Towards Enabling Cyber-Physical Systems in Brownfield Environments

Leveraging Environmental Information to Derive Virtual Representations of Unconnected Assets

Sebastian R. Bader[1], Clemens Wolff[1], Michael Vössing[1], Jan-Peter Schmidt[1]

Karlsruhe Institute of Technology (KIT), 76133 Karlsruhe, Germany
{sebastian.bader, clemens.wolff, michael.voessing, jan-peter.schmidt}@kit.edu

Abstract. The digital transformation based on internet technologies comprises huge potentials but also challenges for the production industry. Even though some design characteristics are generally accepted for the digitized integration of machines, applications and surrounding components the inherent complexity and variety of interaction protocols, data formats and interdependencies of existing deployments in so called brownfield environments hampers the data-driven manufacturing of the future.
We propose an iterative approach where existing context data is used to encapsulate the specific complexity of each resource in order to create a flexible integration layer. Nearly all relevant resources are modeled as self-descriptive cyber-physical systems or Virtual Representations according to the setting of the physical production environment, therefore drastically reducing the required access barriers. We present a reference implementation and discuss its business implications by the example of industrial maintenance.

Keywords: brownfield deployments · industrial internet · distributed systems

1 Introduction

Within the industrial sector, manufacturers of industrial machines have realized the potential of offering services [4]. Today, driven by the process of Servitization, many manufacturers offer complementary services to their products, which are usually referred to as *Product-Service-Systems* [3, 16]. Even more, some authors like Vargo and Lusch argue that services are the main reason for purchasing products at all [24]. The trend of Servitization is further complemented by the digital transformation in the manufacturing sector. Currently, the Internet of Things (IoT) and cyber-physical systems (CPS) are new paradigms how involved machines, their components, and any other related actor – even related services – communicate with each other in an industrial internet. Indeed, the development of the IoT and CPS are seen as core enablers for new smart services, and thus, the further development of Servitization.

Inspired by the great success of the Web – and the internet as its underlying infrastructure – its basic design principles are now generally accepted. Furthermore, one can note a common agreement that future communication patterns for an industrial internet [15] or a platform for industrial data exchange [6] in the manufacturing industry need to follow these established and mature techniques. In contrast, existing setups of production lines are usually grown environments driven by short-term requirements rather than a long-term design and compliance to internet standards. Therefore, strategies transforming mostly hard-wired communication lines towards a flexible, internet-inspired state requires in-depth analysis.

Basically, two approaches need to be separated. First, a so called *greenfield deployment* starts at the design of a production site without any preliminary conditions by already deployed plants. Any communication pattern can be optimally designed and protocols, interfaces and interaction methods aligned according to the current best practices.

Nevertheless, in the majority of cases, the production site is already in place and running. Neither can potentially inappropriate devices be replaced nor the production process be interrupted for a significant amount of time. The transformation process therefore needs to be aligned to the same extend with the given setup as well as the desired architecture. At the same time, a successful transformation requires an iterative approach as established processes must stay fully operable until the successors are in place their capability is sufficiently tested. Such a scenario is called a *brownfield deployment* where established parts build the basis and previous actions affect the conditions for new developments.

Our contribution to the topic is an iterative deployment technique within a brownfield approach to gain an internet-powered integration architecture. The lack of suitable hardware for observations is tackled by flexible data integration techniques making use of context information and related data sources in order to create a detailed, consistent digital representation of the physical shop floor in the form of *Virtual Representations*. We outline methods how this virtual shop floor enables the deployment of analysis at runtime which have not been foreseen at design time and can be adjusted as necessary.

The remainder of this work is structured as follows: In section 2, we elaborate on fundamentals and related work. In section 3, we introduce a use-case frequently referred to in this work. In section 4, we present a technology stack relying on wide-spread and well supported internet and web technologies in order to enable communication within brownfield approaches. The core of this work, the proposed framework, is presented in section 5. In section 6, business cases enabled by the presented framework are highlighted. Finally, in section 7, this work is concluded.

