Digital Twin of manufacturing systems: a case study on increasing the efficiency of reconfiguration

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Digital Transformation

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Digital Twin of manufacturing systems: a case study on increasing the efficiency of reconfiguration

Digitaler Zwilling für Fertigungssysteme: Eine Fallstudie zur Effizienzsteigerung von Rekonfigurationen

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Abstract: The added value of a Digital Twin for reconfiguring manufacturing systems promises an increase in system availability, a reduction in set-up and conversion times and enables the manufacturing of customer-specific products. To evaluate this claim, this paper selects an architecture of the Digital Twin and realizes it on the basis of an application scenario for a cyber-physical manufacturing system. A case study is used to test the reconfiguration of a manufacturing system by comparing two different methods, one without and one with use of the Digital Twin. In this paper, the process steps of both reconfigurations are described and discussed in detail and a qualitative and quantitative evaluation of the reconfiguration results is presented. Finally, this paper gives an outlook on future research on intelligent automation of manufacturing systems using the Digital Twin.

Keywords: Digital Twin, architecture of Digital Twin, reconfiguration, assistance systems

Zusammenfassung: Der Mehrwert eines synchronisierten Digitalen Zwillings zur Rekonfiguration eines Fertigungssystems verspricht eine Verkürzung der Rekonfigurationszeit und damit eine Erhöhung der Systemverfügbarkeit sowie die kurzfristige Herstellung kundenspezifischer Produkte. Zur Evaluierung dieser Aussage wird in diesem Beitrag eine Architektur des Digitalen Zwillings ausgewählt und innerhalb eines Anwendungsszenarios für ein cyber-physikalisches Fertigungssystem implementiert. Innerhalb einer Fallstudie erfolgt darüber hinaus die Rekonfiguration dieses Fertigungssystems mit zwei verschiedenen Methoden, zum einen ohne Verwendung des Digitalen Zwillings und zum anderen unter Verwendung des synchronisierten Digitalen Zwillings. Dabei werden in diesem Beitrag die Prozessschritte beider Rekonfigurationen detailliert beschrieben und verglichen sowie eine qualitative und quantitative Evaluierung der Rekonfigurationsergebnisse gegeben. Schließlich gibt dieser Beitrag einen Ausblick auf zukünftige Forschungen zur intelligenten Automatisierung und Autonomie von Produktionssystem unter Verwendung des Digitalen Zwillings.

Schlagwörter: Digitaler Zwilling, Architektur des Digitalen Zwillings, Rekonfiguration, Assistenzsysteme

1 Introduction

Digital Twins and the Internet-of-Things (IoT) are going to boost many applications based on information and communication technology. A study of [9] indicates that the technology of a Digital Twin is about to be established in industry. It was found that "62 percent (of companies questioned) are either in the process of establishing Digital Twin use or plans to do so". Many authors agree that these new technologies will connect virtually everything from customers to machines and logistics. In the near future, it is expected that machines will communicate with one another, logistics and machinery will be self-controlled and all plans can be projected by simulation, which supports decision-making. From this perspective, the Digital Twin is a novel and enabling technology. The demands of markets to release constantly market-driven innovations, compel industrial manufacturing companies to increase both the use of automated production systems and their reconfiguration during their lifecycle. Increasing product variety and shortening product life cycles require a fast and in-

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expensive reconfiguration of existing production systems [1]. To face these challenges, one solution is to use the Digital Twins of automated manufacturing systems. The value-add of a Digital Twin for reconfiguration, promises the reconfiguration time to be reduced and thus an increase of the system availability as well as customer-specific products to be manufactured at short notice. A simulative environment using a Digital Twin enables automated systems to be quickly and easily reconfigured by a virtual test in simulation. The recommissioning and reconfiguration of the real manufacturing system therefore require less working time and thereby, reducing costs.

Objectives: In this paper, existing approaches for the integration of tools and their cross-domain models to create a Digital Twin of a manufacturing system are discussed first (Section 2). Furthermore, the characteristics of a Digital Twin are studied in the literature. Thereon, based on an example of a typical architecture of the Digital Twin, a use case scenario of a cyber-physical manufacturing system on which an evaluation of efficiency of the reconfiguration using a Digital Twin of an automated system is derived. Section 3 presents a detailed description of the technical realization of the physical asset and its Digital Twin. For the evaluation, this system is reconfigured once using its synchronized Digital Twin of the system and once without using a Digital Twin. The process steps of both reconfigurations are described and compared in detail in Section 4. Finally, this paper gives an outlook on future research on intelligent automation and autonomy using the Digital Twin (Section 5) as well as possible applications (Section 6).

