenance packages based on predictive modeling.

        - *Data-driven product development*: Utilization of collected data to continuously improve and adapt product design and production processes.
4. **IaaS provider**: As a provider of infrastructure resources, this participant acts as a service provider:
    - **Service provider (computational node)**: Provides the necessary storage and computing capacities required for analyzing and providing the prediction models.
    - **Business models**:
        - *IaaS*: Offers scalable storage and computing resources on a usage or fixed subscription basis.
        - *Extended services*: Provision of additional services such as data management, security, data protection conformity, and compliance management.

4.2.4 The Value of Continuous Model Training and Potential for Improving the Lifetime Models

A key element of the "Wear & Tear-Aware Components as a Service" model is the ability to continuously access application data from the field and use it to improve service life prediction models. In contrast to traditional approaches, which are often based on static data sets from controlled laboratory environments, this solution enables dynamic and continuous adaptation of the models to real operating conditions and a wide range of wear scenarios.

Data is continuously supplied via the Gaia-X ecosystem, in which production data is securely and confidently exchanged between participants. The incoming data from the field serves as the basis for continuous model training, which is supported by adaptive learning algorithms such as meta-learning and incremental learning. This approach offers several key advantages:

1. **Solving the small sample problem:** In production engineering, the availability of comprehensive and representative data sets covering different wear states and operating conditions is often limited. This "small sample problem" is addressed by the continuous integration of field application data into the training of the models. A constantly growing base of training data enables a more precise recording of failure mechanisms and more robust modeling of service lives.
2. **Improved generalization of service life models:** Field application data is characterized by a large number of variables such as different operating conditions, environmental factors, and usage patterns. The continuous integration of this data into the modeling processes significantly improves the generalization capability of the models. The prediction models are thus able to cover a wider range of scenarios and provide reliable forecasts even under non-standardized conditions.
3. **Continuous model optimization:** Adaptive model use makes it possible to continuously monitor and optimize models. Through the continuous feedback of field data, the models can be continuously adapted and optimized to the latest data, which leads to a sustainable improvement in prediction quality. This approach is particularly valuable

for components and machines whose wear behavior can vary greatly due to production fluctuations or material tolerances.

4. **Economic benefits through improved predictive accuracy:** Greater predictive accuracy with regard to the remaining service life of components contributes directly to better planning and resource utilization. Companies can plan maintenance measures with foresight, avoid unplanned downtime, and optimize the service life of their machine components. This leads to cost reductions and increased operational efficiency.
5. **Utilization of the Gaia-X ecosystem to promote data availability and cooperation:** The Gaia-X infrastructure enables continuous and secure access to data from various participants. This not only creates trust and transparency but also enables new business models, such as the "pay with data" model, in which data is traded as a valuable resource. Forecasting services providers benefit from a larger database, while users benefit from more precise and robust models.

Overall, the integration of continuous application data from the field enables a dynamic and constantly improving prediction model. The solution to the small sample problem and the improved generalization are essential steps towards a more robust and economically efficient use of machine components in a data-driven production environment.

4.3 Tool Wear & Tear Recognition as a Service

Ehsan Karimi, Volker Schulze

4.3.1 Introduction

In the Gaia-X4ICM ecosystem, the “Tool Wear & Tear Recognition as a Service” offers on-machine tool condition monitoring, providing in-line tool condition assessment to save time compared to off-line monitoring. This approach maximizes tool life and optimizes machining parameters. The service uses direct sensor technology, machine learning techniques, and industrial communication technology to analyze the tool condition and predict the RUL of the cutting tool [47].

Section 3 generally introduced the principles of self-sovereign and privacy-compliant data exchange in the Gaia-X ecosystem. These principles are central to the implementation of a viable Tool Wear & Tear Recognition as a Service solution. Using self-sovereign identities and decentralized trust systems enables secure and transparent data transfer between the different actors in the ecosystem, including service providers, consumers, and intermediaries.

4.3.2 How it Works: Tool Condition Monitoring Pipeline

Figure 9 presents a proposed pipeline for tool condition monitoring, which comprises distinct sections. Each section addresses a specific challenge and processes the corresponding data.

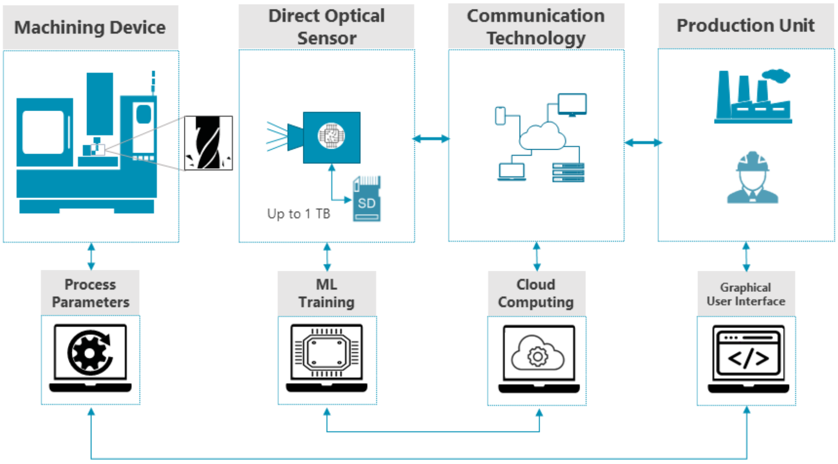

Figure 9. Cloud-based adaptive model for tool wear analysis

1. **Direct Optical Sensor**: This service incorporates a smart camera capable of executing AI algorithms. The camera acquires high-resolution images of the cutting tool surface via an external trigger from the machining device. By analyzing these images, the wear area on the cutting edge can be quantified. A training dataset was thus assembled, pre-processed, and employed to train a segmentation model, which was then utilized for subsequent analysis. Figure 10 depicts the methodology employed for the analysis of wear [47].

