Cloud-based Plug and Work architecture of the IIC Testbed Smart Factory Web

1st Sascha Heymann
Fraunhofer IOSB-INA
Lemgo, Germany
sascha.heymann@iosb-ina.fraunhofer.de

2nd Ljiljana Stojanovic
Fraunhofer IOSB
Karlsruhe, Germany
ljiljana.stojanovic@iosb.fraunhofer.de

3rd Kym Watson
Fraunhofer IOSB
Karlsruhe, Germany
kym.watson@iosb.fraunhofer.de

4th Seungwook Nam
KETI
Pangyo, Korea
skietree23@gmail.com

5th Byunghun Song
KETI
Pangyo, Korea
bhsong@gmail.com

6th Hans Gschossmann
Microsoft
München, Germany
johanng@microsoft.com

7th Sebastian Schriegel
Fraunhofer IOSB-INA
Lemgo, Germany
sebastian.schriegel@iosb-ina.fraunhofer.de

8th Jürgen Jasperneite
Fraunhofer IOSB-INA
Lemgo, Germany
juergen.jasperneite@iosb-ina.fraunhofer.de

***Abstract*—The Smart Factory Web (SFW) is a platform that connects Smart Factories over a network to enable flexible sharing and management of resources, assets and inventory to maximize production and efficiency. In order to become part of the Smart Factory Web, network participants describe not only their products, but also the factory capabilities to order to improve factory-to-factory collaboration. A Smart Factory Web Portal (SFWP) enables secure data and service integration in cross-site application scenarios as well as 'plug & work' functions for devices, machines, and data analytics software by applying industrial standards, Open Platform Communications Unified Architecture (OPC UA), and Automation Markup Language (AutomationML or AML for short).**

OPC UA serves as a comprehensive and secure communication protocol from the machine level into the cloud. A Cloud Coupler on the shop floor publishes the availability of a factory and selected process data in the SFWP. Customers or even smart machines can use this information to make decisions for placing an order and track their orders in real time. In order to simplify the setup of the connection to the cloud and minimize the commissioning time the cloud coupler also aggregates all OPC UA servers on devices in the factory into a single OPC UA aggregated server address space.

In this paper an architecture is proposed which uses cloud coupler and plug and work techniques to make a new or retrofit factory available in a SFW to share capability information towards a new marketplace for manufacturing. It is shown that the integration efforts are decreased but also the use of standards reduces the effort to define interfaces.

***Index Terms*—cloud edge, OPC UA, AutomationML, IIC, Testbed, Smart Factory**

I. Introduction

Industry 4.0 is a broad umbrella term that is used to describe the latest trends in the industrial sector where physical manufacturing plants and software components are integrated together resulting in more efficient management of manufacturing resources, increase in revenues and decrease in production costs. Factories which deploy the trends in Industry 4.0 are called 'Smart Factories'. They are more intelligent than traditional factories in that they make use of sensor technologies, the internet and the cloud to not only increase automation in the manufacturing process, but also to manage the resources intelligently to maximize production by optimization based on the dynamic conditions in a service oriented network of connected systems [1].

These new features present new challenges to be dealt with during the design and operation of such smart factories. The requirements of increased resource utilization and increased level of dynamic reconfiguration of production systems have to be considered during design time to achieve flexibility in the types of products they manufacture. This means that engineers from various engineering disciplines have to come together to design all aspects of the manufacturing system to fulfill these requirements. There needs to be a way to integrate these engineering activities which use different tool chains. AutomationML (AML) has been introduced to provide a data exchange format between the tools used by engineers coming from different engineering disciplines during design time [2]. From the technological point of view, Industrial Internet of Things (IIoT) is the next wave of innovation impacting the way the world connects and optimizes machines. The IIoT, through the use of sensors, advanced analytics, and intelligent decision making, will profoundly transform the way field assets (e.g., machines or robots) connect and communicate with enterprise applications [3]. With the applications and IIoT services for manufacturing, the fourth stage of industrialization (referred to as Industry 4.0) is approaching [4]. Sensors, machines, and Information Technology (IT) systems will be able to interact with one another using industrial internet technology. Further, they will be able to

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analyze data to predict failures, configure themselves, and adapt to changes.

IT advances enable more flexible and responsive manufacturing and paradigm shifts on the shop floor. This is not a new concept. Leading automation and software suppliers have been working to address this demand for decades. However, business practices until now have not always been successful due to the vendors dependency on the underlying production infrastructure [5]. The high variability of systems and equipment in a factory, by line and even by manufacturing process, combined with a mix of new equipment and legacy investments, leads to challenges in interoperability and flexibility.