2 State of the art

This chapter discusses the importance of tools and their models to create a Digital Twin of a manufacturing system along with the model-exchange, model integration and subsequently, a typical architecture.

2.1 Tools and models integration approaches

In the past years, considerable effort has been expended in the so-called PLM and Simulation markets, which provide an important baseline for further digitalization. As per the state of the art (SOA), engineering and simulation tools have been well established in industry with a steady growth rate and a rich ecosystem. As indicated by [8] and [12] the Engineering Software has a yearly turnover of €39 billion with a CAGR of 7.3 % and the Simulation Software at €4.6 billion with a CAGR of 8.9 %. These numbers are particularly worth considering as they indicate that there already is a large base of digital tools available in industry especially, in the engineering and production area.

The decisive factor here is the linking and collaboration of these tools. In this context, the topic of model consistency between the tools gains great importance in the context of creating a Digital Twin. For the generation of these models different tools have to be used. In [18] the frequently used tools of different manufacturers without a specific system were listed to illustrate their diversity during the functional engineering of an automated system, as shown in Figure 1.

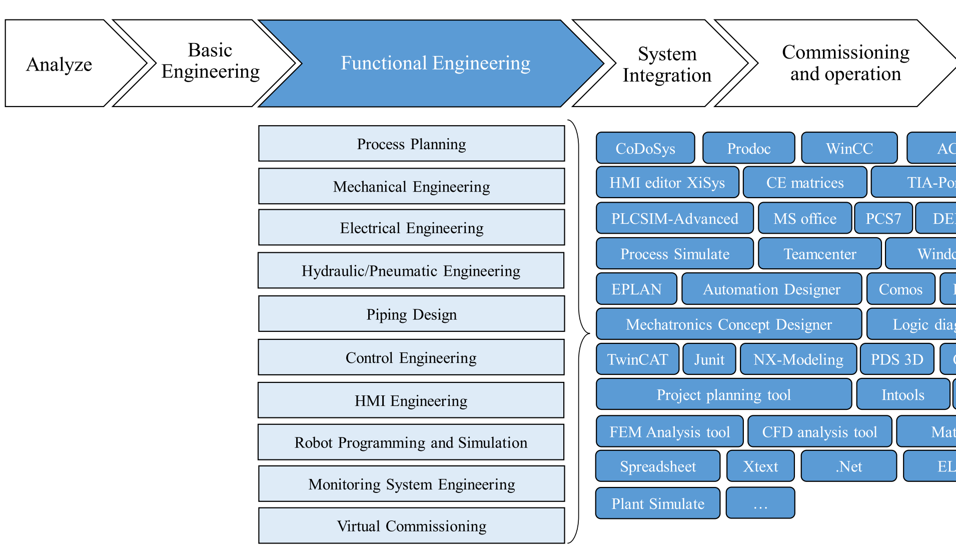

Figure 1: An overview of tools, which are used during functional engineering of an automated system, according to [18].

An important aspect in this context is the integration of data and models of a system into a Digital Twin, which were generated by various tools. A literature review revealed three distinguishable basic model-integration mechanisms: (1) standardized neutral exchange formats, (2) structured data, (3) semantic technologies for model integration.

– (1) Standardized neutral exchange formats: The first approach for achieving cross-domain model integration is through the utilization of neutral data exchange formats such as PLCopenXML, AutomationML [10] and PLMXML [14]. AutomationML is a very common neutral data exchange format. AutomationML is specially developed with a focus on engineering in the field of industrial automation technology and has the goal of being able to represent complete manufacturing systems.
– (2) Structured models: This approach can be divided into two types of realization: Data warehouse and single IT systems; "A data warehouse is a physical database with contents composed of data from different sources. The data is loaded into the data warehouse by various operational tools to enable an integrated view of the data, especially for analysis purposes" [5, 6]. Technological examples for the application of the Single IT System are Product Lifecycle Management Systems, PLM Systems. These systems structure cross-domain models of an asset and can reference them to each other [6].
– (3) Semantic technologies for model integration: Semantic technologies can be used for data exchange between tools and machines to support their interoperability. Draht describes interoperability [11] as follows "Interoperability between tools pursues the goal of being able to establish consistency between the data of a tool chain in a computer-supported, systematic and repeated manner." For this purpose, for example, the ontology languages RDF and OWL can be used to describe information and its dependencies in a structured way and to formulate rules and conclusions [6].