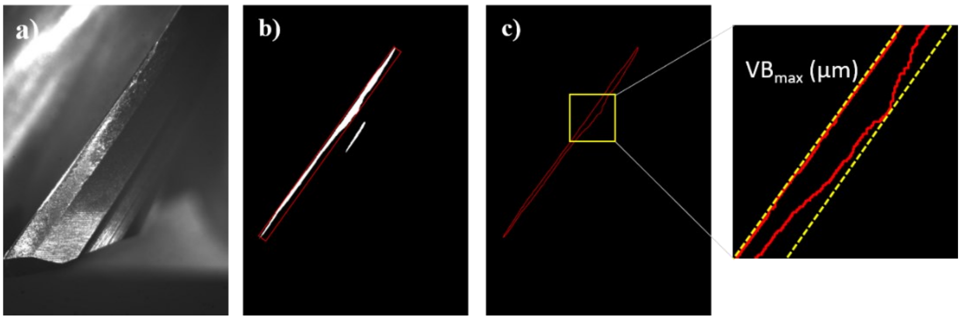

Figure 10. a) Original image, b) Segmentation result with target cluster, c) Wear measurement

2. **Communication Technology**: Communication between the cloud/PC and the smart camera is achieved via either a Secure Shell (SSH) connection or the OPC UA protocol. A significant advantage of the smart camera is its capacity to be readily managed remotely via an SSH connection or configured as a server. OPC UA is regarded as a highly valuable technology within the Gaia-X4ICM ecosystem, facilitating seamless interoperability between diverse actors and systems. The utilization of OPC UA guarantees the secure transmission of data while upholding the Gaia-X tenets of self-sovereignty and trust.
3. **Production Unit**: A graphical user interface (GUI) is designed to facilitate comprehensive access to the camera and enable wear analysis for a range of cutting tools while simultaneously monitoring the wear diagram. The GUI can be utilized for both offline and in-line images, thereby enabling the production unit to train new models for specific types of cutting tools.

4.3.3 Integration into the Gaia-X Ecosystem: Roles and Business Models

The "Tool Wear & Tear Recognition as a Service" solution facilitates the integration of diverse participants within the Gaia-X ecosystem, thereby enabling in-line tool condition monitoring. Each participant assumes a specific role based on their respective functions and needs. This distribution of roles not only fosters synergies but also supports the development of different business models, thereby providing participants with new opportunities for value creation.

1. **Tool Manufacturer**: This participant acts as both service provider and service consumer:
    - **Service Provider (Wear Analysis)**: The tool manufacturer offers a wear measurement model tailored to specific cutting tools, facilitating the sale of wear detection models and RUL predictions to machine operators or machining devices manufacturers. Such models may be employed in the formulation of maintenance schedules, thereby obviating the occurrence of unanticipated periods of downtime.
    - **Service Consumer (Computational Node)**: Utilizes computing resources provided by an IaaS provider to host and operate the models.
    - **Business Models**:
        - *Sale of wear analysis model*: The tool manufacturer can sell wear analysis models directly to end customers or machine manufacturers.
        - *Subscription model for updates and new tool*: The tool manufacturer could introduce a subscription model that gives customers continuous access to the desired cutting tool type.
        - *Data-based "pay-per-use" model*: Customers pay according to the scope and frequency of use of the forecast models and access to real-time data.
2. **Machine operator**: The machine operator is primarily a service consumer:
    - **Service Consumer (Tool Condition Monitoring)**: The model provided by the tool manufacturer is utilized for in-line tool condition monitoring, thereby enabling operators to ascertain when the tool requires replacement. This approach is more time-efficient than the traditional method of offline tool examination.
    - **Business models**:
        - *Cost optimization through in-line maintenance*: Utilizing in-line maintenance significantly reduces machine downtime, optimizing overall costs.
        - *Cost optimization through timely tool changes*: Changing the tool at the right time decreases energy consumption for cutting. As the cutting tool wears, cutting forces and energy consumption increase, leading to higher costs. Timely tool changes also improve the surface quality of the end product.
        - *Pay-per-use for prediction services*: The operator can pay for the use of wear prediction services based on the number of predictions used or the amount of data transmitted.

        - *Performance-based models*: The operator can make agreements with the machine or component manufacturer based on the performance and availability of the machines.
3. **Machine manufacturer**: The machine manufacturer acts as a service provider and service consumer:
    - **Service Provider (Process Parameters)**: Provide an optimized machining process for different cutting tools and materials, with the aim of maximizing tool life.
    - **Service Consumer (Tool Condition Monitoring)**: Utilize the condition monitoring system to optimize product performance and enhance the quality of the end product.
    - **Business Model**:
        - *Data-driven product development*: Leveraging collected data to continuously refine and adapt product design and manufacturing processes.
4. **IaaS provider**: The infrastructure resources provider is primarily a service provider:
    - **Service Provider (Computational Node)**: Provides the infrastructure for cloud communication and computing capacity to support the use of the service.
    - **Business Models**:
        - *IaaS*: Offers scalable storage and computing resources on a usage or fixed subscription basis.
        - *Extended services*: Provide additional services such as data management, security, privacy, and compliance management.

4.3.4 The Value of In-Line Tool Condition Monitoring

One of the most important aspects of "Tool Wear & Tear Recognition as a Service" is its flexibility, as it can be used both locally and via the cloud in the Gaia-X ecosystem. The smart camera used in this service is equipped with an NVIDIA Jetson Xavier NX processor and supports up to 1TB of storage. Communication between any machining device and the camera is possible with a simple trigger signal (5~48 V) from the machine to the camera to initiate image capture and subsequent wear analysis, so when the wear width on the cutting edge reaches a specified threshold (200 µm VB), a signal can be sent from the camera to the machine to stop the process and notify the operator to change the tool [47].

The service can also be configured as an OPC UA server, where the camera acts as a server within the communication protocol, meanwhile the machining device can also act as server or communication between the camera and the machine can also be through direct triggering. Data is transferred using protocols such as TCP/IP. A cloud server or a local PC can act as a client and be used to store data for eliminating the need for large storage capacity on the camera itself.