According to a study commissioned by Forrester Consulting [6], 67% of surveyed manufactures are concerned with lack of standard interfaces and interoperability challenges. Another survey conducted by the World Economic Forum [7] on the perceived barriers to the adoption of the IIoT revealed that almost two-thirds of respondents agree with the widely-held view that security and interoperability are the two biggest hurdles for IIoT. In response to these concerns, major standard organizations and industry consortia have already started teaming up to address the standardization challenges and to promote open interoperability and the widespread usage of a common architecture. For example, the Industrial Internet Consortium (IIC) [8] was also founded to accelerate the development, adoption, and widespread use of interconnected machines, devices, and intelligent analytics. The IIC members are concerned with creating an ecosystem for interoperability and collaborate via a reference architecture and real-world implementations.

There are still open questions to be answered in terms of the industrial use of IIoT technology. Recently, industrial providers and academic researchers have initiated real-world testbeds to demonstrate how technologies from different organizations can work together and support new innovations. These testbeds for smart production technologies (referred to as experimental factories) are being actively operated with the purpose of establishing interoperability guidelines and applying new IT technologies in existing automated systems. However, there has been no notable attempt to interconnect the experimental factories and allow them to flexibly adapt their production capabilities based on cross-site demands. Because the experimental factories have a great deal of freedom to experiment, they can promptly react to changing requirements from an integration point of view. Thus, the Korea Electronics Technology Institute (KETI) and the Fraunhofer Institute of Optronics, System Technologies and Image Exploitation (IOSB) have launched a joint testbed project called Smart Factory Web (SFW),[1] which links the heterogeneous infrastructures of each experimental factory [9]. Fraunhofer IOSB operates experimental factories in

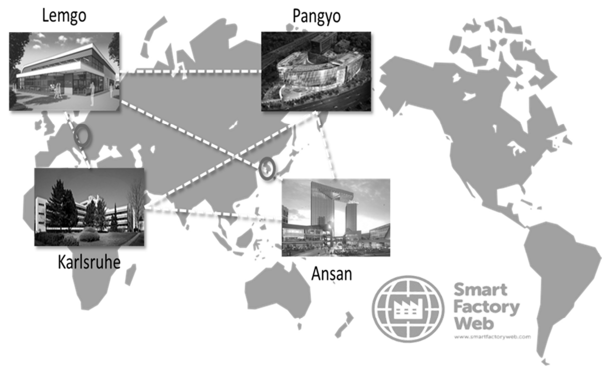

Fig. 1. Smart Factory Web Map.

Karlsruhe and Lemgo, Germany, to demonstrate new concepts related to Industry 4.0 and IIoT. KETI has established two factories for IIoT services in Pangyo and Ansan, Korea in 2017. (See Fig. 1).

The vision of SFW is to network a web of smart factories to improve order fulfillment by aligning capacity across production sites with flexible adaptation of production capabilities and sharing of resources, assets, and inventory. To realize this vision, secure data and service integration has been implemented in cross-site application scenarios as well as 'plug & work' functions for devices, machines, and data analytics software by applying the industrial standards OPC UA [10] and AutomationML [11].

Experts of different domains in the OT and IT realms can test and resolve issues related to factory-to-factory interoperability on the basis of the industrial standards as well as IIoT concepts. Additionally, the adaptability, system engineering and security of cross-site production can be validated between factories.

The paper is structured as follows. Section 2 gives an overview of related work. Section 3 explains the architecture of the SFW. Section 4 shows the implemention and the evaluetion of the architecture. Section 5 concludes the paper.

II. RELATED WORK

A. *Industrie 4.0 Communication based on OPC UA*

Companies from the machine and plant building industry and operators are currently confronted with abstract concepts about Industrie 4.0. These concepts promise high efficiency and flexibility, but there is often a lack of concrete recommendations and specifications for implementation and action. Today, companies use a variety of industrial communication solutions with the associated large effort for integration. Industrie 4.0 communication does not refer to yet another industrial communication solution for real-time data processing and control. It complements the existing solutions and is

[1]The Smart Factory Web was officially approved as an IIC Testbed in September 2016

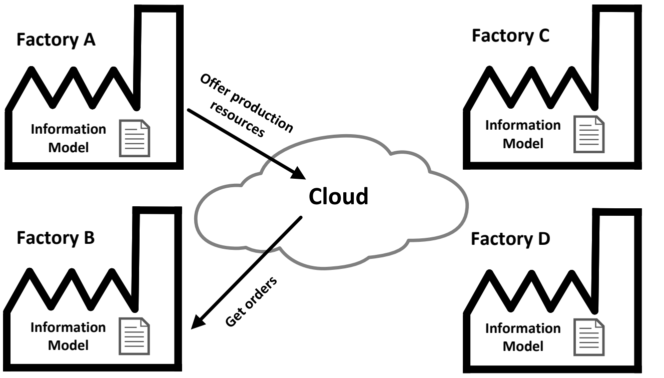

Fig. 2. Factory-to-Factory Communication in the application scenario Order-driven Production