In this section, various mechanisms for cross-domain model integration have been briefly presented. These mechanisms are applicable considering the complexity of the system as well as its design requirements. For the development of the Digital Twin, it is necessary that exchanged data be referenced in a way that is coherent and comprehensible for the integration of external systems to use.

2.2 Characteristics of the Digital Twin

A decisive factor is the characteristic of a Digital Twin with the question, to what extend can the models of a physical system be defined as a Digital Twin. In order to answer this question, it is necessary to study the concepts and characteristics of the Digital Twin in literature. However, presently many different characteristics and architectures of a Digital Twin are discussed in literature which cannot all be reviewed in this paper. Cornerstones of the concepts are presented on the basis of one exemplary architecture along with further aspects which are briefly summarized.

According to [17] a Digital Twin is a general service architecture for Cyber-physical manufacturing system comprising of multiple models and software services which interact with the real asset. The concept is illustrated in Figure 2 and integrates the Digital Twin, the physical environment as well as human operators of the overall systems. A Digital Twin consisting of models and software services is created in unison with the physical system and its assets.

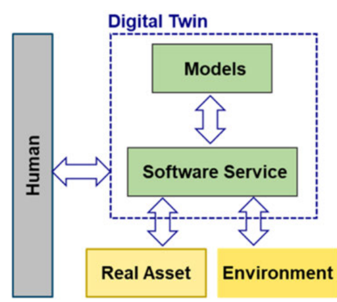

Figure 2: Architecture of a Digital Twin, in accordance with [17].

Depending on the application domain, the Digital Twin comprises of very different models, which cover multiple aspects of data and information. Software services are available as part of the Digital Twin to obtain, provide and analyze the models in interaction with the environment, the real asset and the human. The span of models is very broad and reaches from 3D-CAD models, via differential equations, state machine to requirement model, object models etc.. [13] defines a Digital Twin according to a survey of various definitions of the Digital Twin as a "digital representation of the features, states, and behaviours of a real asset that is realized through models and data".

Malakuti & Grüner [16] mention four characteristics for a Digital Twin: (1) a Metamodell for the Digital Twin with its internal models and their relations, (2) connection between the tools and the models of a Digital Twin, (3) modularization of the contents of the Digital Twin and to extend the contents, and finally (4) standards that must be used to define the contents of the Digital Twin to realize the exchange of information. In order to realize Digital Twins characteristics, the "Administration Shell" is proposed in context of "Industry 4.0". This is a mechanism for combining several Digital Twins to one "Digital Twin" in order to create a Digital Twin of the overall automated system [7].

Furthermore, in [3] a survey of existing definitions and intended characteristics of a Digital Twin in the CPS is conducted. In [3] a Digital Twin is presented as a virtual representation of a physical asset in a cyber-physical system that can represent its static and dynamic characteristics. A Digital Twin includes and maps cross-domain models of a physical asset. It states that not all models of the Digital Twin need to be executable; therefore, the Digital Twin is more than just a simulation of a physical asset.

In this paper, the mentioned architecture presented above and refined in [3] is chosen as a concept for the subsequent realization of a Digital Twin.

3 Case study on using a Digital Twin for the reconfiguration of a manufacturing system

In this section, the development of a flexible manufacturing system and its Digital Twin is presented as a use case scenario. Based on this system and its Digital Twin, two reconfiguration methods were carried out and compared to each other. Subsequently, the results were evaluated quantitatively and qualitatively.

For this purpose, an intelligent warehouse, so called iWarehouse, is designed and built in a flexible manufacturing system. It serves as a testbed in order to evaluate the increase in efficiency and potential reconfiguration. The flexible manufacturing system consists of four automated systems with decentralized control (welding machine, movable robot, iWarehouse and control cabinet as a head control system), which produce a model car from four metal sheet parts. The automated systems are not arranged in a fixed, conventional line system, a movable robot as a driverless transport vehicle connects them. This enables a variable and easily modifiable production process. The iWarehouse is used as a warehouse for the pre-produced sheet metal parts, which are made available to the movable robot. The sheet metal parts are grouped together in different work piece carriers for better handling. The position of the iWarehouse is flexible due to its movable structure and the robot can detect its position by communication via WLAN. The iWarehouse consists of 37 sensors, 25 actuators, as well as its own PLC, WLAN module for communication between the decentralized peripheral system and its battery as a power supply.