2 Fundamentals and Related Work

The recent developments in miniaturizing electronics and the enhancement in (wireless) network technologies paved the way for equipping more and more *things* like machines, components, and even sensors with internet connectors. Gubbi et al. [10], similarly to others, define the IoT as the combination of large scale sensing or actuating capability of devices with sharing information based on internet standards. Well-established technologies like URIs for identification and TCP/IP for data exchange lay the foundation for higher level integration. Their main benefit is the loose coupling of clients and servers, allowing high scalability in distributed networks.

Cyber-physical systems (CBS) as e.g. discussed by Lee et al. [13] combine the connected device with a virtual dimension. The enhancement of the physical IoT resource with software-based counterpart enables additional information of the resource and its characteristics and features. Both the IoT and CBS mainly focus on connected objects. That means physical components or devices equipped with e.g. Ethernet or Wi-Fi connectors to send or receive digital messages. In contrast, a regular production line contains of a high number of not connected or even not connectable objects that cannot be equipped with internet-capable devices with reasonable investments. Information on these components is at least as important than the one represented through cyber-physical systems but not yet regarded by the paradigm.

The connected, data-driven manufacturing is often referred to as the industrial internet or industry 4.0 (after steam powered manufacturing, mass production, and digitalization). All relevant players are continuously exchanging information on the state of regarded products, production units and materials over the whole supply chain and product lifecycle [21]. IoT devices and cyber-physical systems form global networks and flexibilize the production. International organizations like the Industrial Internet Consortium or the Platform Industrie 4.0 drive the development of standards to enable the seamless integration of machines, software applications and products. The target is to reach a secure but at the same time flexible integration of any kind of production related unit based on the internet. Main advantages are the reduction of applied protocols, formats and interaction patterns to simplify the digital information exchange and to support a plug-and-play like deployment. This will not only allow faster adjustments to existing production processes but also to apply analysis driven by existing information and not hampered by previously designed interfaces, data silos or interaction patterns. Yet, the current specifications are still high level proposals how a connected production shall be implemented. Commonly agreed technology stacks and transaction formats are still missing, therefore a seamless connection is yet not possible.

Smart Manufacturing [8] comprises efforts to establish a reference architecture with nodes representing physical components in the manufacturing facility to ease the integration and create a generic platform. The promoted modularized approaches model virtual resources similar to their physical counterpart in order to enable rapid deployments and portability. But even though they outline a reference architecture, the targeted integration aspect is still unclear and directly implementable specifications are missing. Hedengren and Eaton [11] further discuss time based mathematical simulation and optimization on highly dynamic measurements. They discuss various types of update frequencies and how to derive predictions. All of the discussed models require decent preprocessed and, most of all, accordingly synchronized input data. Especially in brownfield scenarios, such a state is a major accomplishment and not a prerequisite.

Data Lakes, as e.g. discussed in [20] or [23], are one concept to make data from heterogeneous sources and in different formats accessible. Established technologies like Apache Hadoop provide solutions for NoSQL clusters and enable queries also on dynamic data without a fixed schema. The Data Lake concept is only partly scalable in terms of the underlying cluster but also forms a single point of failure and potentially another data silo with tight coupling which will hamper the data usage in future cases. The not required data format enables the simple data storage but makes an effective data integration without previous knowledge on each data object a challenging task.

The Industrial Data Space [17] provides solutions on how to exchange data between organizations with the focus on data security and sovereignty. While specifying the connectors, gateways and architectures it doesn't provide features to connect the data to the physical world. Information on unconnected resources are only implicitly given in data flows but not explicitly described. Interpretation of the data therefore still requires deep insights in the actual production setting and its dependencies.

3 Use Case

We illustrate the basic concept of our integration approach by presenting how the components of an industrial metal saw can be brought to a Virtual Representation. A Virtual Representation [2] is a digital resource which acts on behalf of an unconnected component or device. It represents its current state by providing descriptions in the semantically defined Resource Description Format (RDF) and serves as a generic container to provide all known information on the otherwise not describable object. In particular, implicit knowledge on e.g. local processes can be made explicit by delivering and executing according algorithms whenever the state of the Virtual Representation is requested.