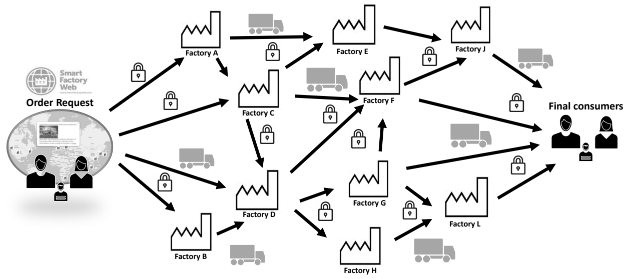

Fig. 3. Supply chain to the consumer with many stakeholders.

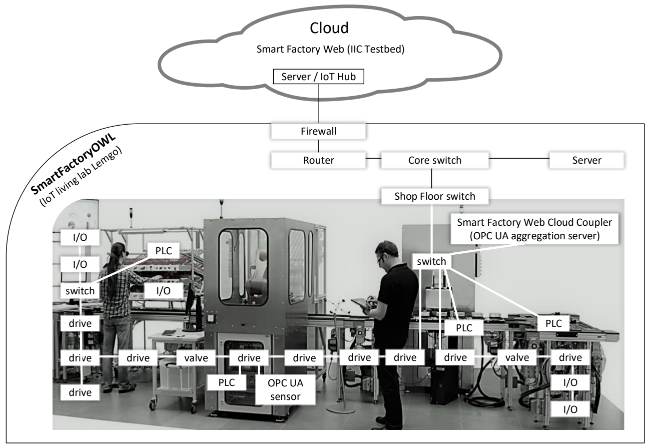

Fig. 4. Modular Production System of SmartFactoryOWL connected to the Smart Factory Web

based on fundamental new concepts, such as service oriented architecture (SOA) and information models for the description of devices and their capabilities [13]. SOA allows components, machines, and systems to be more flexible because they are not configured and programmed for a specific production task, but rather offer their capabilities as services. Component services can be orchestrated into more abstract machine and equipment services. Industrie 4.0 aims to simplify the integration of components, machines and plants and to increase efficiency based on simple connections to condition monitoring and optimization systems. These connections do not depend on existing fieldbus or real-time communication systems. In addition, the use case plug & work allows for a more flexible commissioning and retrofitting of machines, plants and factories. This feature saves time and costs. The open standard Open Platform Communications Unified Architecture (OPC UA) fulfills all requirements for Industrie 4.0 communication. OPC UA is rapidly becoming an established standard in the machine and plant building industry.

In the vision of Industrie 4.0, communication does not end at factory level. The application scenario “Order-Driven Production” of the Plattform Industrie 4.0 depicted in Fig. 2 is based on the interaction of factories in order to adapt production capabilities and capacities to rapidly changing market and order conditions. Fig. 3 shows a supply chain to the consumer with many stakeholders. Today, most of the external communication in the manufacturing industry is done by phone or e-mail. The human factor is often the reason for an incorrect order and is also the reason for a high latency of order requests. A standardized Industrie 4.0 communication allows automated scheduling, distribution and control of orders including all required production steps and production resources. Individual process modules can thus be combined more flexibly than before and their specific capabilities can be exploited. As shown in Fig. 4, Industrie 4.0 communication for this application scenario can use a cloud. [19].

B. Engineering Efforts for Sensor to Cloud communication using OPC UA of SmartFactoryOWL and the IIC Testbed Smart Factory Web

The engineering efforts are evaluated using a modular production system in the SmartFactoryOWL. The production system is connected to the SFWP. Fig. 4 shows the modular production system. PROFINET is used for the real-time communication. The production system is connected via a shop floor switch and a core switch to a server and to a router. Until now, each device has to be manually re-configured, leading to substantial engineering effort. Different engineering tools and web interfaces are in use: PLC and PROFINET engineering, Phoenix Contact PCWorX (device name, IP address, data mapping), shop floor switch web interface, core switch, router/ firewall, cloud portal.
Result: The overall engineering time to add prozessdata from the shopflor to the cloud visualisation (e.g. of a new production station or even a singel Sensor) was estimated at 3 hours based on the actual experiences of the responsible IT Expert in the SmartFactoryOWL. [14]–[17]