Figure 3 shows the components of iWarehouse within the flexible manufacturing system. The system consists

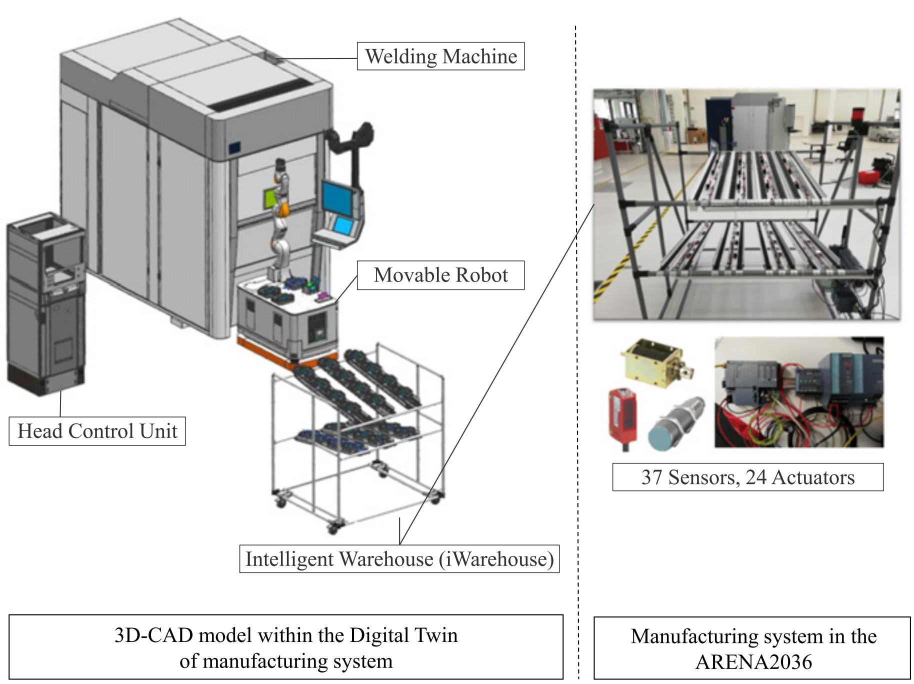

Figure 3: Intelligent Warehouse ("iWarehouse") as a part of the flexible manufacturing system.

