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EuProGigant – A Concept Towards an Industrial System Architecture for Data-Driven Production Systems

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Abstract

Today, most IoT solutions for the production ecosystem stem from trends that first established at the consumer market. Although these concepts have been adapted well in the industrial environment, it led to fragmented solutions that require complex interfaces. With the recent introduction of GAIA-X, it becomes possible to develop platform independent IoT solutions tailored to the needs of manufacturers. Until now, GAIA-X is only a concept proposed by governments and economic advisory boards. This paper extends the concept into an industrial system architecture that enables the reliable exchange of information among the supply chain of a highly distributed production network.

Keywords: System Architecture; Conceptional Design; GAIA-X; Smart Factory; Industrial Internet of Things

1. Introduction

The predominant paradigms of highly automated serial production and global supply chains with low stock levels, as well as maximized productivity through specialization result in a flexibility deficit in the industry. Prevalent mechanisms to compensate a sometimes very sudden disappearance of market demand for established products [10], supply bottlenecks [9] and employee absences are unable to keep economic losses in check or even avert bankruptcy. These vulnerabilities are further aggravated by the ongoing increase in individualization of consumer goods. To counter said weaknesses of state-of-the-art production systems, the endeavour of creating an industrial data ecosystem in the sense of GAIA-X by presenting a manufacturing oriented blueprint for a node according to the GAIA-X infrastructure [5] is introduced. It shall mark the starting point and describe the first integral part of EuProGigant which is designated to be digitally networked across locations in order to enable resilient, data-driven and sustainable value creation. For this effort to not only remain a pure concept, a consortium of scientific institutions and companies active in the areas of mechanical and software engineering, data engineering and analysis and such where manufacturing represents the main process of value generation work on the realization of the common vision, an industrial ecosystem with the two properties of

1. self-orchestration, i.e. independent and autonomous organization of participants, data and services, and
2. calamity reduction, i.e. the ability to mitigate threats from crisis situations.

Hence, the proposed architecture represents the first building block of EuProGigant, for the latter to be able to master the complexity given by market changes, high variety of product variants and interdependencies between value-adding stages.

In section 2 the state of the art of value generation through usage of data in current production ecosystems is reflected and current research to enable data-driven value generation in a manufacturing environment is addressed, as well as selected aspects from the GAIA-X architecture. With all that in mind the EuProGigant concept is outlined in section 3 starting with the identification of the key drivers that directly lead to the subsequent description of the derived blueprint architecture. Finally a concept study is used to further exemplify the solution in section 4.

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2. Data-Driven Value Generation

2.1. Infrastructure Determines Data

The typical structure of IT systems in industrial enterprises cannot be addressed as a single architectural construct but rather as a heterogeneous accumulation of legacy components. The latter has grown from the continuous development of expanding the application of automation and information technologies [19]. Intra-corporate architectures can therefore be described by using models generated along the way, whereas the automation pyramid is very common. However, there is no commonly used variant and the various versions promote hierarchisations from three to seven levels [15]. This only reflects the aspiration to express the significant change of information content (i.e. upwards abstraction) when transitioning between levels through separation on the one hand and that those levels simultaneously are deeply intertwined in their purposes through aggregation on the other hand. The classic vertical hierarchical structure suffices reality only partially nowadays and models including the aspect of multidimensionality like reference architecture model industry 4.0 (RAMI4.0) [7] and its more user-centered derivate the asset administration shell [14] have been proposed. The industry seems to be currently transitioning by breaking vertical hierarchies and simultaneously integrating horizontally through enhancing connectivity with the user base and original equipment manufacturers (OEMs). An enterprise information architecture (EIA) will only cover certain areas of said models, e.g. by focusing on vertical integration. How widely the EIA extends along a dimension and if multi-dimensional aspects are implemented (e.g. orthogonal integration) really indicates how big the potential to generate additional value through data utilization is. Kaufmann and Servatius [12] describe enterprise IT-architectures in four different evolutionary stages, i.e. IT-architecture 1.0 to 4.0, where the lowest number indicates a mostly heterogeneous landscape of software and databases fulfilling different purposes and following different paradigms. Said environment lacks interfaces and compatibility leading to potentially yielding data to lie fallow. The IT-architecture 4.0 of course is the concept to overcome said drawbacks not only inside an enterprise but beyond its borders.