One goal of an analysis might be a cost calculation of a current cut on a sawing machine or an estimation of its current abrasion state. Unfortunately, the high speed of the blade itself make it impossible to directly observe the abrasion without stopping the whole sawing unit. On the other hand, information from different components of the machine, e.g. cutting parameters and energy consumption of the engines, is available. To grab such data, we are using the Virtual Representation integrates the context information from cyber-physical resources and other internet-accessible sources and computes its state on the fly. We show how Virtual Representations can encapsulate all necessary information at the level of the internet-based integration layer and thereby encapsulate required knowledge at the resource itself, even though the physical object has no direct connection to the internet itself.

Our prototype is divided into two sub projects. The core project contains the Virtual Representations and a resource manager as a cloud server hosting them[1]. Additionally, we provide a web project that serves as a UI[2] for different communication protocols for a simple communication testing with the server of the core project.

4 Iterative Brownfield Deployment

Several architecture approaches are possible in order to digitally connect production machines with an organization's control systems. In the most basic scenario, a document-based information exchange (e.g. relying on proprietary formats, emails or even office documents) transfers jobs either directly to a customized interface. Pulling and polling, varying protocols and data formats, differing data syntax and identifiers hamper a direct data exchange. In our scenario, a script-based application could periodically query the data from some databases and send an email to a certain account. Any change in the setup, the used databases or new information on the abrasion process would then require a manual adjustment of the script, a text-based interpretation of the received email and sufficient information on the requirements of the downstream applications.

Moreover, the connection of machines from different manufacturers requires a deep understanding of each deployed device, its characteristics and limitations and the design, creation and maintenance of highly customized interfaces and control software. In a point-to-point wiring approach like the one mentioned, any necessary change in either its features or at the composition of the production line (like introducing a new unit or replacing an outdated one) leads to mandatory and very complex adjustments at any related device and application. The thereby created organic growing results in inconsistent data models, varying interaction patterns and applied protocols is hardly maintainable. Especially small and medium companies do not have the possibilities to employ the according staff to cope with the thereby created consequences.

Hybrid approaches relying on combinations of field bus architectures (like e.g. the CAN bus) and Ethernet connections combine polling information from a data producer with pulling data to a consuming system. Installing both paradigms is mostly the case when one subset of machines is initially designed for bus communication whereas other systems require a request-response pattern. The resulting environment makes it even harder to understand the existing dependencies and data flows.

On the other hand, industry 4.0 promises consistent, well-structured architectures with plug-and-play like deployment patterns. Even though a majority of

[1] `https://github.com/sebbader/VirtualRepresentationFramework/tree/master/VirtualRepresentationCore`

[2] `https://github.com/sebbader/VirtualRepresentationFramework/tree/master/VirtualRepresentationWeb`

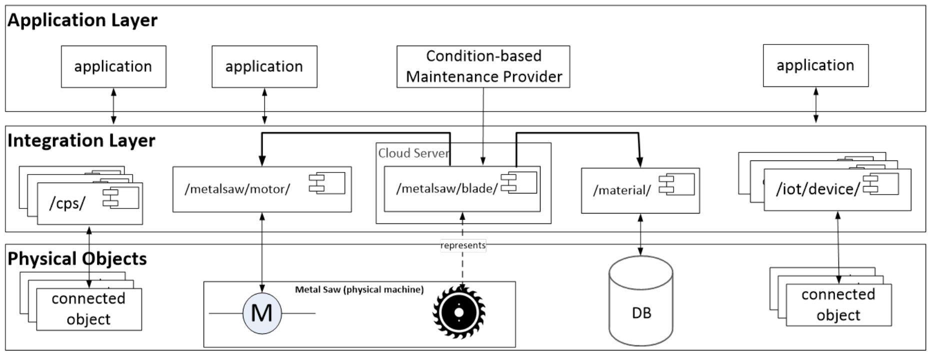

Fig. 1. The integration layer contains both connected objects (as e.g. cyber-physical systems) and unconnected objects (as Virtual Representations).

responsible managers agree on its relevance for future manufacturing [5] a common agreement on its technical characteristics and real world manifestations is still missing. Especially in scenarios where existing production lines need to be upgraded to industry 4.0 standards, well established strategies and procedures are in place yet. So called Brownfield Deployments are common use cases as only in rare cases the gained benefits of a newly created fabric from scratch justifies its investment costs.