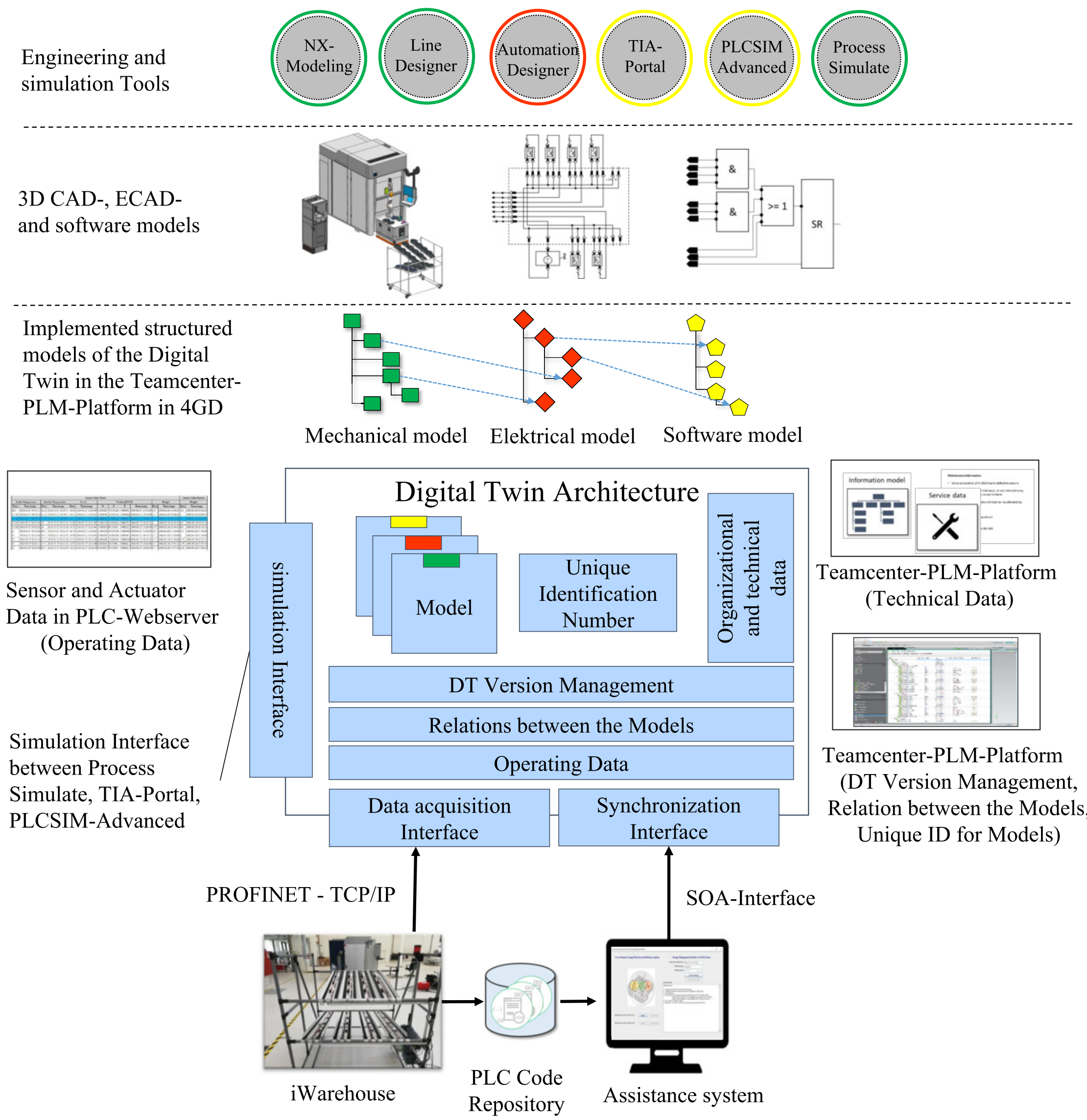

Figure 4: Overview of technical implementation of the component of the proposed architecture of the Digital-Twin in [3].

of state-of-the art industrial manufacturing units installed in the research campus ARENA2036, (Active Research Environment for the Next Generation of Automotive), a research cooperation between the institutes of the University of Stuttgart and industrial partners. Due to the industrial relevance, many commercial systems could be utilized for a seamless integration of research results.

In addition to the actual construction of the iWarehouse, its Digital Twin was also realized. To realize the Digital Twin and the iWarehouse the architecture described in [3] was chosen and it was implemented. It consists of various models and their relations, operation data and an interface for active data acquisition, organizational and technical specifications, and, finally, a synchronization interface.

Figure 4 summarizes the implemented technologies and components of the Digital Twin architecture. The components of a Digital Twin are shown in Figure 4 according to [3]. A Digital Twin consists of models and associated interfaces to tools, model version management, the operating data of the physical asset, the organization and technical data of the real asset, information about its relations to other Digital Twins in the real world, a unique identification number and an interface for communication with other Digital Twins, and an interface for communication with the real system. The implementation of these are explained below.

The Digital Twin of the iWarehouse consists of all its cross-domain models, e. g., its 3D-CAD, electrical circuit, functional and simulation models, as well as the organizational and technical specifications in the Teamcenter PLM-Platform under a unique ID for each mechatronic component in the system. Within this demonstrator, the commercially available tools such as NX-Modelling, Line Designer, Automation Designer, TIA-Portal, and PLCSIM Advanced were used to create multi-disciplinary models of the Digital Twin of the iWarehouse on the Teamcenter PLM-Platform.