The service offers a wide range of models to analyze different cutting tools. If a customer requires analysis for a specific tool type, a new model can be trained via a GUI (e.g., Figure 11) provided with several options, including the ability to train a new model with selectable hyperparameters. Other available features include image pre- and post-processing and wear analysis for both offline and in-line conditions. Users can upload a batch of images, select the number of cutting edges and plot the wear curve, or analyze in-line images and monitor the results in real-time.

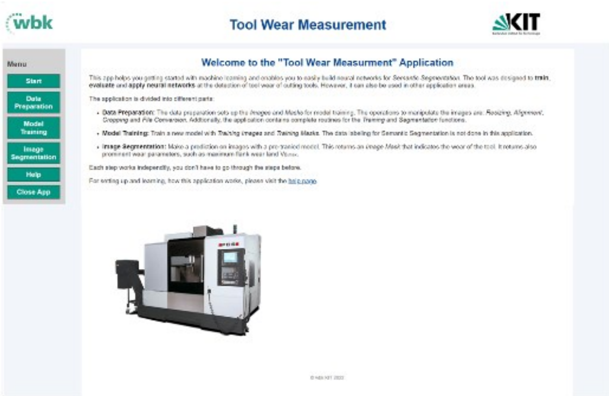

Figure 11. Example Graphical User Interface

An adaptive data filtering method is already implemented in the model, in case of inaccurate results due to model errors or data conditions (e.g., light reflection, chip formation), the data filtering method ensures accurate wear analysis results. If the continuous wear values exceed the predefined threshold, the service issues a warning and stops the machining process.

From an economic perspective, 3-12% of production costs are attributed to cutting tool condition and replacement. A reliable Tool Condition Monitoring system can increase cutting speed by 10-50%, reduce downtime by 75%, and save approximately 30% in maintenance costs. “Tool Wear & Tear Recognition as a Service” ensures that tools are used to the end of their useful life and replaced at the optimum time. Companies can use this service to avoid unplanned downtime and optimize the life of their machine components [48].

The Gaia-X ecosystem ensures continuous and secure data access from multiple participants, building trust and transparency and supporting new business models like the "pay with data" approach, where data is treated as a valuable asset. “Tool Wear & Tear Recognition as a Service” providers benefit from diverse implementations across production units and a larger database, giving users access to more precise and reliable models.

4.4 Laser Analysis as a Service

David Brinkmeier

4.4.1 Introduction

“Laser Analysis as a Service” (LAaaS) within the Gaia-X4ICM project aims to transform laser-based manufacturing by integrating state-of-the-art data analytics and cloud technologies through the Gaia-X ecosystem. This initiative leverages the developments of two laser processes - Easy Metal Printer (EMP) (please refer to project ICM-EMP[3] and related research like [49], [50]) and Self-Learning Functional Laser Micromachining (SELF) (please refer to project ICM-SELF[4] and related research such as [51], [52], [53]) - to enable real-time optimization and control. By synchronizing sensor data from industrial laser systems and using advanced machine learning algorithms, LAaaS provides scalable and efficient laser processing solutions.

4.4.2 Real-Time Adaptive Metal Additive Manufacturing Through Decentralized Data Ecosystems and Optical Process Visualization

EMP uses additive laser manufacturing processes to produce highly complex and precise metal parts. One of the key innovations of EMP is the real-time transmission of the actual deposition geometry, which is recorded using optical coherence tomography (OCT) during the deposition process. This advanced sensor technology captures the geometry of the workpiece layer by layer as it is formed, allowing process experts to remotely track the workpiece's formation in real-time. This data is instantly shared for remote viewing and analysis, allowing experts to monitor and optimize the process from anywhere. This real-time monitoring ensures high-quality production, reduces material waste, and improves efficiency.

The workflow within the GAIA-X4ICM ecosystem begins at the laser machine, where the laser process takes place. The process data is recorded in real-time and transmitted to a local data processing system via a real-time capable fieldbus. At this stage, machine data and sensor readings are collected and monitored and made available to external systems via the OPC UA protocol. The aim is for this data to be processed within the Gaia-X4ICM ecosystem for further analysis. In a cloud environment, advanced algorithms, including machine learning models, are used to analyze and optimize the laser process. This optimized information is then fed back into the laser machine for adjustment, enabling precise remote control and refinement of the laser printing process.

4.4.3 Autonomous Laser Micromachining Optimization via Integrated Neural Network Analytics and Bayesian Process Modelling

The SELF process brings precision and adaptability to laser micromachining. SELF uses advanced machine learning techniques, including neural networks and Bayesian Gaussian methods, to optimize the laser machining process continuously. Neural networks allow the system to learn and adapt from historical data, while Bayesian Gaussian processes provide probabilistic models that adjust parameters based on real-time sensor inputs and uncertainties. This dual approach allows the system to dynamically refine its operations, resulting in higher accuracy and a reduced need for manual adjustments. SELF's advanced learning capabilities make it ideal for applications that require intricate laser processing, such as electronics, medical devices, and micromechanical components, providing a highly adaptive, intelligent solution for precision manufacturing.

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[3] https://www.icm-bw.de/forschung/projektuebersicht/detailseite/ic7-easy-metal-printer-emp
[4] https://www.icm-bw.de/forschung/projektuebersicht/detailseite/ic6-self

In SELF, the workflow begins with the proprietary 'KAmeL' process control system at IFSW. The raw data is collected and stored locally in files. A watchdog service monitors the datasets, which are then processed with Collectu (ISW) and sent to the machine via an InfluxDB client for analysis and feedback. This local processing will be moved to a cloud service where machine learning techniques, including neural networks and Bayesian Gaussian methods, will be used to optimize the micromachining process.

