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Towards a scalable implementation of digital twins – A generic method to acquire shopfloor data

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Abstract

New strategies in factory management focus on shopfloor data as a mean to achieve more flexible mass productions. In reality, the value adding usage of smart manufacturing approaches depends on the effort it takes to provide sensor and actuator data for further analysis. The concept of digital twins, that are based on a physical, a virtual and a communication component, promises a scalable solution to read and standardize shopfloor data. So far, there exists no generic method describing the implementation of the data acquisition as part of the communication component of digital twins. This contribution therefore focusses on necessary steps to consider when realizing a scalable data acquisition and examines how existing standards and open source solutions can support the implementation. The first part of the paper derives the necessary steps for acquiring shopfloor data. It starts by defining the architecture and aim of digital twins. Afterwards, a method to implement the generic data acquisition of digital twins is introduced. The approach is inspired by the Plug-and-Produce paradigm of the control engineering field and is adapted to the concepts of data acquisition and management. The second part examines the technical implementation of the proposed method. Identified approaches from a literature review are structured within the generic method. This describes the realization of the individual steps but also systematically differentiates existing approaches to build Digital Twins. With the aim of creating scalable architectures, a special focus is set on available open source solutions and standards when presenting the implementation part of the generic method.

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Keywords: Digital Twin; Data Architecture; Data Acquisition; Plug-and-Play; Smart Manufacturing;

1. Introduction

Broader product ranges and the need to reduce costs in the mass production lead to new strategies in factory management. These new approaches in the context of smart manufacturing set their emphasis on shopfloor data as a mean to further optimize processes and equipment usage [1]. The acquired data fosters plant simulations and facilitates variable production facilities enabling flexible mass customizations [2]. The pitfall is, that the value adding usage of shopfloor data depends on its availability. Singular digital representations of individual machines are currently implemented and help to optimize the operation of singular systems. The challenge is to implement these selective retrofits company-wide. A methodical implementation of digital representations can support the scalability to meet the requirements of the factory management nowadays.

Digital representations describe architectures of virtual objects that are based on physical objects and the communication between them [3]. The physical object represents field devices such as sensors, actuators, the programmable logic controllers (PLCs) and the connecting fieldbus profiles. The virtual object includes different semantical information models, or views, that organize data from the physical object, context providing simulations and analyzing algorithms [4]. The communication

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component translates, structures and transfers shopfloor data. Besides this definition, there are further characterizations of Digital Representations [5]. The communication can be distinguished based on the level of automation of the data transport. Representations with a fully automated communication component are defined as Digital Twins [3]. The architecture of a Digital Twin is shown in Figure 1. One aim of Digital Twins is thus to build a virtual component, that reflects the behavior of the physical part via a fully automated data acquisition. It offers useful information regarding its counterpart based on the acquired data [6]. The data acquisition is consequentially a central part of the architecture of Digital Twins [7]. One major challenge regarding the realization of Digital Twins is in practice, that there exists so far no generic method describing the implementation of the data acquisition from the physical to the virtual object. The diversity of the chosen approaches in the literature and the praxis leads to higher investment costs for the individual projects realizing digital representations.

The paper is structured as follows. Chapter 2 presents the generic stepwise method to implement the data acquisition. The third chapter focusses on the implementation technology. It identifies steps from the existing literature and assigns further open source solutions and standards to the stepwise method. The last chapter summarizes and identifies next steps.

2. The methodical domain - A generic data acquisition

The required knowledge regarding operational technologies (OT) such as fieldbus profiles and required IT knowledge makes the implementation of Digital Twins challenging for project teams. In literature, there exists little guidance regarding the necessary steps to follow when building Digital Twin architectures. AIVALIOTIS ET AL. describe a stepwise method on how to derive a meaningful information model of singular machines [8]. Considering the architecture of Digital Twins, this approach needs to be extended as for the fact that multiple devices in a factory need to be included in an aggregated virtual object [9]. The method thus needs to reflect potential implementations on factory level while guiding project teams through the OT/IT-domain.