The engineering process started with the creation of 3D-CAD models from each mechatronic component of the system by the NX Modelling Tool. Each 3D-CAD model is stored under a unique ID on the Teamcenter PLM platform. These 3D models are then instantiated by the Line Designer tool from the data backbone and a compilation of the function groups and their mechanical dependencies in the system is created. The completed 3D-CAD of the iWarehouse is saved as an overall system model on the data backbone via a direct interface between Line Designer and Teamcenter. Subsequently, the overall system model in the mechanical domain is retrieved from Teamcenter by the Automation Designer tool and an electrical model is referenced on the created 3D CAD models. The signal list (input and output signals of components), control function blocks of the function groups, appropriate controllers and peripherals for the system, and the electrical schematic model of each component are created via a direct interface between Automation Designer, EPLAN tool and TIA Portal. An electrical schematic model for the iWarehouse was not realized in this thesis. After the electrical models had been created, the signal and function block models were transferred from Automation Designer to TIA Portal via a direct interface. The entire PLC control program for the system's process flow is then created in TIA Portal. The industrial partners were responsible for creating the Digital Twins of the other automated systems within the flexible manufacturing system such as welding machine, movable robot and control cabinet in Teamcenter on the ARENA2036 server with the same engineering tools. The final PLC control program is tested during a virtual commissioning. Here, the entire model car production process was simulated and validated in a virtual commissioning with the tools Process Simulate, PLCSIM Advanced and TIA Portal.

All models created with the tools NX-Modelling, Line Designer, Automation Designer and TIA Portal are integrated as Digital Twin at the reference time using 4^{th}-Generation-Design technology, 4GD technology, and stored on the Teamcenter PLM platform. After validation of the overall system by virtual commissioning to meet customer requirements, the PLC control software of the iWarehouse was stored on a control repository with the reference time labelled.

During the operation of the flexible manufacturing system, the iWarehouse had to be continuously adapted or optimized by the industrial partners, e. g., through maintenance, replacement of components, optimization of the entire process flow, etc. The important aspect here is the synchronization of the models of the Digital Twin. In this case, the SOA interface of the PLM-Platform is used as the Digital Twin's model synchronization interface in the Digital Twin Architecture. This interface allows access to the engineering models of the iWarehouse for system engineers or for assistance systems to synchronize themselves automatically.

In [2] and [4] the authors described in detail a concept for the automated synchronization of the models of the Digital Twin based on Anchor-Point-Method and its realization by means of an assistance system. This assistance system can detect the changes in the system by means of rule-based analysis of the system's control software at two different points of time and automatically adapt the models of the Digital Twin by means of its SOA based interface. The PROFINET and TCP/IP as well as a database are implemented to realize the active data acquistion and operating data components according to the architecture proposed in [3].

4 Qualitative and quantitative evaluation of the reconfiguration of the flexible automated system with and without the Digital Twin

For qualitative and quantitative evaluation of the system reconfiguration using its Digital Twin compared to the conventional approach in the industry, a case study was carried out in ARENA2036 as part of a student research project. The reconfiguration of the iWarehouse was carried out in two different ways:

The first approach involves the synchronization of the models of the Digital Twin with the assistance system and the reconfiguration of the iWarehouse using its Digital Twin. The second approach comprises the reconfiguration of the iWarehouse after a currently common reconfiguration process in the industry without the support of the Digital Twin. In other words, in the second approach the potentials of the Digital Twin, such as model-based system engineering, cross-domain reusable component libraries, what-if simulations, virtual commissioning and the resulting benefits are not used for reconfiguration.

To determine the sequence and duration of the reconfiguration process without using the Digital Twin, a survey was conducted in ARENA2036 utilizing available expert. A questionnaire was designed to collect comparative data and filled out by *eleven different specialists* from the fields of plant construction and reconfiguration. The respondents work as development engineers, project managers and PLC programmers with professional experience with real automated systems. In addition, the scientific staff who are researching in the field of reconfiguration were interviewed. These comprised of experts from Bär Automation GmbH, Kuka AG, Siemens AG, Siemens Industry Software GmbH, Schunk GmbH & Co. KG, the Fraunhofer IPA and the IAS of the University of Stuttgart. The survey was conducted exclusively in direct reference to the iWarehouse. The respondents were shown the real structure of the iWarehouse and then the basic task of the system was described. The existing models were pointed out and the changes that occurred in the system were mentioned, without exactly naming their content. With this prior knowledge, the survey participants were asked to answer the questionnaire. The work steps of the most frequently mentioned methods and their sequence were combined and average processing time of the individual steps was calculated. Figure-5a outlines the sequence of the process steps and the average duration for the individual steps of the reconfiguration without using the Digital Twin as well as the results of the actual reconfiguration of the iWarehouse using the synchronized Digital Twin.