4.5 Computing Resources as a Foundational Ecosystem Service

Olga Andriushchenko, Oleksandr Shcherbakov, Dennis Hoppe, Matthias Leander-Knoll, Keerthana Jaganathan, Klaus Scheibenberger

This section explores the implementation of cloud infrastructure for the Gaia-X ecosystem, a collaborative effort between the *Scientific Computing Center (SCC)* at KIT and the *High Performance Computing Center Stuttgart (HLRS)*. The SCC and HLRS are responsible for providing a cloud infrastructure as a service for the Gaia-X4ICM ecosystem with the following work packages as objectives:

1. Provisioning OpenStack -based cloud platform to the Gaia-X ecosystem interconnected with the HLRS
2. Systems and user integration
3. Continuous service operation
4. Further development and sustainability of the cloud platform

These objectives are fulfilled through an OpenStack-based cloud platform, thereby supporting the Gaia-X initiative's goal of creating a federated, secure, and sovereign data infrastructure for Europe. We next discuss key work packages, including the provisioning of the cloud platform, systems and user integration, continuous service operation, and the platform's further development and sustainability. Such infrastructure is crucial in realizing Gaia-X's vision of a trusted, interconnected data ecosystem that fosters innovation while maintaining control over data assets.

4.5.1 Basics of the Service

The provision and operation of the required cloud platform with Hyperconverged Infrastructure included the following tasks: 1) Hardware Procurement, 2) Building the Cloud Platform, 3) Provisioning Services and User Integration. A Hyperconverged Infrastructure (HCI) is an IT framework that combines storage, computing, and networking into a single system to reduce data center complexity and increase scalability. By integrating these resources with hypervisor software and typically managed from a single interface, HCI allows for centralized control, streamlined management, and ease of deployment [54]. Figure 12 illustrates the cloud infrastructure at SCC and HLRS.

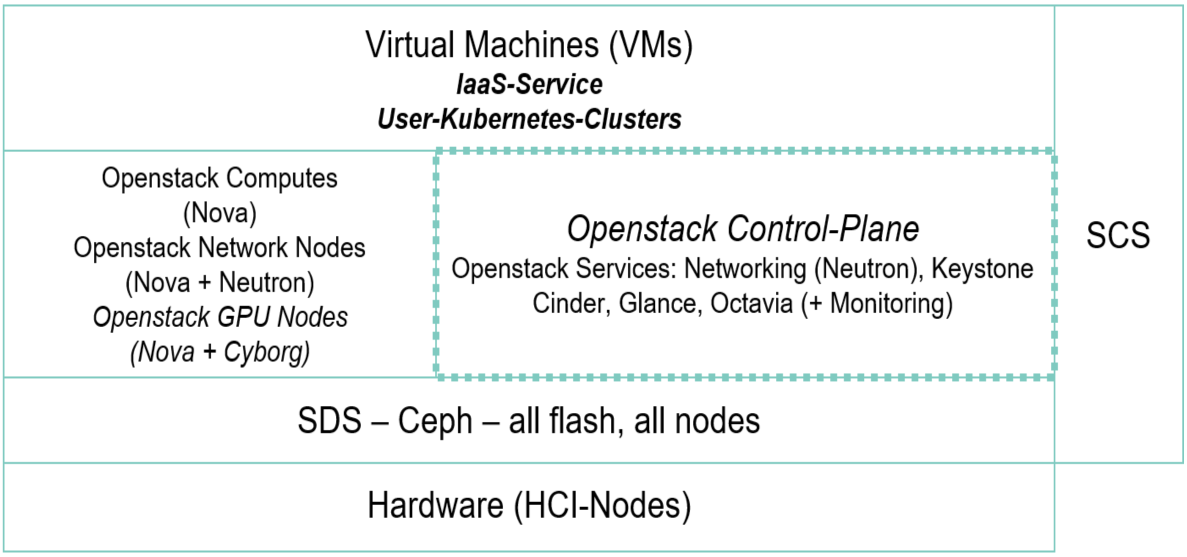

Figure 12. Overview of the cloud infrastructure at SCC and HLRS with HCI-Servers, software-defined storage and OpenStack services

1. Hardware Procurement

Based on the requirement analysis conducted in close coordination with our service provider partners SCC, HLRS, and other consortium partners, the technical architecture was finalized to meet the performance (CPU/GPU) and storage (HDD/SSD) requirements. The hardware components were procured, integrated into a present rack, and connected to the existing network infrastructure at the SCC and HLRS. The hardware systems were also connected to the power grid and the data center-wide UPS infrastructure. Table 1 shows details about the hardware, such as the total number of servers, the number of CPUs, RAM, Storage, and network components per server.

Table 1. The hardware systems at SCC and HLRS

Provider	Server Count	CPU	RAM	Storage	Network
SCC	10	2x64 Core AMD Milan	1024 GB	6xSSD 3,84 TB NVMe	2x 25GBit (SFP28)
HLRS	8	2x36 Cores Intel Xeon	512 GB	6xSSD 3,84 TB	2x25GBit (SFP28)

2. Integration of Hardware and Software components

In the infrastructure setup at SCC, Foreman[5] was utilized as a key tool for the automated deployment of operating systems across our hardware nodes. Foreman is an open-source lifecycle management tool that simplifies the process of provisioning, configuring, and managing

[5] https://theforeman.org/

physical and virtual servers. By leveraging Foreman, we were able to streamline the initiation of operating systems, ensuring consistency and reducing the time required for setup. Similarly, at HLRS, Kickstart and Ansible were used for provisioning and setting up servers.

On both sites, Kickstart automated the initial operating systems installation, allowing for custom configurations during deployment, while Ansible managed post-installation tasks such as software provisioning, configuration management, and orchestration across the infrastructure.

The OpenStack Cloud Infrastructure and services were deployed based on Kolla Ansible[6] installation scripts[7]. This approach aligns with the principles of Sovereign Cloud Stack (SCS)[8], an open-source project and part of Gaia-X that aims to create a standardized and sovereign cloud computing platform. Kolla Ansible provides an automated and containerized deployment of OpenStack services meaning each of the OpenStack services such as neutron, nova, glance, and other services are running as docker containers in the chosen nodes/servers. The SCC and HLRS have customized OpenStack service configurations to include other components, such as storage, and also to suit the common needs of the project partners.