2.2. Data Determines Value

The rather vaguely outlined term big data (cf. [4, 19]) is usually used as a description for a set of data so general in nature that it is non-describable. Going by this, the definition fits the raw state of potentially valuable data derivable from processes inside and around an industrial enterprise. Focusing on potentially valuable information an industrial data ecosystem may yield is immanent to a data-driven approach in value generation. Manufacturing represents the core value generating process in that context.

Consequently raw data created alongside manufacturing processes have to carry value, a fact to be emphasised by the term industrial data. To characterize the term the distinction between the manufacturing internet of things (MIoT) and consumer internet of things (CIoT) made by Dai et al. [3] shall be used. So industrial data is generated within a MIoT which gives it the following attributes

- of being monitored rather immediate to the process,
- with a high data rate,
- in real time,
- with poor contextualisation and
- is reused.

The latter two attributes take the precondition of a brownfield environment [6] into account, where sensors are abundant. That is, because in combination with programmable logical controllers (PLCs) and actors, sensors act as part of machine control and continuously produce information. This data will be directly utilized inside the control loop without passing it on. Such are the data sources most immediate to the process and when made available for reuse provide the basis for optimizing value generation processes.

Arguably, higher level information, i.e. data descending from enterprise resource planning (ERP) or a manufacturing execution system (MES) albeit already being abstracted, is very promising regarding data-driven value generation. It is more fitting to data descending from the CIoT which makes technologies coming from the consumer sector easier applicable and scaling effects are more prominent. To be concise, data available on higher levels of the automation pyramid is more fitting to the term of smart data, i.e. data with elevated contextualisation to be input-ready for decision making [8] in opposition to industrial data.

2.3. Enabling Value Generation

Noteworthy hindrances for data-driven value generation independent of the kind of data are legacy and proprietary systems [6], data silos [19], the lack [18] or even the abundance [11] of communication protocols and interfaces, as well as poor or no contextualisation [2] of information from the outset. Whilst the origin of said hindrances lies in historically grown infrastructure, an architecture to be fully integrated with the internet of things (IoT) and artificial intelligence (AI) has yet to be found and Kaufmann and Servatius [12] further exemplify that in an IT-architecture 4.0 there will exist parallel structures embodied by innovation ecosystems decoupled from the core processes keeping up the value chain. In this regard the international data space (IDS) association has developed a reference architecture that builds up in the horizontal plane in reference to RAMI4.0 and parallels the broader GAIA-X initiative [5].

It describes the linkage between industry sectors and introduces new roles, e.g. the data broker that orchestrates data flow throughout architecture levels. In the IDS data will be held available in a virtual data space with the data producing party as data owner [16]. Innovation ecosystems seem not fit to touch value generation in the first run, but their establishment may come around and have a disruptive effect on how industrial enterprises generate revenue, whilst there is already a shift in the industry to take on the provision of services in addition to their products [17]. Both GAIA-X and the IDS rely on standardization of interfaces, semantics and terms of use in accordance with European law regarding data protection (e.g. GDPR), where the former sets the general conditions for our research.

2.4. The Innovation Ecosystem GAIA-X

GAIA-X is an initiative with the aim to build the infrastructure for a European data ecosystem. The current state of the GAIA-X technical architecture is outlined in a publication of the German Federal Ministry for Economic Affairs and Energy [5]. The significant aspects of GAIA-X when considering manufacturing will be addressed briefly in this section.