The reconfiguration process without using the Digital Twin begins with studying the behaviour of the system and identifying its components. This is followed by an expert discussion about the necessary modifications and components in the system to meet customer requirements. Afterwards the appropriate components are ordered and the iWarehouse is modified. In the next step, the PLC program is written directly to the system based on the target process and the system is tested for various scenarios with manual tests in a verification period. If no errors occur in the system, the iWarehouse is put into operation. According to the answers to the survey, there is a probability that in practice, an error is detected during the buffer time in the system and the modification process is repeated accordingly.

In the reconfiguration approach using the Digital Twin, the first step is to use the assistance system to detect changes. In approximately 2 minutes, the assistance system had successfully completed the analysis of the PLC control software at the reference point in time and the actual state, and correctly identified all changes occurring in iWarehouse and their dependencies during operation. Furthermore, it was possible to adapt the iWarehouse models automatically on the PLM platform during this period. However, the detection of the exact mechanical localizations of the changes is a challenge that cannot be solved automatically with the assistance system alone and in-

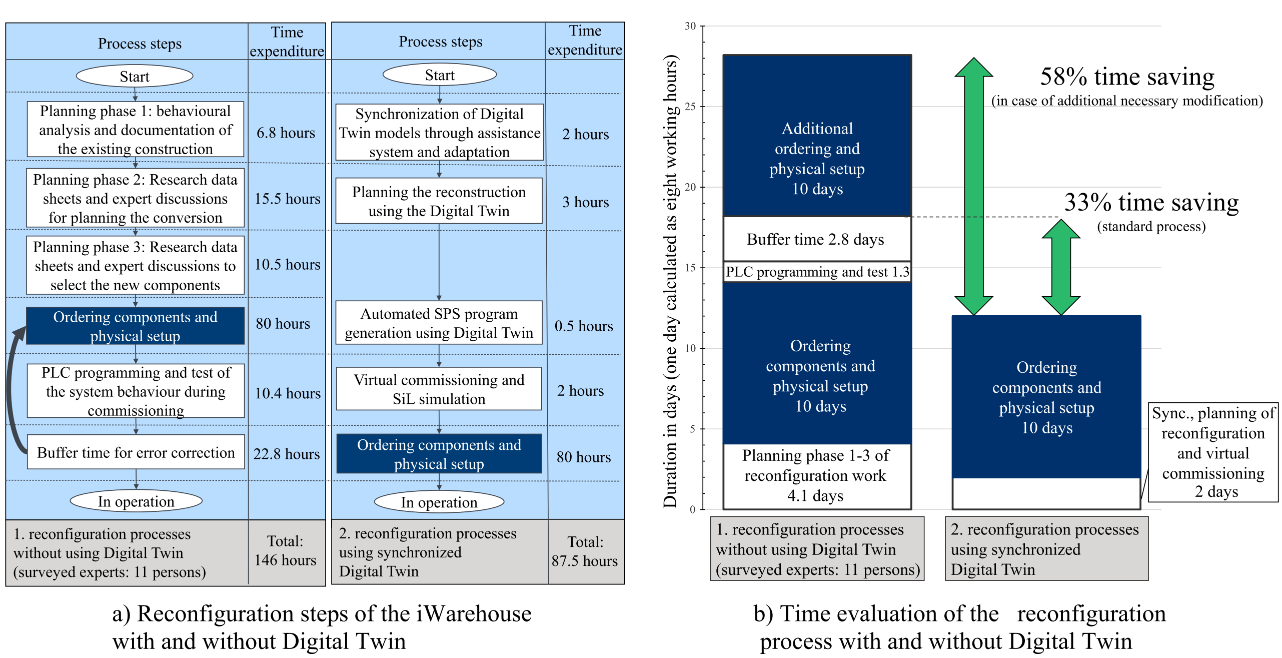

Figure 5: Process steps of both reconfiguration approaches and a quantitative time evaluation of the results.

evitably requires the cooperation of a systems engineer. However, the exact location of the changes in the models can be adjusted within a few hours, depending on the scope of the changes. In the case of the iWarehouse, the changes could be implemented in less than two hours. The entire reconfiguration process was carried out by the student in about one week. This period includes the adaptation of the cross-domain models of the Digital Twin of the iWarehouse and the execution of what-if simulations to meet new product requirements as well as the automated creation of the PLC control software for the iWarehouse with engineering tools.

The results of the survey on reconfiguration without Digital Twin and the determined times for reconfiguration with a synchronized Digital Twin serve as a basis for an evaluation of the added values by the Digital Twin. Figure-5b compares the time evaluation of both reconfiguration processes.