Ceph[9] is used as the software defined storage service. Both partners used Cephadm ansible scripts[10] to install a Ceph cluster that uses SSD of the newly commissioned hardware infrastructure. This Ceph cluster is integrated with the OpenStack cloud infrastructure and acts as storage backend (object and block storage) for the OpenStack instances.

3. Provisioning Services and User Integration

After the successful deployment of OpenStack services and infrastructure components and their integration with the Ceph storage cluster, the cloud infrastructure is fully equipped to provision virtual machines (VMs) for users.

The VMs are the main service the SCC and HLRS provide to the users via this cloud platform. These VMs act as the essential resources for setting up Kubernetes[11] clusters, which can be utilized to orchestrate and manage containerized workloads. Using open-source tools such as Kubespray[12] or Rancher[13], Kubernetes clusters can be configured within this environment to be provided to the project partners.

An identity management system facilitates users to securely and automatically create an account to access the solution via OpenStack Dashboard (Horizon). OpenID Connect/OIDC provides a secure protocol for identity management and is supported by OpenStack – making it suitable for Gaia-X's vision of a federated and interoperable cloud ecosystem. Integrating

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[6] https://docs.OpenStack.org/kolla-ansible/latest/
[7] https://opendev.org/OpenStack/kolla-ansible
[8] https://scs.community
[9] https://docs.ceph.com/en/quincy/
[10] https://github.com/ceph/cephadm-ansible
[11] https://kubernetes.io
[12] https://kubespray.io
[13] https://www.rancher.com/

identity management services enables decentralized and user-centric access to the platform. One of such fully-featured identity management services is bwIDM[14].

4.5.2 Advanced Features of the Service

Multi-tenancy in the OpenStack cloud platform allows multiple users or organizations (tenants) to share the same cloud infrastructure while maintaining data isolation, resource allocation, and security [55]. This capability enables efficient utilization of hardware resources, reduces operational costs, and simplifies cloud management [56]. By supporting multi-tenancy, OpenStack facilitates the development of scalable, customizable cloud services, providing a foundation for innovation in areas like Platform-as-a-Service (PaaS) offerings, container orchestration, and self-service portals while ensuring that each tenant's environment remains independent and secure.

By leveraging OpenStack's multi-tenancy features, the SCC and the HLRS aim to build a scalable, secure, and cost-effective cloud environment that facilitates diverse user needs while maintaining operational efficiency.

4.5.3 Lessons Learned from Embedding the Service in the Ecosystem

To embed our cloud IaaS provider in the Gaia-X ecosystem, we need to include components from GXFS into our OpenStack system, such as:

- Develop detailed SD for our OpenStack VM services, including service capabilities, data handling practices, security measures, and compliance with Gaia-X standards
- Identity and Trust: We implement authentication and authorization services
- Sovereign Data Exchange: Secure data sharing capabilities are enabled via OpenStack and the Ceph storage backend. By using a multi-tenant architecture, the SCC and HLRS not only achieve resource isolation but also enhance data security.

Key insights of bringing a typical cloud service into an ecosystem include:

- **Integrating with Federated Identity Management:** By implementing OIDC, our IaaS services can participate in Gaia-X's federated identity framework, enabling cross-provider authentication.
- **Scalability and Flexibility:** A cloud service should be designed to scale efficiently within the ecosystem, handling varying loads and adapting to the needs of different applications and users. This flexibility is crucial for maintaining performance and reliability as demands change.
- **Interoperability:** To achieve interoperability between services offered by different providers, adherence to common standards, APIs and data models (like Sovereign Cloud Stack) are required.

[14] https://www.bwidm.de

- **Security and Compliance:** Ensuring that the cloud service meets security standards. This includes implementing robust authentication, authorization, and encryption mechanisms to protect data within the ecosystem.
- **Multi-tenancy:** As an infrastructure provider, using the multiple domain concept in OpenStack is helpful to isolate and manage multiple users or tenants in the cloud platform.

4.5.4 Outlook

Future work could focus on advancing interoperability standards and protocols to enable seamless integration between diverse cloud services, platforms, and container registries. Emphasis should also be placed on improving the user experience by simplifying cloud service interfaces, enhancing PaaS offerings, expanding management tools, and ensuring accessibility for users with varying technical skills.

5 Concluding Remarks and Outlook

Florian Frick, Sebastian Lins

The digital transformation of manufacturing is of strategic importance and an ongoing process. With the focus shifting from digitalization within single companies to cross-vendor value chains and networks, the relevance of ecosystems is constantly increasing. Enabled by the IT-OT convergence and technology trends like the IoT continuum, the integration of manufacturing and digital ecosystems remains a key challenge.

The presented work highlights four use cases and the underlying infrastructure that together build the Gaia-X4ICM ecosystem. The DPP provides essential product information, such as legal documents and carbon footprint, and includes details from all phases of the product lifecycle, such as design, materials, and transportation. It promotes decentralized data exchange and data sovereignty through secure technologies like EDC. Gaia-X4ICM also offers manufacturing-relevant services like "Wear & Tear-Aware Components as a Service" and "Tool Wear & Tear Recognition as a Service", which use sensors and machine learning to monitor and predict the RUL of components and tools. In addition, "Laser Analysis as a Service" optimizes laser-based manufacturing processes using real-time data and machine learning. The SCC and HLRS provide the required cloud infrastructure for the Gaia-X4ICM ecosystem through an OpenStack-based platform to ensure secure, federated data management.