In the terminology of GAIA-X an *Asset* can be a *Service*, a *Service Instance*, *Data Asset* or a *Node*. The latter is a generic computational resource that can range from basic hardware (e.g. sensors) to sophisticated infrastructure (e.g. virtual machines, containers). This generic definition implies Nodes to be applicable on a rather high level, i.e. by representing a whole company's IT infrastructure and providing punctual entry points to or from GAIA-X. Whilst said utilization of Nodes is to be expected as a first step for companies to participate in GAIA-X, the fact that Nodes themselves can hold Nodes and the possible representation of basic hardware through Nodes is of special interest for industrial applications. With reference to the conditions given in a manufacturing environment by infrastructure (cf. 2.1) and the situation of valuable data sources (cf. 2.2) Nodes will mostly represent and make accessible basic hardware (sensors, PLCs). Therefore, Nodes can be used to, directly or via other Nodes, enable target-oriented communication between very low level components, e.g. along a value chain, and superordinate control and monitoring. Within such a data ecosystem, full control over single Assets can be guaranteed, meeting many businesses' needs for strictly restricting access but simultaneously openly sharing data with strategic partners. This is a significant requirement for future resilient production systems and self-orchestration. Most data is not available as Data Assets, i.e. existing data sets, on the field level. Thus, Nodes in said context will heavily focus on hosting Services. GAIA-X Services are intended as cloud offerings but are not designated to be the counterpart of common as-a-service concepts. It is understood that the data ecosystem provided will enable now isolated Data Assets and Services to be made available as cloud offerings and furthermore, generate complex Service networks by intertwining them with other Services.

In the GAIA-X ecosystem Participants and Assets have to be identified and their characteristics have to be expressed. The architecture stipulates the aforementioned to be self-describing in a machine-readable way. Thus a framework is created that, itself does not provide, but enables

- the discovery of Assets in a catalogue, i.e. a basic search engine,
- *Tool*-assisted evaluation, i.e. the selection and integration of Service Instances and Data Assets,
- continuous trust monitoring and validation of *Usage-Control Policies* (GAIA-X: *Enforcement*) and
- the *Negotiation* of contractual terms concerning Assets and *Participants*.

Interrelations between Assets are expressed using the *Self-Description Graph*, i.e. subject-property-value relationships, leaning heavily on the resource description framework (RDF).

The Self-Description of an Asset comprises metadata, a unique identifier, proof info and a testimonial i.e. a descriptor section. The latter in turn can contain multiple claims. Using the example provided in the document describing the technical architecture a Node can claim to be certified according to a standard, like ISO 27001. The same way a Node could make other claims that describe technical properties of the Data Asset or Service it provides. The contextualisation of Assets, i.e. the enrichment of information by adding machine-readable technical specifications, is the main aspect of the GAIA-X architecture to be beneficial in an industrial setting. The future requirement for the GAIA-X Self-Description is that it must be compatible with the identifier of the asset administration shell in the RAMI4.0 Information Model of the Plattform Industrie 4.0. This ensures that future digital twins of entities in the value network can be used, for example, in interaction with GAIA-X-compatible digital services. A common standard is the International Registration Data Identifier (IRDI) according to ISO/IEC 11179-6.

3. The EuProGigant Concept

3.1. Architectural drivers

Derived from the status quo regarding data-driven value generation and the possibilities offered by the GAIA-X technical architecture, EuProGigant is an implementation of a relevant subset of principles tailored to the manufacturing domain. The blueprint architecture is initially focused on a building block, i.e. a partial representation of the greater GAIA-X concept, in the form of a manufacturing oriented node.

The blueprint architecture of the EuProGigant node will be illustrated in 3.2. Beforehand a fundamental statement is made that EuProGigant is not primarily designated to set standards for coming IT-architectures but much more as an enabler for enhancing existing production environments through including legacy systems, i.e. the integration of components in a brownfield environment. Furthermore, by following a bottom-up approach in establishing the EuProGigant data ecosystem concrete benefits for users and sufficient incentives for service providers shall be created. That is, by implementing the first building blocks of the infrastructure on the field level at the very bottom of the automation pyramid still being able to integrate with GAIA-X. The reasoning is that predefined and rigid structural concepts, like the aforementioned architectures for industry 4.0, are dominated by hierarchisation, classification and generalisation, thus not fit to represent the intertwined assets in a data ecosystem that could rather be described as fractal, although they may be useful when establishing a greenfield environment.