C. Automation ML

Standards are use to ensure broad usability and maintainability in production environments. Especially for SMEs, standards are the key for reusability instead of proprietary (company-specific) solutions. Currently, there is no lack of standards, but there are a lot of overlapping standards focusing on different aspects, domains, or applications. Therefore, standards are preferable which fit well together. In the context of automation engineering, AutomationML is an important standard series. The AutomationML data format, developed by AutomationML e.V.[2], standardized in IEC 62714, is an open, neutral, XML-based, and free data exchange format, which enables the transfer of production system engineering data across domains and companies in a heterogeneous engineering tool landscape. AutomationML explicitly supports the cooperation and interoperability with other standards such as PLCOpenXML (for logic and behavior), Collada (for geometry and kinematic), and eCl@ss (for product property descriptions). A proposal for multilingual expressions in AutomationML was recently made [21]. However, there is no tool that offers this functionality. Since support for multiple languages is very important for the SFW, we have developed such a tool. The tool takes as input a multilingual vocabulary in form of an Excel file and user preferences (e.g. which languages to consider) and extends the entities of an AutomationML model with the child attributes that are the labels within the respective language(s).

III. ARCHITECTURE

A. Industrial Internet Consortium Testbed Smart Factory Web

The Smart Factory Web is an approved IIC testbed with two model factories in Germany and two in South Korea as shown in Fig. 1. The model factories of IOSB in Germany are also members of the Labs Network Industrie 4.0 [3] where IOSB can investigate and demonstrate architectural compatibility between IIC's IIRA - RAMI4.0 of Industrie 4.0. The Smart Factory Web testbed makes extensive use of the standards OPC UA and AutomationML which are also recommended standards in Industrie 4.0. IIC has testbeds in a wide range of verticals covering not only manufacturing, but also energy, water, health, agriculture and mobility [4]. Like all IIC testbeds, a primary goal of the Smart Factory Web is to provide feedback in the form of defined deliverables on reference architectures, whitepapers and best practices for usage of IIoT technologies. The Smart Factory Web project is being implemented in four phases up to mid 2019, cf. Fig. 5. The third phase will be completed in June 2018. This paper presents results mainly from Phases 2 and 3. The vision of the Smart Factory Web is to provide the foundation for a manufacturing marketplace as depicted in Fig. 6. Further projects at the enterprise and business level are being planned to advance towards this vision.

[2]https://www.automationml.org
[3]https://lni40.de
[4]http://www.iiconsortium.org/test-beds.html

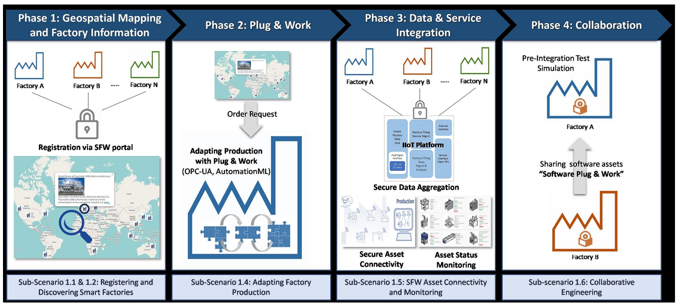

Fig. 5. Phases of Smart Factory Web Project

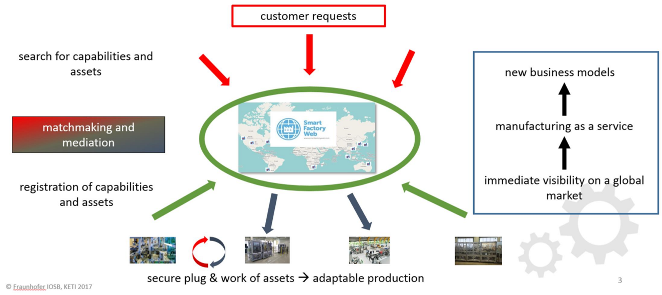

Fig. 6. Smart Factory Web as a manufacturing marketplace

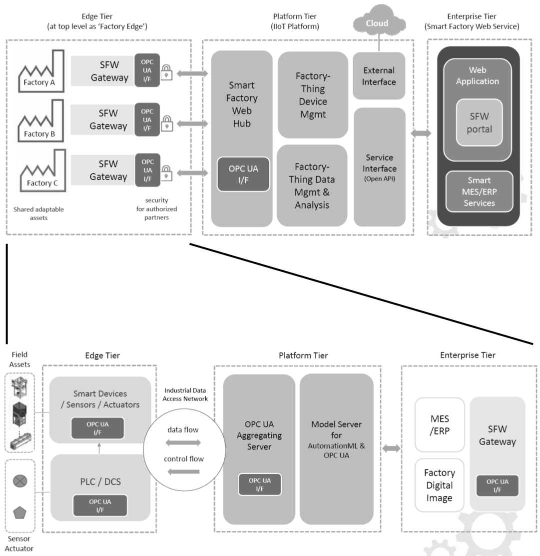

Fig. 7. Overall Smart Factory Web architecture.