The project results not only show the potential of an ecosystem-based approach but also highlight the importance of future work regarding ecosystems, digital infrastructures, and the transformation of manufacturing. For instance, building on and applying the principles of Gaia-X revealed the central importance and role of federation services like the federated catalog and identity & trust management services. Although there are first prototypes for federation services (i.e., Gaia-X digital clearing house services) and related GXFS projects (e.g., the XFSC toolbox), we still lack federation services that can be applied to novel ecosystems like Gaia-X4ICM. Setting up GXFS is complex, challenging, and not economically feasible for most federations, hampering the practical implementation of ecosystems. Practice and research may elaborate on how to set up a basic technical foundation for federations, aligning with the Gaia-X principles and being economical viable. Furthermore, the project revealed that a digital infrastructure reaching far in the OT domain is a necessity to efficiently connect production systems with larger ecosystems. Topics like converged communication down to the field level, converged compute platforms, common data models, services as well as security require further research. Solving these challenges with open standards and solutions is specifically important for small and medium-sizes companies.

We thank the Baden-Württemberg Ministry of Science, Research and the Arts for its financial support of the ICM. We are also grateful for the efforts of the ICM team, who have made our project possible and provided ongoing support.

References

[1] Forschungsbeirat der Plattform Industrie 4.0/acatech – Deutsche Akademie der Technikwissenschaften, Ed., *Blinde Flecken in der Umsetzung von Industrie 4.0 – identifizieren und verstehen*. Munich, Germany, 2022. doi: 10.48669/fb40_2022-1.

[2] B. Dattée, O. Alexy, and E. Autio, "Maneuvering in Poor Visibility: How Firms Play the Ecosystem Game when Uncertainty is High," *Acad. Manage. J.*, vol. 61, no. 2, pp. 466–498, Apr. 2018, doi: 10.5465/amj.2015.0869.

[3] E. Autio, "Orchestrating ecosystems: a multi-layered framework," *Innovation*, vol. 24, no. 1, pp. 96–109, Jan. 2022, doi: 10.1080/14479338.2021.1919120.

[4] F. Möller *et al.*, "Industrial data ecosystems and data spaces," *Electron. Mark.*, vol. 34, no. 1, p. 41, Dec. 2024, doi: 10.1007/s12525-024-00724-0.

[5] M. G. Jacobides, C. Cennamo, and A. Gawer, "Towards a theory of ecosystems," *Strateg. Manag. J.*, vol. 39, no. 8, pp. 2255–2276, Aug. 2018, doi: 10.1002/smj.2904.

[6] D. J. Teece, "Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance," *Strateg. Manag. J.*, vol. 28, no. 13, pp. 1319–1350, Dec. 2007, doi: 10.1002/smj.640.

[7] R. Adner, "Match your innovation strategy to your innovation ecosystem," *Harv. Bus. Rev.*, vol. 84, no. 4, p. 98, 2006.

[8] A. Hein *et al.*, "Digital platform ecosystems," *Electron. Mark.*, vol. 30, no. 1, pp. 87–98, Mar. 2020, doi: 10.1007/s12525-019-00377-4.

[9] M. I. S. Oliveira, G. D. F. Barros Lima, and B. Farias Lóscio, "Investigations into Data Ecosystems: a systematic mapping study," *Knowl. Inf. Syst.*, vol. 61, no. 2, pp. 589–630, Nov. 2019, doi: 10.1007/s10115-018-1323-6.

[10] F. Von Scherenberg, M. Hellmeier, and B. Otto, "Data Sovereignty in Information Systems," *Electron. Mark.*, vol. 34, no. 1, p. 15, Dec. 2024, doi: 10.1007/s12525-024-00693-4.

[11] O. Granstrand and M. Holgersson, "Innovation ecosystems: A conceptual review and a new definition," *Technovation*, vol. 90–91, p. 102098, Feb. 2020, doi: 10.1016/j.technovation.2019.102098.

[12] J. Pohle and T. Thiel, "Digital sovereignty," *Internet Policy Rev.*, vol. 9, no. 4, Dec. 2020, doi: 10.14763/2020.4.1532.

[13] M. Hellmeier and F. von Scherenberg, "A Delimitation of Data Sovereignty from Digital and Technological Sovereignty.," in *ECIS*, 2023.

[14] BMWi and BMBF, "Project GAIA-X: A Federated Data Infrastructure as the Cradle of a Vibrant European Ecosystem; Executive Summary." Accessed: Jan. 06, 2021. [Online]. Available: https://www.data-infrastructure.eu/GAIAX/Redaktion/EN/Publications/das-projekt-gaia-x-executive-summary.html

[15] BMWi, "GAIA-X: A Pitch Towards Europe," GAIA-X: A Pitch Towards Europe. Accessed: Jan. 06, 2021. [Online]. Available: https://www.data-infrastructure.eu/GAIAX/Redaktion/EN/Publications/gaia-x-a-pitch-towards-europe.html

[16] Gaia-X European Association for Data and Cloud AISBL, "Gaia-X Mission. Vision and Strategy 2024." 2024. Accessed: Sep. 25, 2024. [Online]. Available: https://gaia-x.eu/wp-content/uploads/2024/03/Gaia-X_Mission_Vision_Strategy_2024_Online_Spread.pdf

[17] Gaia-X European Association for Data and Cloud AISBL, "Ecosystems - Gaia-X: A Federated Secure Data Infrastructure." Accessed: Sep. 25, 2024. [Online]. Available: https://gaia-x.eu/who-we-are/vertical-ecosystems/