In order to focus on the main requirements for the Node's blueprint architecture the key drivers have to be determined. A method for evaluating software architecture requirements described by Knodel and Naab [13] has been used to derive the

Table 1. Architectural drivers for a GAIA-X conform node on an edge device in the manufacturing environment

Driver	
Assets are self-describing	Integration of legacy components
Quality Aspect	
compatibility ▹*co-existence* ▹*interoperability* usability ▹*appropriateness recognizability*	compatibility ▹*interoperability* maintainability ▹*reusability* portability ▹*adaptability*
Environment	
• On the field level data and services hosted on nodes are the dominant assets. • Mainly basic hardware on the edge (e.g. sensors, PLCs, edge computers) have to be represented as a Service or a Data Asset hosted on a Node whilst virtual machines and public cloud instances cannot be excluded. • Each node hosts one or multiple services. • The majority of services concerns the provision of data streams. • Data is abundant but data assets are scarce. • Data may already be accessible but contextualisation is weak.	• Production machines are relatively long-lasting which leads to an almost exclusive brownfield environment. • Most components on the edge cannot host Nodes themselves, thus devices hosting Nodes (e.g. edge computers) have to bundle multiple basic hardware components on a sub-GAIA-X level. • The better part of sensors acts inside a control loop. • Machines and corresponding devices can be very diverse because of the diversity of underlying processes. • Edge data storage is severely limited in comparison to cloud data storages.
Stimulus	
A user needs to access an asset (e.g. a service for data provisioning).	A physical component (e.g. a sensor) is to be made available as a service.
Response	
• A cryptographically verified (*Trust*) *Identity* grants access to the ecosystem. • Assets are clearly identifiable and separable, thus can be easily found in the federated catalogue. • The data to be queried is contextualized enough to be interpretable, i.e. information about the origin of the data and its quality is accessible. • Data can be synchronized and harmonized.	• Nodes are flexibly designed to either represent a single data source or a system of the former. • Nodes meet the upwards requirements of GAIA-X whilst the interfacing with physical components downwards remains outside of the ecosystem. • New Nodes and components within a Node are registered via GAIA-X and undergo access control management to ensure sufficient self-description.

nodes specifications. The two main drivers, the relevant environment, a stimulus (i.e. an event to be handled) and the desired response have been identified and are listed in table 1. In analogy to Antonino et al. [1] the standard ISO/IEC 25010 has been used to describe quality aspects.

3.2. Blueprint Architecture

Based on the GAIA-X concepts of Nodes and Self-Description which can be used very versatilely, as described in section 2.4, a blueprint architecture to bridge the gap between the given environment with the associated architectural drivers, as listed in table 1, and the GAIA-X ecosystem can be derived. For this purpose EuProGigant extends the GAIA-X Node functionality. A general approach was chosen to ensure sufficient Node flexibility for manufacturing related applications. Figure 1 provides an overview of the blueprint architecture.

In order to provide sufficient distinction, the abbreviations for components outside the GAIA-X environment (that means non-compliance), are defined as

- *non-compliant asset (nca)* considering assets and
- *non-compliant self-description (ncsd)* considering self-description.

Beyond that abbreviations for components whose conformity is pending are defined as

- *indefinite asset (ia)* considering assets and
- *indefinite self-description (isd)* considering self-description.

The aforementioned will be used in the following, whereas terms with a capital initial letter (e.g. Node, Asset) are furthermore used for GAIA-X compliant components.

I/O Services: In the given context flexibility refers to an architecture that can be implemented at any point in a network. Thus, I/O interfaces in the EuProGigant architecture are not mere interfaces but Services or sets of Services responsible for

- authentication,
- authorization and
- de-/serialization of different formats.

Due to the variety of protocols currently in use in an industry 4.0 environment, it is necessary to create a wide variety of Services. For example, it is possible that the input is done via OPC-UA, but the output must be done according to MQTT. Therefore, multiple I/O services have to be provided covering different communication protocols, even if it makes sense to create a single de-/serialization service for each protocol. An internal data transport protocol for Nodes has not yet been defined in course of the GAIA-X architecture. It is evident to use a uniform internal protocol, likely similar to Remote Procedure Call (RPC). Such an internal protocol regarded as predetermined and is therefore not discussed in further detail.