We propose a self-descriptive integration approach where each physical object is represented by a digital resource, either a cyber-physical resource if an object can send or receive messages and a Virtual Representation otherwise. Every resource is identified and accessible by an URI, allowing its referencing natively through the internet without additional efforts. Every resource contains information on itself which describes its category, location, functionality and capabilities together with Web links to additional information. The data format for these descriptions are provided in RDF which provides syntactically and semantically defined statements on the resource itself, its characteristics and its current state. Other formats like e.g. XML or JSON lack the semantic part out of the box. The self-descriptive aspect is essential as only the close provisioning of information together with the regarded resource itself guaranties a true modular landscape (see Fig. 1).

Additionally, we restrict the data interaction pattern to four basic methods, namely *create*, *read*, *update* and *delete* (CRUD). Limiting calls to these methods drastically reduces the possibilities to model actions. Nevertheless, we argue that only the reduction towards the basic operations has the chance to make as much of the implicit assumptions behind more powerful interfaces explicit. Higher level functionality always requires a deep understanding of the existing dependencies and design decisions which are not possible to explain in a suitable interface description.

As the integration layer forms a distributed network using internet protocols and identification and access mechanisms, it can be connected to the global internet without any adjustments. For security purposes a gateway with an appropriate access control is mandatory but the technical communication will work without any adjustments. Furthermore, with the same mechanisms proven in the Web, new data provider and resources can be added, updated or replaced as the loose coupling of data producers and consumers guarantees a future-proof architecture. The iterative characteristic takes affect that any necessary change can be directly introduced at the concerning resource with only a minimal effect on others. The scalability of the network is directly provided by same features as any number of new resources, servers or cyber-physical systems can be added, similarly to the well-known Web.

5 Framework for Virtual Representations

Restricting the interaction methods to CRUD operations restricts but also simplifies the data management. Another relevant challenge in industrial environments are different communication protocols. Our prototype supports the nowadays most common protocols namely HTTP, WebSockets and OPC UA. HTTP is the most commonly used protocol in the internet and the basis for its most popular domain, the Web. It plays a fundamental role in the success of the internet as the dominant worldwide communication infrastructure and its characteristics are well known. Its low entrance barrier and the broad dissemination make it the protocol of choice for a fast and reliable decentralized communication. Its clear client-server separation is one of its major success factors. As showed in [2] Virtual Representations are solely relying on RESTful interactions on Virtual Representations which adds the clear semantics of CRUD operations to compliant APIs. We propagate this pattern to the other protocols in order to keep interactions consistent and gain a loosely coupling of producers and consumers of data.

WebSockets rely on HTTP but allow bidirectional message exchange. Thus, on event occupation the server can push information to subscribed clients. Another advantage is the higher efficiency due to data compression. Though WebSockets are an extension of HTTP only GET operations are supported. To enable CRUD operations, we use WebSockets sub protocols for operation distinction. For every operation type one connection is established. Sub protocols cannot be changed after connection establishment. Hence we need to keep four connection open for each virtual representation as long as we want to interact with it.

The third protocol that we examine is OPC UA. It is announced as the coming standard communication technique for industry 4.0 applications [19]. OPC UA ships with two different communication protocols named HTTP/SOAP and UA TCP. We already have a HTTP communication implemented so we decided to use UA TCP. Other common IoT protocols like CoaP, MQTT or XMPP basically follow similar patterns and are therefore not yet implemented.

The core project contains various virtual representations that are managed by the virtual representation manager. It is responsible for every incoming operation request. The platform itself has a backend for each protocol. These backends

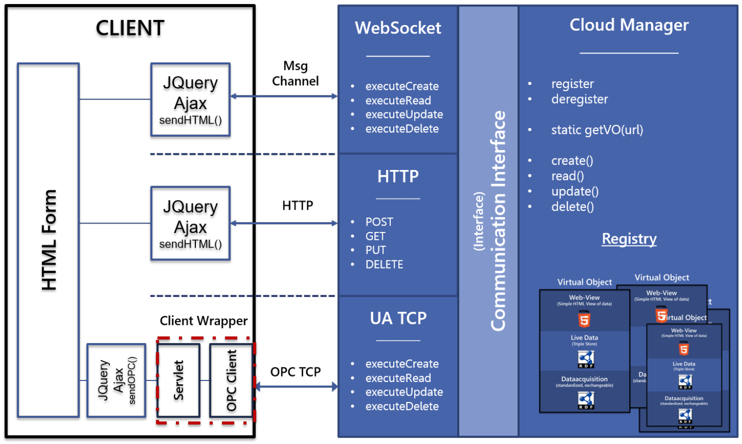

Fig. 2. Cloud Manager for Virtual Representations and communication scheme

implement the communication interface that ensures equal effects on the targeted resource. Every implementation has two main jobs: First, convert request to CRUD methods on the virtual representation manager. Second, translate given response in protocol typical response (e.g. exchange status codes or add header information).