B. Three-Tier Architecture pattern

The three-tier architecture pattern comprises edge, platform and enterprise tiers. These tiers play specific roles in processing the data flows and control flows involved in usage scenarios. They are connected by three networks, as shown in Fig. 7.

The edge tier collects data from the edge nodes, using the proximity network. The architectural characteristics of this tier, breadth of distribution, location, governance scope and the nature of the proximity network, vary depending on the specific use cases.

The platform tier receives, processes and forwards control commands from the enterprise tier to the edge tier. It consolidates processes and analyzes data flows from the edge tier and other tiers. It provides management functions for devices and assets. It also offers non-domain specific services such as data query and analytics.

The enterprise tier implements domain-specific applications, decision support systems and provides interfaces to end-users including operation specialists. The enterprise tier receives data flows from the edge and platform tier. It also initiates control commands to the platform tier and edge tier. [22]

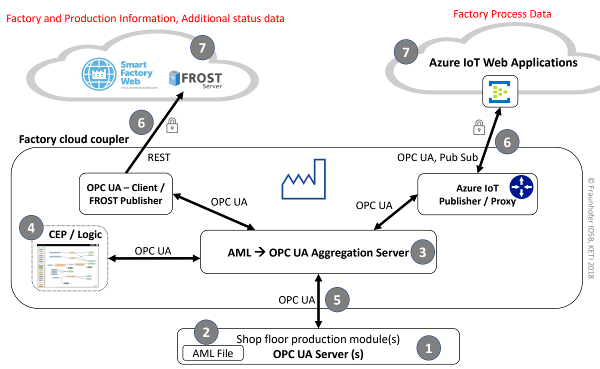

Fig. 8. Cloud-based Plug and Work architecture.

The Fig. 8 shows the entire architecture from the machine level to the cloud.

1) OPC UA devices registered in network (Plug and Work)
2) AutomationML (AML) model of device is loaded dynamically from OPC UA Server in the shop floor on right. (Plug and Work)
3) AML Management adds meta-information for OPC UA Aggregation Server
4) CEP (Complex Event Processing) reduces the amount of data to be sent to the cloud by extracting higher level, context-sensitive information in real-time and sending a notification (or a complex event) when a situation is detected.
5) AML2UA generates the aggregation server based on the AML models of the relevant devices
6) The Publishers establishes a connection to the SFW Server and the IoT Hub in the Azure Cloud and tunnels the OPC UA data.
7) The Smart Factory Web Portal and the IoT Web Applications visualize the OPC UA data using the same AML file for configuration

C. AML to OPC UA Aggregation Server

Creating an information model of an OPC UA server is still a mostly manual process, very time-consuming, expensive and error prone. There is a growing need for automated methods that are able to leverage information that already exists in different sources (e.g. software systems) in order to build useful OPC UA information models. The AML2UA converter [5] is a software service that automates creation of an OPC UA information model by reusing information already included in an AutomationML model. The service has been developed based on the companion specification[6], which defines how to combine the two standards (i.e. OPC UA and AutomationML) with the goal of simplifying the creation of OPC UA information models [20]. We note here that an OPC UA server can be created based of multiple AutomationML models. Such a server is called an OPC UA aggregation server. In this case, the AML2UA converter resolves references between individual models, ensures consistency of the whole information model and eliminates redundancy. The AML2UA service has been used in the SFW to automatically create the OPC UA information models of our demo factories. An example is shown in Fig. 9 and Fig. 10. Fig. 9 shows a part of the AutomationML model of our model factory in Karlsruhe. The corresponding part of the OPC UA model is shown in Fig. 10.

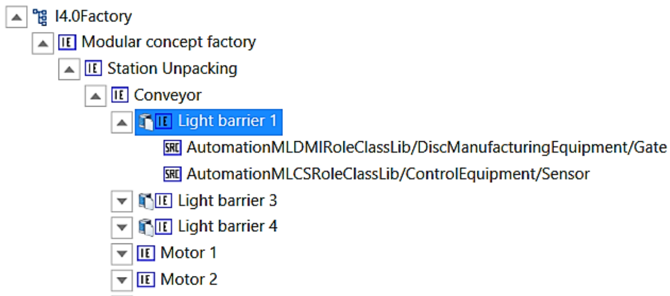

Fig. 9. AutomationML example for the demo factory in Karlsruhe.

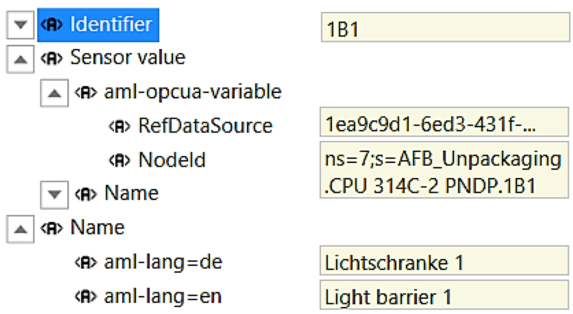

Fig. 10. A part of the OPC UA information model for the AutomationML example shown above.