Self-Description mapping Service: To facilitate data flow Self-Descriptions and ncsd have to be aligned. An assessment is made whether an ia that states a request, can provide a Self-Description or if it is a nca whose ncsd has to be extended, altered or added as whole using an existing repository. In the former case, the description can be retrieved directly from the Self-

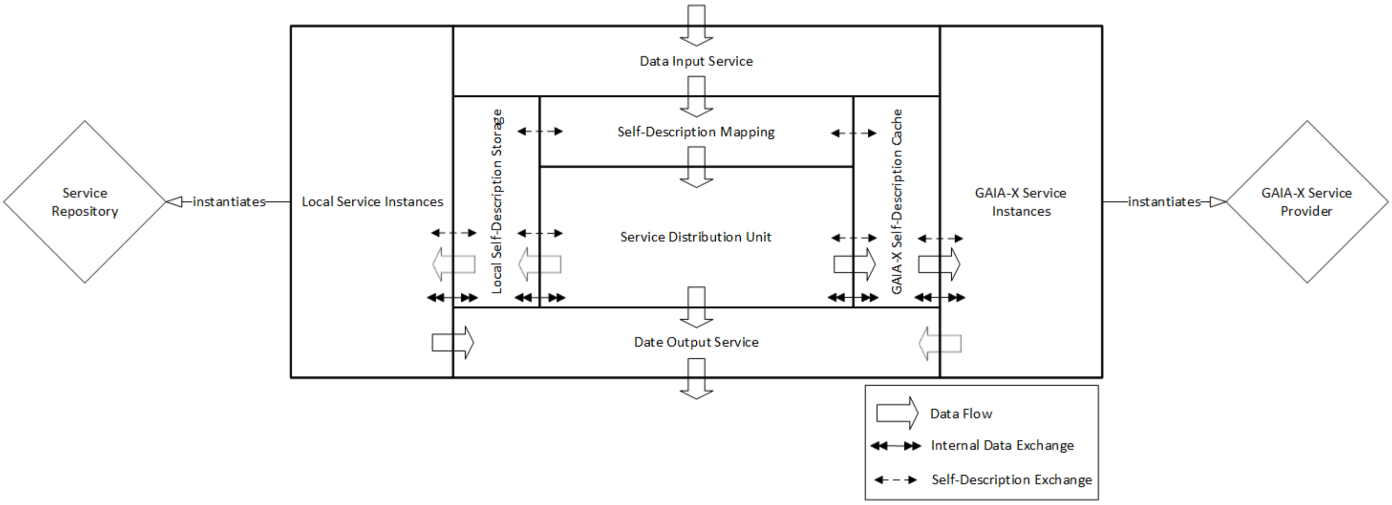

Fig. 1. Architecture overview

Description Storage and data flow between Services is permitted. When a compliant description is absent but a local ncsd is available, the Node establishes GAIA-X conformance, i.e. Self-Description and links the latter to the request. The GAIA-X Self-Description Storage and the local storage of ncsds are used to cache descriptions of Nodes, machines, sensors, etc. on the Node so that this data can be semantically linked with incoming data in order to store or pass on enriched data to enable subsequent processing.

Service distribution unit (SDU): The SDU is a key service of the blueprint. On a Node Services stemming from the GAIA-X ecosystem as well as local services can be used and have to be differentiated. In the simplest case, a request is made that has already been expected from another Service. In that case the SDU passes on the request directly. In all other cases the request has to be analyzed first. There are several possible scenarios where local resource availability is included additionally to Self-Description:

1. The request itself indicates which service it wants to consume.
2. It is a regularly occurring, thus registered request and the service to be consumed is known.
3. It is still unknown how to proceed with the request.
4. The request cannot be handled due to a lack of resources.

GAIA-X stipulates Self-Description to be used for tool-assisted selection and integration of Services. The SDU represents such a tool, whilst simultaneously supporting local services. To select the right Services, it is important to analyze the GAIA-X Self-Description Graphs (cf. section 2.4) of the Self-Descriptions. Following claims and information the graphs provide a proper service can be selected. Furthermore, with both the knowledge of Service and data properties an estimation on computing resources can be made. If the resources are not sufficient or the requested service can not be made available, the SDU forwards the request to another Node. The SDU is also responsible for managing the communication between local and GAIA-X Services. Given the aforementioned, it acts as a broker by passing data to the right consumer. This is important since computing resources may be limited where the Node is hosted and the broker may have to redirect the request to another Node, e.g. when computing resources are not sufficient.