[18] Gaia-X European Association for Data and Cloud AISBL, “Gaia-X: Togethers Towards a Federated & Secure Data Infrastructure.” 2024. Accessed: Sep. 25, 2024. [Online]. Available: https://gaia-x.eu/wp-content/uploads/2024/04/Gaia-X-Brochure_Overview-FINAL-V5_Online.pdf
[19] A. Benlian, W. J. Kettinger, A. Sunyaev, and T. J. Winkler, “The Transformative Value of Cloud Computing: A Decoupling, Platformization, and Recombination Theoretical Framework,” *J. Manag. Inf. Syst.*, vol. 35, no. 3, pp. 719–739, Jul. 2018, doi: 10.1080/07421222.2018.1481634.
[20] S. Lins, K. D. Pandl, H. Teigeler, S. Thiebes, C. Bayer, and A. Sunyaev, “Artificial Intelligence as a Service: Classification and Research Directions,” *Bus. Inf. Syst. Eng.*, vol. 63, no. 4, pp. 441–456, Aug. 2021, doi: 10.1007/s12599-021-00708-w.
[21] J. Schlechtendahl, F. Kretschmer, A. Lechler, and A. Verl, “Communication Mechanisms for Cloud based Machine Controls,” *Procedia CIRP*, vol. 17, pp. 830–834, 2014, doi: 10.1016/j.procir.2014.01.074.
[22] L. Furmanek, S. Lins, M. Blume, and A. Sunyaev, “Developing a Hybrid Deployment Model for Highly Available Manufacturing Execution Systems,” in *2024 47th MIPRO ICT and Electronics Convention (MIPRO)*, Opatija, Croatia: IEEE, May 2024, pp. 2095–2100. doi: 10.1109/MIPRO60963.2024.10569530.
[23] M. Blume, S. Lins, and A. Sunyaev, “Uncovering Effective Roles and Tasks for Fog Systems,” in *Service-Oriented and Cloud Computing*, vol. 14183, G. A. Papadopoulos, F. Rademacher, and J. Soldani, Eds., in Lecture Notes in Computer Science, vol. 14183. , Cham: Springer Nature Switzerland, 2023, pp. 119–135. doi: 10.1007/978-3-031-46235-1_8.
[24] M. Blume, S. Lins, and A. Sunvaev, “Understanding Interdependencies among Fog System Characteristics,” in *2022 IEEE 24th Conference on Business Informatics (CBI)*, Amsterdam, Netherlands: IEEE, Jun. 2022, pp. 126–135. doi: 10.1109/CBI54897.2022.00021.
[25] P. Danielis *et al.*, “Survey on real-time communication via ethernet in industrial automation environments,” in *Proceedings of the 2014 IEEE Emerging Technology and Factory Automation (ETFA)*, Barcelona, Spain: IEEE, Sep. 2014, pp. 1–8. doi: 10.1109/ETFA.2014.7005074.
[26] IEEE 802.1 Working Group, “Time-Sensitive Networking (TSN) Task Group.” Accessed: Oct. 07, 2024. [Online]. Available: https://1.ieee802.org/
[27] IETF Datatracker, “Deterministic Networking (detnet).” Accessed: Oct. 07, 2024. [Online]. Available: https://datatracker.ietf.org/wg/detnet/about/
[28] C. Von Arnim, M. Dragan, F. Frick, A. Lechler, O. Riedel, and A. Verl, “TSN-based Converged Industrial Networks: Evolutionary Steps and Migration Paths,” in *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Vienna, Austria: IEEE, Sep. 2020, pp. 294–301. doi: 10.1109/ETFA46521.2020.9212057.
[29] E. Casalicchio and S. Iannucci, “The state-of-the-art in container technologies: Application, orchestration and security,” *Concurr. Comput. Pract. Exp.*, vol. 32, no. 17, p. e5668, Sep. 2020, doi: 10.1002/cpe.5668.
[30] M. M. Strljic, D. Brovkina, T. Korb, O. Riedel, and A. Lechler, “Platform architecture concept for the composition of collective cloud manufacturing,” in *2018 25th International Conference on Mechatronics and Machine Vision in Practice (M2VIP)*, Stuttgart, Germany: IEEE, Nov. 2018, pp. 1–6. doi: 10.1109/M2VIP.2018.8600839.
[31] Z. N. J. Peterson, M. Gondree, and R. Beverly, “A position paper on data sovereignty: the importance of geolocating data in the cloud,” in *Proceedings of the 3rd USENIX conference on Hot topics in cloud computing*, Portland OR, 2011.

[32] BMWi, "GAIA-X - the European project kicks off the next phase," GAIA-X - the European project kicks off the next phase. Accessed: Jul. 31, 2020. [Online]. Available: https://www.bmwi.de/Redaktion/EN/Publikationen/gaia-x-the-european-project-kicks-of-the-next-phase.html

[33] Gaia-X European Association for Data and Cloud AISBL, "GXFS and the XFSC Toolbox," GXFS.eu. Accessed: Sep. 25, 2024. [Online]. Available: https://www.gxfs.eu/set-of-services/

[34] Gaia-X European Association for Data and Cloud, "Gaia-X Architecture Document - 24.04 Release." Gaia-X European Association for Data and Cloud AISBL, Apr. 2024. Accessed: Aug. 16, 2024. [Online]. Available: https://docs.gaia-x.eu/technical-committee/architecture-document/24.04/

[35] Gaia-X, "Gaia-X Digital Clearing House." Accessed: Oct. 07, 2024. [Online]. Available: https://gaia-x.eu/gxdch/

[36] Gaia-X European Association for Data and Cloud AISBL, "xfsc · GitLab," GitLab. Accessed: Sep. 25, 2024. [Online]. Available: https://gitlab.eclipse.org/eclipse/xfsc

[37] Gaia-X European Association for Data and Cloud AISBL, "Gaia-X Trust Framework - 22.10 Release," Gaia-X Trust Framework - 22.10 Release. Accessed: Sep. 18, 2024. [Online]. Available: https://docs.gaia-x.eu/policy-rules-committee/trust-framework/22.10/

[38] Gaia-X European Association for Data and Cloud AISBL, "Gaia-X secure and trustworthy ecosystems with Self Sovereign Identity: Developing a Decentralised, User-Centric, and Secure Cloud Ecosystem." eco – Association of the Internet Industry (eco – Verband der Internetwirtschaft e.V.), 2022. Accessed: Sep. 11, 2024. [Online]. Available: https://gaia-x.eu/wp-content/uploads/2022/06/SSI_White_Paper_Design_Final_EN.pdf