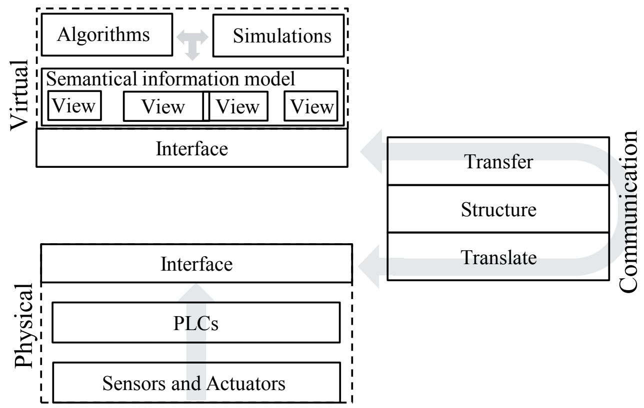

Figure 1 Schematic architecture of Digital Twins

2.1. From Plug-and-Produce to a stepwise method for Digital Twins

The aim of a generic stepwise method to implement Digital Twins shows parallels to the Plug-and-Produce paradigm of the control engineering field. Plug-and-Produce aims at an automatized configuration of fieldbus devices so that they can start operation. For that purpose, the available description of a newly detected field device needs to be extracted, transformed and loaded (ETL) into the existing network configuration. The central controlling unit aims at providing required information to the device to enable real-time communication [10]. A detailed stepwise description of Plug-and-Produce is provided by KRUG [11]. The steps of the method cover the physical connection of a new device, its identification and the enabling of a basic communication to a semantical interpretation, review and integration of the device description into the control architecture. In this work, the ETL logic will be adapted to the field of Digital Twins.

Before applying the Plug-and-Produce approach on Digital Twin architectures, relevant differences need to be regarded. Control networks set their primary focus on implementing and ensuring the required function of field devices [12]. The data on field level is merely a mean that needs to be communicated to meet this goal. On the basis of the control networks, Digital Twin architectures set their focus on optimizing production processes [5]. To this end, the shopfloor data needs to be contextualized, combined and analyzed. This difference leads to the following adjustments with regards to the presented ETL model.

- It is assumed that the field device is already included in the control network (i.e. the physical connection as first step in the approach of KRUG is disregarded).
- The target architecture is defined as the set of semantic information models incorporating different views of the physical objects in the virtual space.
- Target architectures can cover acquired data of field devices controlled by different PLCs.
- The device data is currently provided via intermediary sources such as PLCs (i.e. no Pub/Sub functionalities of the single sensors or actuators are assumed).
- The device description is defined as the semantic information model of the field device as physical object (see [8] for a stepwise method). This semantic information model contextualizes the payload provided by the device.
- It is assumed, that time stamps and unambiguous locations are essential metadata to enable analyses [13]. The timestamps, if available, thus need to be synchronized and the provision of the data by the device description needs to be checked.

With these changes regarding the procedure presented by KRUG, the generic stepwise method can be defined covering the steps from the initial device recognition to the cyclic communication between the physical and the virtual object.

2.2. The stepwise method to implement the data acquisition

The aim of the first step, the device recognition, is to detect new devices within the physical object. Firstly, the fieldbus profile needs to be identified, since it cannot be assumed that the physical object covers only one protocol. Afterwards, a search for new devices is initialized. At the end of the first step, the new device can be addressed via an identifier.
The setup of the basic communication as subsequent second step provides the necessary drivers to enable the communication between the target architecture and the field device. It might depend on the use case, which protocol is being used to model the different views of the target architecture. Thus, the target architecture has to be identified before determining the respective drivers. With the target architecture available, it has to be ensured that the system times of the target architecture and the underlying field controllers are synchronized. The method assumes that the network architecture requires no further certificate handling to establish the basic communication with the new field device. The first two steps, device recognition and basic communication, depicted in Figure 2 highlight the interpretation of the syntax of the newly detected and identifiable device.