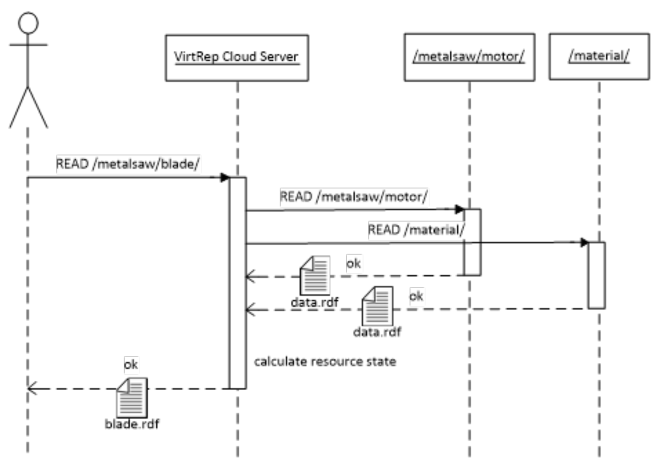

Fig. 3. Virtual Representations are computed at request time

If a client starts a query on a virtual representation data aggregation is started. As stated in [2] Virtual Representations collect their data dynamically at request time. This avoids data inconsistency on different application layers and solves the problem of time synchronization. The acquisition algorithm is configurable for now by a configuration file in N3 syntax but shall be enhanced to script-based solutions (e.g. Python) and Machine Learning models. It is also possible to define direct connections to resources, e.g. a OPC UA Server where the parts of the necessary context data are provided. We provide different serializations due to different possible requirements.

With our approach it is easy to access data that are stored in the virtual representation framework. Nonetheless it is necessary to manually add these representations to the framework, because one has to define where the representation should take the data from. Even if virtual representations could discover data for themselves there is a need to make for example sensors data somehow accessible.

6 Business Case

In the industrial sector, industrial maintenance is a prominent example for an industrial service [9]. Given its importance, concepts behind industrial maintenance have evolved over time. Traditionally, the maintenance business was organized in a transactional fashion [25]. This indicates that a maintenance service was provided as a reaction of an event—usually a machine failure, therefore, allowing equipment to run until failure [18]. Such maintenance actions are commonly referred to as reactive maintenance. However, researchers recognized the potential of preventing a machine failure in the first place and developed proactive maintenance strategies [22]. Within proactive maintenance, researchers differentiate between time-based (TBM) and condition-based maintenance (CBM) [1]. Under TBM, maintenance actions are triggered periodically based on a failure time analysis [14]. Under such scenario, historic data is analyzed in order to estimate a mean time until failure which is used to schedule periodic maintenance actions. Therefore, the core assumption behind TBM is that failure behavior of equipment follows a behavior that is expressed in historic data. Within this approach, researchers further differentiate between simple time or actual machine usage time based maintenance [1]. In CBM, maintenance actions are undertaken as soon as a certain condition threshold has been met [12]. Whilst not only aiming at preventing a failure in the first place, CBM furthermore tries at minimizing costs as maintenance is only performed when necessary and not after a certain time has passed.

Whilst pro-active maintenance strategies bring additional performance to manufacturers [22], they also require data. Especially CBM strategies rely heavily on real-time machine data [7]. Unfortunately, the dependency on data harms the broad application of CBM, as not all machines have the required connectivity or sensors installed and, as a matter of fact, only cyber-physical resources or otherwise observable components can be regarded. As, for example, the previously introduced example of the metal saw, data on the motors allows a CBM approach. However, the saw does not have any sensors equipped and thus is not available for CBM. Using the proposed solution above, we are able to use the data of surrounding machines encapsulated in order to create a virtual representation of the metal saw. Using the provided virtual representation, the CBM provider is able to estimate the current condition of the metal saw and provide an according maintenance service without needing to know the details of the metal saw, its job history or the details of the production line. Therefore, the above proposed approach is an enabler for CBM in brownfield environments. Once the virtual representation is created, it may also be used for other services. For example, the metal saw producer may analyze certain behavior and provide consulting services for the industrial customer.