In the case of reconfiguring without using the Digital Twin, it is expected that the reconfiguration will not be completely successful at the first attempt due to the lack of simulation. For this reason, the reconfiguration process without using a Digital Twin is expected to involve an additional ordering process and a new reconfiguration phase of 10 days. With regard to the quantitative evaluation, which is based on the evaluation results, the anchor point method and the use of a Digital Twin shortened the rebuilding process of the intelligent warehouse by about 33 percent in the standard process and 58 percent in the additionally required rebuilding. A reduction in downtime was also achieved with regard to the availability of the warehouse. The physical test operation of the system can be neglected, since this has already been carried out virtually in simulation. In the context of a qualitative evaluation, it should be noted that due to the completeness of the test results by simulating several production scenarios, reconfiguration using the Digital Twin reduces the production risk after commissioning.

5 Towards future research of Digital Twin

The Digital Twin technologies promise a variety of new applications. However, what could be a major application apart from increasing the efficiency of reconfiguration?

To date industrial production is based on supply chains, e. g., the flow of goods and services towards the original equipment manufacturer (OEM) where the customer is rather static. The suppliers deliver parts, components and modules, which are requested upfront with a time delay by the OEM. The role of the OEM is to integrate these components, manage their interfaces and organize specially the supply chain. The customer utilizes the product and certainly influences the demand.

In future, there is a lot of potential for value networks in which the organization between the customer, the OEM and their supplier is far more flexible and dynamic. Future scenarios envision [15] value networks with a cluster of social and technical resources which can be managed tangibly. This would result in a „self-organizing network" interconnecting the multiple suppliers and OEM in a flexible manner. Slow ramp-up due to new products or disturbances caused by supply issues can be balanced out by an efficient organization of a greater overall network.

A scenario of complex value network is based on interconnected resources such as logistics (trucks, trains), factory, production, warehouse or buildings, which could all have a Digital Twin. Based on such interconnected control networks a transparency, with prediction, self-optimizing and self-control might become feasible and enhance the industrial application.

What would a complex "real world" value network scenario require to be operational?

- The nodes of the network should be tangible and dynamically connect or disconnect
- "Self-x" characteristics should enable sub-systems to adapt automatically to changing partners and situations
- Prediction functionality is required to help to anticipate and have a prognosis of future scenarios
- A potential for transfer learning based on observation of other scenarios could tremendously assist in operation.

There are various types of Digital Twins available, which enable a distributed control and an anomaly detection. System models of all types represent the multiple node in the value network. Data models help to obtain real data and sensors are utilized to obtain signals. Soft-sensors can be deployed to reconstruct signals from multiple data sources using both real measurement and model information.

As a result, the number of functionalities are relevant to the processing of the Digital Twin of the future. Firstly, there is the aspect of management, identification and analysis of a Digital Twin and all its heterogeneous information. Secondly, standardized interfaces between the Digital Twin in order to allow an exchange of information are very much required in order to cope with the complexity.

Thirdly, a capability to deploy a co-simulation for prognosis is in demand. Co-simulation can be used to couple the multiple and heterogeneous simulation based on the diversity of different models.

6 Summary

This paper provides exemplary definitions and a best practice example from research on the Digital Twin and presents multiple facets of the present research. The following aspects are discussed:

– The context of creating a Digital Twin from an automated system was discussed and different approaches for this purpose were summarized.
– The characteristics of the Digital Twin based on its definitions in the literature were studied.
– Design and physical setup of an automated system were described and based on that, the creation of its Digital Twin with different tools was presented.
– For evaluation purposes, two reconfigurations were performed and studied, with and without Digital Twin.

Despite the tremendous achievement demonstrating that the Digital Twin can substantially reduce the time of the reconfiguration process by up to 58 percent, more research is required. It became evident in the implementation and evaluation that it is vital to put simulation, models and data in different perspectives. This also includes questions on how model dimensions can be reduced or expanded or how models could synchronize themselves with other models and real-world data. There are obviously many open questions until a uniform framework is available for the management of Digital Twins.

The Digital Twin however is a prerequisite to create the basis for “self-learning” approaches and somehow move towards intelligent systems in the production domain.

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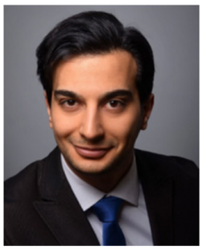
Bionotes



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