With the communication channel established, the semantics of the device data and the target architecture can be aligned in the third step, the information gain. Following the ETL approach, the staging model is a temporary model used to translate the semantics of the field device description into the target architecture. To be able to fill the staging model, the device description semantics has to be mapped onto the semantics of the target architecture. Then, the mapped device description is checked for necessary meta data, such as timestamps and the unambiguous location, if provided via the control unit. At the end of the third step, the staging model is filled with the semantics of the field device. In the fourth step, the semantic description of the staging model is checked for completeness and missing attributes are added. Then, the staging model is deployed and the cyclic communication between field device and target architecture is established. The last two steps of the method depicted in Figure 2 show the interpretation of the semantics of the new device.

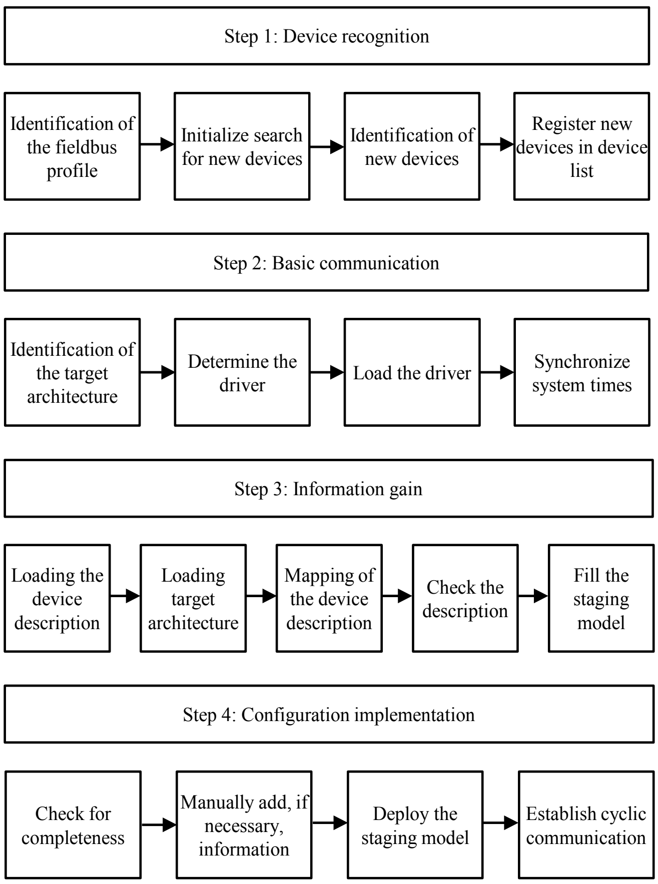

Figure 2 The individual steps of adding new devices into an existing target architecture

The different presented steps show the respective capabilities of the communication component: The detection of new devices, establishing a communication to the peripheral devices, a semantical interpretation of the device descriptions and the cyclic communication between physical- and virtual object. The device recognition and translation of fieldbus profiles requires OT-expertise while the semantical enrichment and the information transfers require IT-experts. Therefore, the differentiation helps to structure the individual tasks for the project teams implementing digital representations.

3. The technical domain – Implementations of the stepwise method

In order to shed light on the technical implementation of the generic method, existing solutions were identified in a structured literature review.

3.1. The literature review to identify implementations of Digital Twins

The review was carried out in April 2020 and included the search term "Digital Twin*" with a plausibility check for the term "Digital*Twin*" to cover different types of spelling. For the search, the data bases of Web of Science and Google Scholar were chosen and the search term was applied on the title, abstract and keywords. The total number of 1260 publications was reduced over three stages. The first stage included a review of the titles and the abstracts. During the second stage, the resulting 96 papers were screened to check for a focus on the data acquisition part of Digital Twins. The chosen 23 publications were then checked for a comprehensible description of the implementation of the data acquisition part. In the end, nine publications were chosen for a detailed examination of their approach to implement a Digital Twin. Figure 3 visualizes the method to derive the publications for further investigation.