It is important to note that using CPS, we are able to create the virtual representation of the metal saw on premise, thus indicating that data is only used locally and not sent to a remote site. This is a very important condition within the industrial sector, as data is usually seen as being proprietary and doesn't want to be shared among others.

7 Conclusion

This work presents a concept for an iterative deployment layer to transform production facilities to industry 4.0 setups. We explain methods to reduce existing interaction patterns and how available information can lead to a use case driven enhancement of the virtual model of the shop floor. Additionally, we show how the reached information gain can create economic benefits. We explained how the new possibilities of a holistic integration approach can change the way the industry is organized and how new business models can be implemented. Therefore, the presented work contributes to ongoing research on the introduction of IoT within brownfield environments.

The main challenge in our approach is the consequent transformation towards a state-based model and the restriction to the CRUD operations. Existing interfaces commonly do not implement these requirements especially when based on proprietary protocols. Even though major trends towards RESTful interactions simplify the communication, existing APIs require wrapper modules in order to translate and transform messages.

We argue that a sustainable transformation strategy for digital integration of manufacturing systems needs to be aligned with well-established practices of the internet. Only the distributed, loose coupling of systems and the encapsulation of relevant information at the resource itself can create a sustainable IT landscape. The outlined framework for various IoT protocols provides one step for a plug-and-play behavior in future data-driven manufacturing.

Future works will include a detailed examination of notifications and event-based interactions in general. Whereas a high-frequent polling approach can comply the requirements to some extent, an efficient integration technique needs to natively comply with the characteristics of current event and push-based systems. In addition, access control policies and reliability of information have not been yet discussed at all. We will further investigate how current state-of-the-art data security and provenance solutions can be adapted to our distributed integration setting and how a transparent and trustworthy mechanisms can comply to the specific requirements in brownfield environments.

Acknowledgement The research and development project that forms the basis for this report is funded under project No. 01MD16015 (STEP) within the scope of the Smart Services World technology program.

References

[1] Ahmad, R., Kamaruddin, S.: An overview of time-based and condition-based maintenance in industrial application. Computers & Industrial Engineering **63**(1), 135–149 (2012)
[2] Bader, S.R., Maleshkova, M.: Virtual representations for an iterative iot deployment. In: Companion of the The Web Conference 2018 on The Web Conference 2018. pp. 1887–1892. International World Wide Web Conferences Steering Committee (2018)
[3] Baines, T.S., Lightfoot, H.W., Evans, S., Neely, A., Greenough, R., Peppard, J., Roy, R., Shehab, E., Braganza, A., Tiwari, A., Alcock, J.R., Angus, J.P., Bastl, M., Cousens, A., Irving, P., Johnson, M., Kingston, J., Lockett, H., Martinez, V., Michele, P., Tranfield, D., Walton, I.M., Wilson, H.: State-of-the-art in product-service systems. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture **221**(10), 1543–1552 (2007)
[4] Baines, T., Lightfoot, H., Benedettini, O., Kay, J.: The servitization of manufacturing. Journal of Manufacturing Technology Management **20**(5), 547–567 (2009)
[5] Bauer, H., Baur, C., Mohr, D., Tschiesner, A., Weskamp, T., Alicke, K., Mathis, R., Noterdaeme, O., Behrendt, A., Kelly, R., Wee, D., Breunig, M., Narayanan, S., Roggendorf, M., Huber, U., von der Tann, V.: Industry 4.0 after the initial hype–where manufacturers are finding value and how they can best capture it. McKinsey Digital (2016)
[6] Bedenbender, H., Bentkus, A., Epple, U., Hadlich, T., Heidel, R., Hillermeier, O., Hoffmeister, M., Huhle, H., Markus Kiele-Dunsche, Koziolek, H., Lohmann, S., Mendes, M., Neidig, J., Palm, F., Pollmeier, S., Rauscher, B., Schewe, F., Wollschlaeger, Wollschlaeger, M., Weber, I., Waser, B.: Industrie 4.0 Plug-and-Produce for Adaptable Factories: Example Use Case Definition, Models, and Implementation (2017), http://www.plattform-i40.de/I40/Redaktion/EN/Downloads/Publikation/Industrie-40-%20Plug-and-Produce
[7] Campos, J.: Development in the application of ICT in condition monitoring and maintenance. Computers in Industry **60**(1), 1–20 (2009)
[8] Davis, J., Edgar, T., Porter, J., Bernaden, J., Sarli, M.: Smart manufacturing, manufacturing intelligence and demand-dynamic performance. Computers & Chemical Engineering **47**, 145–156 (2012)