The advantage of the proposed solution is not only in speeding up the development of an OPC UA information model, but also in enriching this model with explicit semantics. Instead of a flat structure of variables/nodes with non-intuitive

[5]https://aml2ua.iosb.fraunhofer.de
[6]https://opcfoundation.org/developer-tools/specifications-unified-architecture/opc-unified-architecture-for-automationml

naming (c.f. “Identifier = 1b1” in Fig. 10), which is difficult to understand even by humans, the OPC UA model is hierarchically structured and also multi-lingual (cf. “Lichtschranke 1” and “Light barrier 1”).

IV. Implementation and Evaluation

This chapter describes the implementation of the cloud-based Plug and Work scenario including the cloud services, publishers and tools, together with a Plug and Work example. The implementation aims to evaluate the theoretical architecture presented in chapter 3. The description is structured in three parts beginning with the creation of the semantic self-description of a factory in AutomationML, followed by registration in the Smart Factory Web portal and concludes with the commissioning of the cloud coupler.

A. AML Modeling of a Factory

There are several ways to start modeling a factory, but essentially the bottom-up and top-down approaches have proven their worth. In the bottom-up approach, the order of description is 1) sensors and actuators, 2) cable and network connections, 3) controllers such as PLCs, 4) production stations and 5) production lines. In the top-down approach, the system boundaries of the stations are first defined and then the processes of a factory are described in successively greater detail by decomposition. In Fig 11, the KETI I4.0 Factory in Pangyo Korea was modeled using the AutomationML Editor tool with the top-down approach. The level of model detail can be adapted arbitrarily. For the use case shown, the focus is on the description of the capabilities, the OPC UA connections, the relevant process variables and the information needed for the automatic creation of visualizations. A description of the capabilities of a factory is used for searching in the Smart Factory Web Portal and matchmaking. The modeling of OPC UA connections is required for aggregating the distributed servers. The distributed OPC UA servers usually provide interfaces to autonomous stations or production lines of a factory. The modeled OPC UA servers also provide the relevant process variables and are described in more detail in AutomationML, e.g. symbolic names, descriptions, data types, units, value ranges, key performance indicators and overall equipment effectiveness relevance, etc. This information is also used to create a visualization.
It is planned that in future system manufacturers will use engineering tools to describe and deliver their stations and components with AutomationML. The necessary device drivers and interface software will be generated automatically from the AutomationML. This is comparable to device description files of industrial fieldbus couplers. Factory operators would then only have to orchestrate these descriptions with the help of cloud services.

B. Registration in Smart Factory Web Portal

The generated AutomationML file describing the factory is imported via an upload function into the Smart Factory Web Portal. The factories registered in this way are displayed in a list cf. Fig. 12. Configuration files for process data visualization are generated with the import. The generated JSON files for configuring the respective cloud couplers in the factories can be downloaded from here. In this implemented scenario, the visualization is shown in two places.

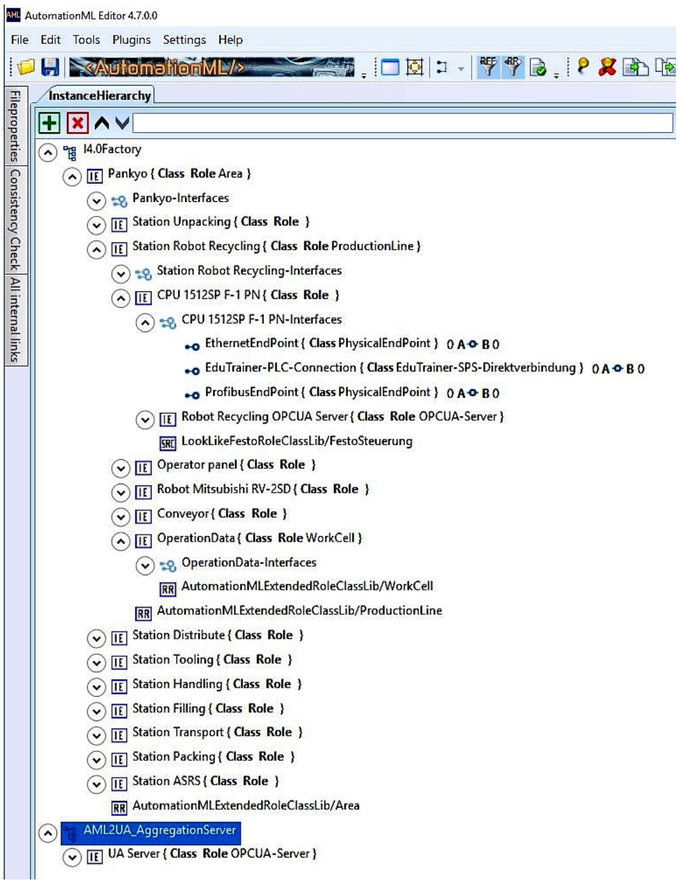

Fig. 11. KETI I4.0 Factory in Pangyo Korea AML model.