The results of the literature review show, that most use cases focus on individual machines such as CNC mills or drilling machines. To receive further data, supporting sensors, such as accelerometers, are installed. Fewer publications focus on Digital Twins of production cells, such as robotic cells. Here, the analysis of the virtual object is limited on the question, if a hierarchically structured data model with different views is included. That is due to the fact, that Digital Twins shall represent the systems behavior. Other possible aspects of the virtual object, such as simulations and algorithms for predictions, are subsequent analyzing parts and not part of the data acquisition as focus of this paper. The implementation of the communication component is most relevant for this paper. It shows, that most use cases rely on OPC UA, MQTT or MTConnect as communication standards.

To analyze the communication component further, the chosen use cases are structured following the proposed stepwise method. This provides helpful guidance regarding future implementations and helps to clarify differences between the existing approaches. Focusing on the communication component, the use cases can be structured within three classes.

- Class 1 did not describe a target architecture with different views or a translation method between device descriptions and the staging model. - [14], [15], [16], [17], [6]
- Class 2 hierarchically structured the variables in the target architecture and provides a semantical mapping between the device description and the staging model. - [18], [19]
- Class 3 clusters use cases that solely focus on aspects of the device recognition [4] and the information gain [8].

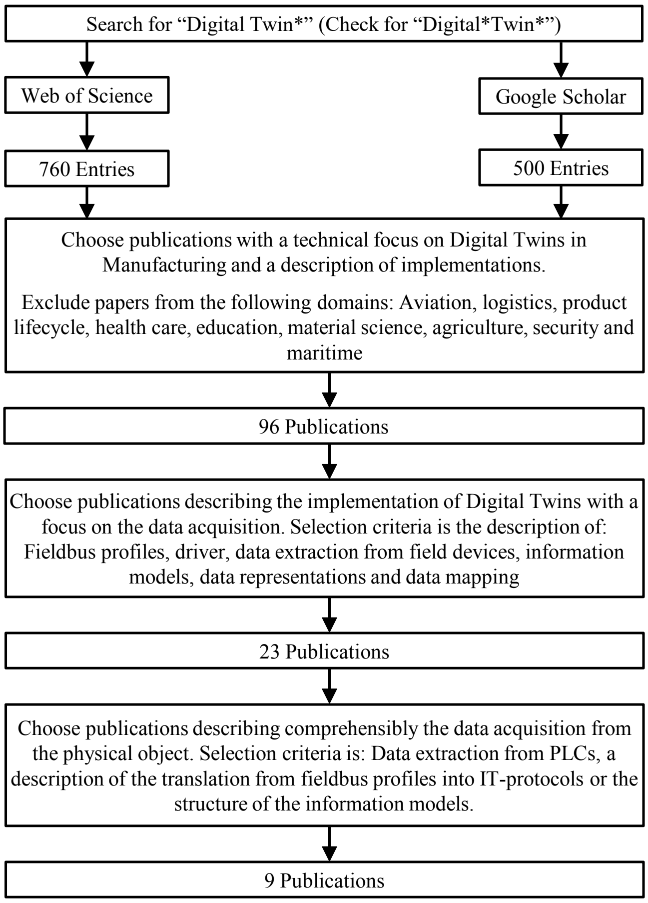

Figure 3 The structured literature review

Besides the classes from the literature review, also different standards and open source solutions can shed light on the implementation of the method. The aim is not to seek for a fully automatized implementation of Digital Twins but to structure the variety of standards and open source solutions to ensure scalable implementations and to identify existing assistances [20]. In the context of Digital Twins, standards, such as the OPC UA protocol, build the basis for open source tools like OPC UA Software Development Kits, to realize the communication component. The following section focusses on a detailed description of possibilities to implement the proposed method.