[9] Gitzel, R., Schmitz, B., Fromm, H., Isaksson, A., Setzer, T.: Industrial Services as a Research Discipline. Enterprise Modelling and Information Systems Architectures **11**(1), 4–1–22 (2016)

[10] Gubbi, J., Buyya, R., Marusic, S., Palaniswami, M.: Internet of things (iot): A vision, architectural elements, and future directions. Future generation computer systems **29**(7), 1645–1660 (2013)

[11] Hedengren, J.D., Eaton, A.N.: Overview of estimation methods for industrial dynamic systems. Optimization and Engineering **18**(1), 155–178 (2017)

[12] Jardine, A.K., Lin, D., Banjevic, D.: A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mechanical Systems and Signal Processing **20**(7), 1483–1510 (2006)

[13] Lee, J., Bagheri, B., Kao, H.A.: A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. Manufacturing Letters **3**, 18–23 (2015)

[14] Lee, J., Ni, J., Djurdjanovic, D., Qiu, H., Liao, H.: Intelligent prognostics tools and e-maintenance. Computers in Industry **57**(6), 476–489 (2006)

[15] Lin, S.W., Miller, B., Durand, J., Bleakley, G., Chigani, A., Martin, R., Murphy, B., Crawford, M.: The Industrial Internet of Things Volume G1: Reference Architecture (2017), http://www.iiconsortium.org/IIRA.htm

[16] Meier, H., Roy, R., Seliger, G.: Industrial Product-Service Systems—IPS2. CIRP Annals - Manufacturing Technology **59**(2), 607–627 (2010)

[17] Otto, B., Lohmann, S.: REFERENCE ARCHITECTURE MODEL FOR THE INDUSTRIAL DATA SPACE. Tech. rep., Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. (2017)

[18] Paz, N.M., Leigh, W.: Maintenance Scheduling: Issues, Results and Research Needs. International Journal of Operations & Production Management **14**(8), 47–69 (1994)

[19] Rauen, H., Mosch, C., Niggemann, O., Jasperneite, J.: Industrie 4.0 kommunikation mit opc ua. Leitfaden zur Einführung in den Mittelstand. Hg. v. VDMA und Fraunhofer-Anwendungszentrum Industrial Automation. Frankfurt am Main (978-3-8163-0709-9) (2017)

[20] Stein, B., Morrison, A.: The enterprise data lake: Better integration and deeper analytics. PwC Technology Forecast: Rethinking integration **1**, 1–9 (2014)

[21] Stock, T., Seliger, G.: Opportunities of Sustainable Manufacturing in Industry 4.0. Procedia CIRP **40**, 536–541 (2016)

[22] Swanson, L.: Linking maintenance strategies to performance. International Journal of Production Economics **70**(3), 237–244 (2001)

[23] Tanuska, P., Spendla, L., Kebisek, M.: Data integration for incidents analysis in manufacturing infrastructure. In: Computing Conference, 2017. pp. 340–345. IEEE (2017)

[24] Vargo, S.L., Lusch, R.F.: Service-dominant logic: continuing the evolution. Journal of the Academy of marketing Science **36**(1), 1–10 (2008)

[25] Wolff, C., Vössing, M., Schmitz, B., Fromm, H.: Towards a Technician Marketplace using Capacity-Based Pricing. In: Proceedings of the 51th Hawaii International Conference on System Sciences. pp. 1553–1562. Waikoloa (2018)