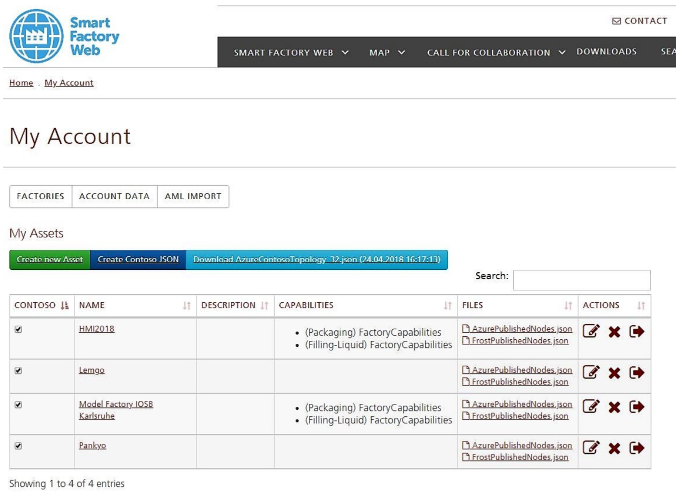

Fig. 12. Smart Factory Web Portal registration service.

The process data is visualized internally in the Smart Factory Web Portal cf. Fig. 13. and externally in the Azure Cloud as another web application cf. Fig.14. The Connected Factory solution in Azure IoT uses a JSON topology description file to configure the solution. This can be generated via a service in the Smart Factory Web Portal. The Connected Factory solution is updated automatically and visualizes the hierarchy of Role Class Area, Role Class ProductionLine and Role Class WorkCell modeled in AutomationML cf. Fig. 11. The modeled properties of the process data are also used for visualization in the Connected Factory solution in Azure IoT, e.g. data type and unit see Fig. 14. However, the prepared visualization of the process data still lacks the live values. These are published from the factories using the cloud coupler.

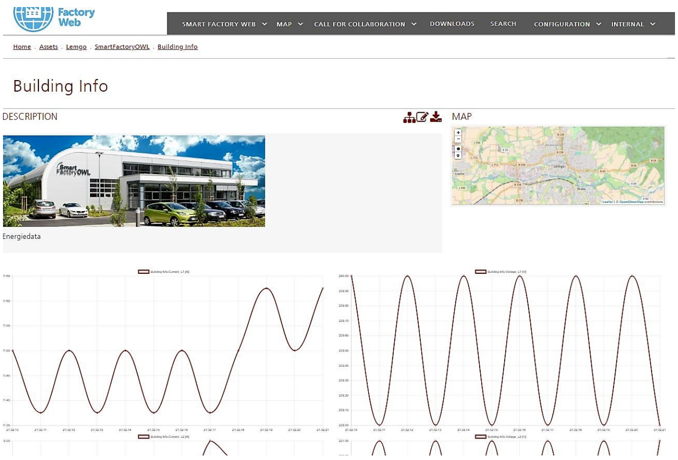

Fig. 13. SmartFactoryOWL Energy Data in Smart Factory Web Portal.

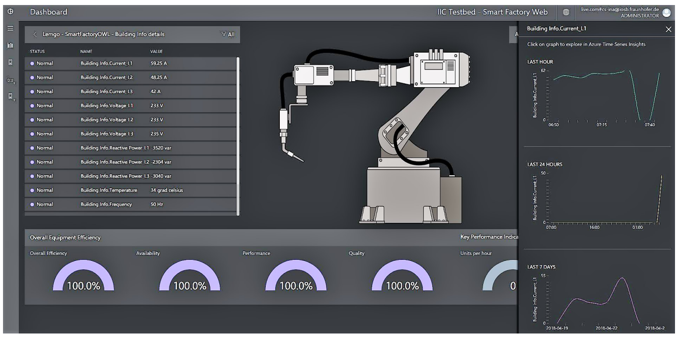

Fig. 14. SmartFactoryOWL Energy Data in Azure Cloud

C. Set-up Cloud Coupler

The cloud couplers essentially consist of an OPC UA aggregation server and the cloud publishers (cf. Fig. 8 and Fig. 15).