3.2. Analyzing the existing implementations of Digitals Twins with the stepwise method

Starting with the detection of new devices, the majority of the identified publications does not focus on a distinctive device recognition. The presented implementations in Classes 1 and 2 are based on known physical devices to be integrated into a digital twin architecture. In order to enhance scalability, it is important, that a given target architecture can digest new devices without being designed solely for the specific device. One crucial aspect for the architecture is a supported detection of changes in the physical object. From Class 3, TALKESTANI ET AL. propose to define anchor points to detect changes in the physical object. The authors combine the possible changes in the automation system with detectable changes in the control code of the physical object [4]. This anchor point method not only aims at detecting new devices but also relevant changes of the PLC code that should be reflected in the virtual object.
Furthermore, in the case of Industrial Ethernet fieldbus profiles, the Ethernet frame incorporates the EtherType indicating the profile. This standard thus supports the protocol identification. The Industrial Ethernet profile also supports the detection of new devices by the possibility to scan for IP addresses to detect changes in the physical object [11]. With its standardized format, the Ethernet frame therefore facilitates the implementation of Digital Twins.
With the detection of the new device, the basic communication needs to be established. Enabling the basic communication between field devices and the target architecture requires to identify the respective view on the target architecture. That is due to the fact, that the ETL concept as basis of the stepwise method permits different usages for the acquired data [21]. This concept is implemented on unit level by LIU ET AL. from Class 2 where the different machine types reside in different information models on the OPC UA server [19]. Thus, for the mapping of the device description, the dedicated view in the target model firstly needs to be defined. The subsequently chosen drivers differ between Class 1 and Class 2. The use cases with a hierarchically structured target architecture describe drivers between the fieldbus protocols to OPC UA and MQTT. The use cases from Class 1 also describe simple text files as standard to communicate the target architecture. Open source tools, such as Node-Red, offer drivers to translate between OT-protocols such as RFC 1006 (S7 PLCs) and IT-protocols such as OPC UA [22]. The finishing step of synchronizing the time stamps of the submitted time series

from the field devices is not described in the use cases. An open source solution is the Linux based package chrony. It synchronizes system times between time giving servers and their clients based on the NTP protocol [23]. The differences of used field devices (e.g. different cycle time settings) have to be regarded when establishing the basic communication. With the required drivers identified and available and the system times synchronized, the semantic integration starts.

The range of sources in the shopfloor leads the information gain to bear the complex task of semantically structuring the data flow. This third step of the method shows high differences between the implementations. In Class 1, the device descriptions from the field devices are provided in singular, unstructured variables. The target architecture is directly linked to the physical object and its structure is thus also related to the device description. This conformity requires no further semantic mapping between the device description and the target architecture. With regard to the review of the mapped description of the field device, time stamps and unique locations are partially described since they are the matching elements to merge the data. The use cases in Class 2 structure the device description based on the functional components of the field device (i.e. the different axis types of a machine tool and their respective views). The target architecture also incorporates this functional structure. Furthermore, mapping algorithms are described to semantically translate the device description into the target architecture. A subsequent check for the timestamps and the location is not described.
A crucial part of the information gain is the structure of the device description. That is due to the fact, that the structure of the target architecture and its different views only needs to be defined for the realizing company. The description of the various devices however needs to be agreed upon by different manufacturers. It is thus a challenging organizational task, especially in the brownfield [24]. One approach to methodically derive these structures is described in Class 3 [8]. The authors present a stepwise method to define meaningful information models of shopfloor devices for Digital Twin architectures. Furthermore, there are standardized ontologies of individual device classes. These descriptions are published by the World Wide Web Consortium (for sensor ontologies), within OPC UA Companion Specifications (e.g. the CNC machine standard) and ISO norms (e.g. ISO 13399) and can provide guidance already for the provided device descriptions [25, 20]. Besides these approaches, the local device description still offers high potential for further standardization.