[39] Gaia-X European Association for Data and Cloud AISBL, "Software Requirements Specification for Gaia-X Federation Services Compliance Onboarding & Accreditation Workflows." eco – Association of the Internet Industry (eco – Verband der Internetwirtschaft e.V.), 2021. Accessed: Sep. 11, 2024. [Online]. Available: https://www.gxfs.eu/onboarding-accreditation-workflows/

[40] Gaia-X European Association for Data and Cloud AISBL, "GXDCH - Gaia-X: A Federated Secure Data Infrastructure," GXDCH - Gaia-X: A Federated Secure Data Infrastructure. Accessed: Sep. 25, 2024. [Online]. Available: https://gaia-x.eu/gxdch/

[41] S. Ettl and J. Diemer, "EDC." [Online]. Available: https://catena-x.net/de/angebote-standards/edc-die-zentrale-komponente-fuer-die-navigation

[42] K. Gleich, S. Behrendt, M. Hörger, M. Benfer, and G. Lanza, "An Asset Administration Shell-Based Digital Product Passport as a Gaia-X Service," presented at the 10th CIRP Conference on Assembly Technology and Systems, 2024.

[43] R. Silbernagel, C. Wagner, A. Albers, T.-U. Trapp, and G. Lanza, "Data-Based Supply Chain Collaboration – Improving Product Quality in Global Production Networks by Sharing Information," *Procedia CIRP*, vol. 104, pp. 470–475, 2021, doi: 10.1016/j.procir.2021.11.079.

[44] G. Lanza, E. Moser, J. Stoll, and B. Haefner, "Learning Factory on Global Production," *Procedia CIRP*, vol. 32, pp. 120–125, 2015, doi: 10.1016/j.procir.2015.02.081.

[45] P. Gartner, M. Benfer, A. Kuhnle, and G. Lanza, "Potentials of Traceability Systems - a Cross-Industry Perspective," *Procedia CIRP*, vol. 104, pp. 987–992, 2021, doi: 10.1016/j.procir.2021.11.166.

[46] A. Bott, B. Liu, A. Puchta, and J. Fleischer, "Machine Learning-Driven RUL Prediction and Uncertainty Quantification for Ball Screw Drives in a Cloud-Ready Maintenance Framework," *J. Mach. Eng.*, vol. 24, no. 3, p. 2024.

[47] E. Karimi, F. A. Schindler, and V. Schulze, "On-Machine Flank Wear Analysis in Cutting Tools Using Artificial Intelligence," presented at the WGP 2024, Chemnitz, Germany, Accepted, to appear.
[48] R. Munaro, A. Attanasio, and A. Del Prete, "Tool Wear Monitoring with Artificial Intelligence Methods: A Review," *J. Manuf. Mater. Process.*, vol. 7, no. 4, Art. no. 129, Jul. 2023, doi: 10.3390/jmmp7040129.
[49] V. Onuseit *et al.*, "Enhancing stability in thin-walled part production with L-DED wire using an adaptive controller," *Procedia CIRP*, vol. 124, pp. 305–308, 2024, doi: 10.1016/j.procir.2024.08.123.
[50] D. Becker *et al.*, "Influence of a closed-loop controlled laser metal wire deposition process of S Al 5356 on the quality of manufactured parts before and after subsequent machining," *Prod. Eng.*, vol. 15, no. 3–4, pp. 489–507, Jun. 2021, doi: 10.1007/s11740-021-01030-w.
[51] M. Buser, M. Hofele, T. Menold, H. Riegel, and A. Michalowski, "Enhanced Scaling of Material Removal Rate with High Surface Quality Through Combined Laser Processes," *Lasers Manuf. Mater. Process.*, vol. 11, no. 2, pp. 218–232, Jun. 2024, doi: 10.1007/s40516-023-00234-5.
[52] M. Buser, T. Menold, and A. Michalowski, "Closed-loop Laser Volume Ablation with Adaptive Scan Paths," *Lasers Manuf. Mater. Process.*, vol. 11, no. 3, pp. 649–660, Sep. 2024, doi: 10.1007/s40516-024-00264-7.
[53] T. Menold, V. Onuseit, M. Buser, M. Haas, N. Bär, and A. Michalowski, "Laser material processing optimization using bayesian optimization: a generic tool," *Light Adv. Manuf.*, vol. 5, no. 3, p. 1, 2024, doi: 10.37188/lam.2024.032.
[54] S. D. Lowe, *Hyperconverged infrastructure for dummies*. John WIley & Sons, 2016.
[55] Gartner, "Definition of Multitenancy - IT Glossary." [Online]. Available: https://www.gartner.com/en/information-technology/glossary/multitenancy
[56] H. AlJahdali, A. Albatli, P. Garraghan, P. Townend, L. Lau, and J. Xu, "Multi-tenancy in Cloud Computing," in *2014 IEEE 8th International Symposium on Service Oriented System Engineering*, Oxford, United Kingdom: IEEE, Apr. 2014, pp. 344–351. doi: 10.1109/SOSE.2014.50.

About the InnovationCampus Mobility of the Future

The mobility and production of the future are sustainable, efficient and come from Baden-Württemberg. This requires new ground-breaking technologies - from innovative vehicle drives to adaptable production processes. The aim of the InnovationCampus Mobility of the Future (ICM), which is funded by the state of Baden-Württemberg, is to shape this change.

At the ICM, the University of Stuttgart and the Karlsruhe Institute of Technology (KIT) are pooling their expertise in research and innovation to develop new technologies quickly and flexibly, test new approaches and create the basis for leap innovations. With over 300 researchers in more than 170 research projects and 60 research institutes, the ICM is one of the largest initiatives on the mobility and production of the future in Germany.

One of the ICM's three research fields deals with the software and architectures of modern and future mobility systems as well as the production systems necessary for their manufacture. The concept of ecosystems for manufacturing is of crucial importance in this context.

Acknowledgements

We would like to thank the Baden-Württemberg Ministry of Science, Research and the Arts for its financial support of the InnovationCampus Mobility of the Future.

We are grateful for the efforts of the ICM team, who have made our project possible and provided ongoing support.