Before data is consumed by any Service Instance it always has to be ensured that not only the Service accountable for offering the data exhibits GAIA-X conformity, but also that a proper Self-Description of the underlying Data Asset or Service is linked to it. The Service Instances in this blueprint are viewed as black boxes, on the one hand as a result of missing definitions within the GAIA-X architecture, on the other hand going by this local implementations can be adapted to company specific demands. For example, on edge devices micro service architectures with containers are rising in usage. It is important that Services either report back to the SDU for further processing or formulate an output.

In the last stage of data flow inside the Node, the data passes through the I/O interfaces once again and is serialized according to the target protocol. The target for outgoing data or requests can be a requesting system or another Node. In case that the input has not come from a GAIA-X certified device, the Self-Description mapping Service has established the Self-Description for the respective Asset. Every output again is an input to another Node or will be fed back to the same Node as new input.

4. Concept Study

The EuProGigant concept presented will be implemented in the context of a joint case study in the demonstrator factories Pilot Factory Industry 4.0 TU Wien and data-based production platform PTW TU Darmstadt. The aim of the case study is to demonstrate possible cross-company and cross-location networking of value chains to create a communicating ecosystem with increased speed of value-adding. Therefore, the production systems are networked via edge computing units, institute

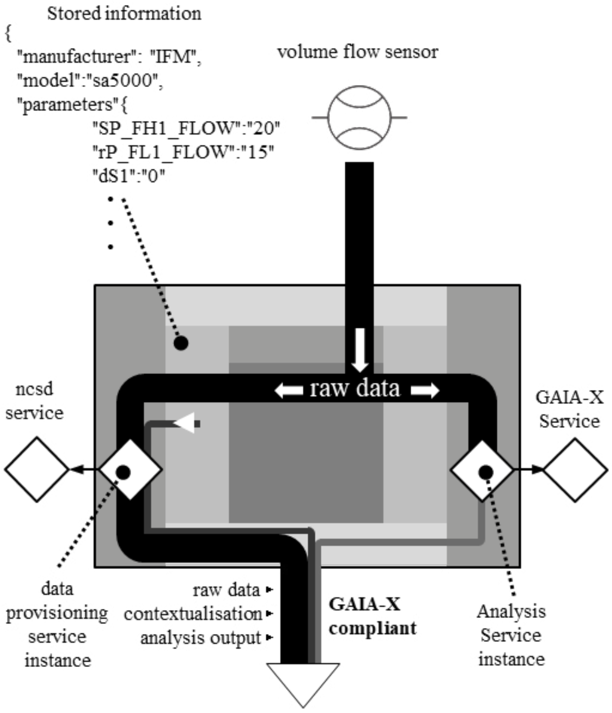

Fig. 2. Implementation of the EuProGigant Node for provisioning raw data and analysis results for a volume flow sensor

servers and public cloud services using GAIA-X components as mentioned in section 2.4.

Whilst the manufacturing centered EuProGigant Node is generalised in architecture to be scalable, i.e. it can be used to represent basic hardware components or an EIA. In the very first concept study, the Node will be implemented to host Services that themselves again provide data streams descending from very basic hardware components in the field. To be precise, an edge device will be used to host the Node described in section 3.2. Said Node in turn will host Services that contextualize (Data) Assets not only in terms of GAIA-X but will also enrich data, as shown in figure 2. The aim is to not only offer information harvested and made available on the very edge of GAIA-X but also to preselect valuable information and enrich data to add value, i.e. by traversing from big to smart data at the earliest possible stage.

5. Outlook

In the EuProGigant project, the GAIA-X technical architecture will be transferred to the industrial ecosystem and implemented using the blueprint architecture presented here, with the superior goal to add data-driven value generation to the value chain. The implementation is based on edge systems on virtual machines (OnPremise/Server) and in the cloud. The Node implementation in figure 2 is one of the most basic applications of the blueprint. By adding Assets, i.e. gradually embedding more sensory devices, Services and ncas, the network interconnecting the two locations will emulate a real industrial environment, thus allowing for the incorporation of still to come GAIA-X architectural elements. This will create a domain-specific demonstrator for GAIA-X for the manufacturing industry in Europe.

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