In the final part of the stepwise method, the configuration implementation, it is verified, if attributes required by the target architecture are missing in the staging model. This step implies general requirements of a device type, production line or a plant depending on the type of the Digital Twin [9]. These requirements also decouple the device data from the further usage of the data. The resulting generic information models are not used in the reviewed literature and thus no semantic verification is described. Besides the mentioned standardized device descriptions, semantical standards such as AutomationML or ecl@ss could assist in structuring the target architecture and help identifying missing data, but they are licensed [26, 27]. Besides these standardization approaches, the target architecture of a given new device offers high potential for further assistance based on already available data in the virtual model of similar devices in the factory. With regards to the final upload of the staging model to the target architecture, Class 1 uses scripts and standards such as OPC UA, MQTT or MTConnect. Class 2 uploads the staging model via OPC UA, MQTT or Rest Interfaces. This communication can be supported via open source tools such as Eclipse Mosquitto acting as MQTT broker [28]. Comparing the available communication protocols, a scalable architecture should use different protocols taking advantage of their individual strengths [29]. This sets, once more, the focus on different views provided within the virtual object of the Digital Twins.

3.3. Benefits, challenges and further case studies of the stepwise method

The analysis of the technical domain shows the benefits and challenges of the proposed stepwise structure. The method is a tool to assess the existing implementations of Digital Twins and the differences in their setup. The method also assists implementations on plant level with redundant structures and enhanced synchronization needs. Furthermore, required capabilities can be derived for Digital Twin architectures and consequentially for the realizing project teams along the individual steps. At last, the presented generic method helps to identify assistance for the communication component of Digital Twins (e.g. semantical standards). Remaining challenges are the assumed flat network design and the availability of target architectures. To impose further security measures in the plant network, the Configuration implementation could be shifted into a demilitarized zone, while the Device recognition and Basic communication might require direct access to the physical component. This separation would demand firewall clearances and certificate handling as additional steps. Their location within the method is use case specific due to the dependency on the existing network design. Besides this, the crucial element of the presented generic method is the availability of standardized device ontologies.

An enhanced case study of the proposed method needs to use published data ontologies, while covering the variety of data sources in a plant. A Digital Twin architecture is scalable, when the used target architectures and methods to implement the steps of the method are accessible beyond the project team. For this purpose, published ontologies such as the internal and joint OPC UA companion specifications can provide assistance to structure device data from the same device groups using equal ontologies [30]. To ensure conformity within a Digital Twin architecture, these structures could be provided via the virtual object to be considered for the target architecture of a new device. The physical objects on plant level need to include the various data sources on plant level (e.g. plastics machinery or weighing technologies). With the combination of a varied physical component and available published ontologies, the stepwise method can be implemented based on the presented open source solutions as assistance.

4. Conclusion

Data produced by field devices can provide valuable insights on available resources in the factory. This helps engineers preparing more precise production plans and thus enhances planning and manufacturing flexibility. The aim of this publication is firstly to define the subsequent steps to implement Digital Twins. This differentiates the tasks on machine level from those of the IT domain and structures implementations independently of the use case. With this method at hand, the literature on Digital Twins is screened to analyze the existing approaches. The literature review shows that current publications focus on digital retrofits of singular equipment or cells with a central control unit. In order to scale the architectures to the plant level, crucial tasks such as the time synchronization need to be regarded. The literature review also showed, that the structures of the target architectures in the virtual component incorporate only use case specific views. Therefore, no semantical check for missing data in the staging model is conducted. Finally, the analysis revealed, that the set-up of individual device descriptions is time consuming and standardization approaches are difficult due to the high number of involved organizations. Assistance provided by the Digital Twin architectures to derive information models of single field devices thus promises to enhance their application in the praxis. Besides the structured literature review, the paper also presents identified open source solutions and standards that help to realize Digital Twins. In a next step, a framework of the presented open source solutions has to be designed and evaluated. Furthermore, a consistent method to model the different views in the virtual object needs to be established for Digital Twins.

With a scalable acquisition of data from the physical- and different views in the virtual component, variable productions plans are possible. This architecture leads Digital Twins to support flexible mass customizations and helps the factory management realizing smart manufacturing approaches.

Disclaimer

Any results, opinions and conclusions expressed in this work are not necessarily those of Volkswagen Aktiengesellschaft.

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