The OPC UA aggregation server is created by a cloud service based on the factory modeled in AML (see Fig. 16). By executing the OPC UA aggregation server locally on the cloud coupler, it connects to all modeled OPC UA servers on the shop floor. The OPC UA aggregation server adds additional semantics to the information model as required. The publishers connect to the OPC UA aggregation server and tunnel the OPC UA data securely encrypted into the Smart Factory Web Portal and the Azure Cloud. The JSON configuration files for the publishers are created during registration in the Smart Factory Web Portal.

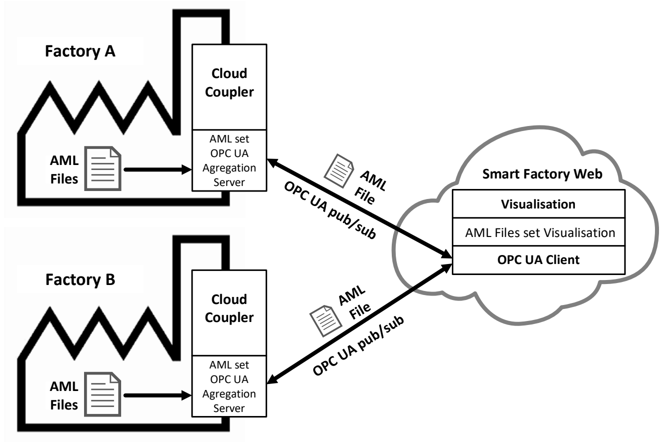

Fig. 15. AML Models set up Cloud Coupler and Cloud Visualisation.

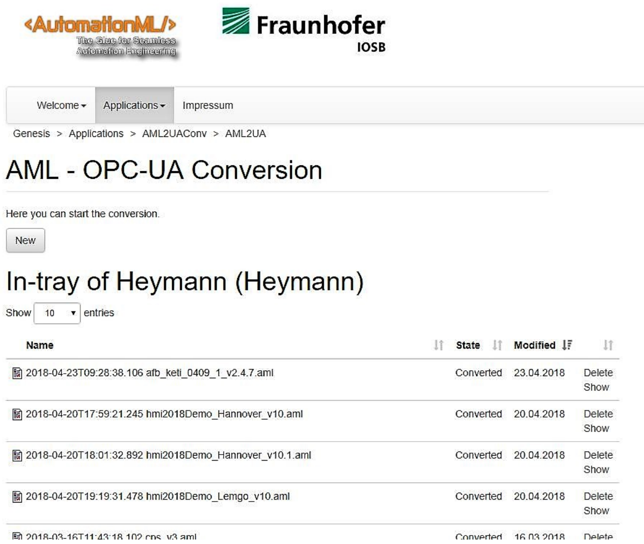

Fig. 16. AML to OPC UA Aggregation Server Web Service

D. Evaluation and Result

Through the semantic modeling with AML there is an enhancement to describe neutrally what the current or future state of a factory is or should be. This means that there is a digital twin for the entire factory, regardless of the large number of the required engineering tools. With the help of the semantic description, manual engineering steps can be automated using cloud services. The automatic generation of configuration files based on the AML represents the greatest time saving.

The evaluation revealed that the previous engineering time of 3 hours for the commissioning of a new production station could be reduced to one hour by using cloud-based plug and work techniques.

V. CONCLUSION

Today, a company's website is the best way to find out what a company has to offer. However, the customer only receives a snapshot of the company and is dependent on the up-to-dateness of the website if he is looking for a product or service. Since the websites of companies do not all look the same and the layout is not standardized either, it is often difficult for people and machines to find the needed information on a website of a company. This paper describes the solution implemented within the IIC Testbed project Smart Factory Web which opens a new marketplace for manufacturing and uses standards to reduce the effort to define interfaces and integrate applications.

The architecture proposed in this paper allows even small and medium-sized businesses to easily enter this marketplace. New and existing plants and factories can be connected with the help of cloud couplers which are easy to install. With the help of cloud services companies can offer their services and products faster and more specifically. Until now, customer relationships have been very strongly determined by supply and demand and need a high level of human communication. As a result, the search, negotiation and coordination for a new order is very lengthy and new customer relationships are seldom established. With the help of the cloud-based plug and work approach implemented in this paper, the time for offering and searching for suitable products and services could be reduced. Fast matchmaking can be achieved through the standardized description of the factory assets. A contractor can get a better picture of where he can place his order through the cloud-based plug and work approach and live information about the status of the factory and through the publication of relevant process data. The implemented architecture is able to handle dynamic factory changes. When new assets and capabilities are added or need to be adapted, then services and automated workflows as described in this paper reduce the manual effort.

VI. ACKNOWLEDGMENTS

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