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Qualitative and quantitative evaluation of reconfiguring an automation system using Digital Twin

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Abstract

Increasing product variety and shortening product lifecycles require a fast and inexpensive reconfiguration of existing manufacturing systems. A synchronized Digital Twin of the manufacturing system is one solution to face these challenges. In order to use the Digital Twin for reconfiguration, a major challenge is to keep the developed Digital Twin of a manufacturing system, which was created during the engineering process, synchronized with the real system after commissioning. To automatically synchronize the cross-domain models of a Digital Twin after the commissioning of a manufacturing system, the authors introduced the Anchor-Point-Method in their previous papers. In this paper, the realization of the Anchor-Point-Method based on an assistance system is presented and the functionality is evaluated. This assistance system enables having an up-to-date Digital Twin of a manufacturing system available during the entire life-cycle of a system. Finally, a qualitative and quantitative evaluation of the advantages of a synchronized Digital Twin for the reconfiguration of a manufacturing system is presented. For this purpose, an automated system has been digitally and physically designed and built. On this system, a reconfiguration using the synchronized Digital Twin was performed and compared with another reconfiguration without Digital Twin collected through a survey. The results show that the Digital Twin can reduce the time of the reconfiguration process by up to 58 percent.

Keywords: Digital Twin; Cyber-physical production systems; Rekonfiguration; Assistance system; Anchor-Point-Method; ARENA2036.

1. Introduction

Today, the industrial sector is increasingly faced with the challenge of delivering customer-specific products in ever shorter production times. This requires the availability of flexible automation systems that can be efficiently reconfigured as needed. In the context of Cyber-Physical Production System, CPPS, the Digital Twin (DT) of an automated system can address the challenge to make systems quickly and easily reconfigurable by implementing and testing reconfiguration scenarios in a simulated environment [1]. The real recommissioning of the automation system therefore requires less time and allows for higher system availability. However, a prerequisite for the usability of the DT of an automation system is the availability of a cross-domain, up-to-date and integrated system model of the real plant during the different phases of its life cycle. This paper discusses first the definition of Digital Twin in CPPS. Subsequently, the challenges of synchronizing the Digital Twin in today's industry are discussed in detail. To meet these challenges, the concept of the "Anchor-Point-Method" and its realization based on an assistance system for automated synchronization of the Digital Twin models will be presented. In the following, the evaluation of the developed assistance system for the synchronization of the Digital Twin of an automation system is presented. Furthermore, a qualitative and quantitative evaluation of the statement of this work, which is "Increasing the efficiency of the reconfiguration use of a synchronized

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Digital Twin" is carried out and the results are described in detail using a use case scenario.

1.1. What is the Digital Twin of an automated system?

The Digital Twin is an up-to-date virtual representation of a physical asset in a Cyber-Physical Production System, capable of mirroring its static and dynamic characteristics. It contains and maps various models of a physical asset, of which some are executable, called simulation models. But not all models are executable, therefore the Digital Twin is more than just a simulation of a physical asset, but also contains operational data [2]. The Digital Twin will be developed in industry during the engineering process of an automated system. The engineering process for an automated system is a cross-domain process where system engineers from different domains such as mechanical, electrical and control engineering have to collaborate [3]. It is typically a sequential process that begins with the mechanics design, continues with the electrical and software design and ends with testing the models in a cross-domain simulation environment with virtual commissioning [4]. In the context of the automotive industry, this engineering process begins about 1.5 years before the start of series production [5]. The data and models generated or used in this process and their relations together represent the Digital Twin of the automated production system. Finally, based on this DT, the system is built and commissioned. From the start of the operating phase, several changes are made to the system, for example, due to aging components, using alternative equipment, optimizing the process flow, repairing the system, etc. [6]. To track these changes in the production system and to synchronize the Digital Twin with it, three major challenges must be solved.

1.2. The challenge of synchronizing the Digital Twin from the time of commissioning

First challenge: There is no or only an incomplete documentation of occurring changes to the automated system since commissioning [7]. Since changes in the production process have to be implemented in a minimum of time [8], they are carried out in practice by experts in the respective domain - mechanics, electrics, software - and are usually documented incompletely, contradictorily and also partly incorrectly [9]. Inadequate documentation is particularly typical for systems that have been modernized stepwise over a period of many years. *Second challenge: hidden dependencies of the changes in the different domains - mechanical, electrical and software* - [10]. Increasing product variety and short life cycles are associated to an increasing complexity in the production process, leading to the construction of more complex and highly automated manufacturing systems. This complexity is also related to the increasing usage and linking of mechanics and electronics as well as software in the form of mechatronic system components. The changes that need to be made quickly to a production system are carried out in practice by domain experts with different professional backgrounds, technical languages and engineering tools [4]. This makes it very difficult to identify the cross-domain dependencies of changes in the real system.

Third challenge: heterogeneity and high complexity between the models and their relations in the Digital Twin [11]. In a large-scale system, each component can be modelled differently even by different engineers in their respective specialist domains [12]. With the increasing complexity of the objects to be designed and the growing number of involved domains and persons during the engineering process of an automated manufacturing plant, the need for consistency between the resulting models, which are developed by engineers with different expertise and tools, increases [13]. In summary, the models of the Digital Twin have to be adapted manually, which requires interdisciplinary knowledge and a high effort.

To meet the challenges mentioned above, the authors have proposed an Anchor-Point-Method for automated change detection in real systems and model adjustment in the Digital Twin. [14], [15].

2. Anchor-Point-Method for automated synchronization of the Digital Twin

An asset in the automated system can be the entire plant or a single unit consisting of many sensors and actuators up to one screw in the system. The object holder in the model of an asset at the level of mechatronic components in the overall system model of an automated system within the mechanical, electrical and software domain are termed the asset's anchor points [15]. Thereby the Anchor-Point-Method is a method to synchronize the anchor points of a DT in domain mechanic, electric and software. In order to synchronize the models of the DT, the Anchor-Point Method consists of three phases with seven steps, which can be applied in an assistance system. Fig. 1 shows a sequence diagram depicting the overall process steps divided into the three phases (1) automated change detection, (2) cross-domain dependency analysis, and (3) model adaption. The first phase, automated change detection, consists of three steps. First, the PLC code of the system at reference-point and the current version is uploaded from a repository. The second and third steps of the sequence diagram describe the formalization and abstraction of the PLC code based on a central control software metamodel. This allows an instance-instance model comparison between both PLC code models. Within the second PLC code model, the anchor points of changed mechatronic components in the system are searched for. For instance, the signals, function or data blocks which have been added, removed or modified in the code are examined. The detected changes are made available for the next step as anchor points of changed components. If changes are detected they are analyzed in the fourth step (second phase) for their cross-domain dependencies within the overall system. The Anchor-Point-Method categorizes the changed anchor points in the control software according to the cross-domain rules in order to identify the changes in the real system and their influence on mechanical and electrical domains. For this purpose, the occurring change scenarios and their relation to the anchor points must be summarized in a rule table using cross-domain expert knowledge.

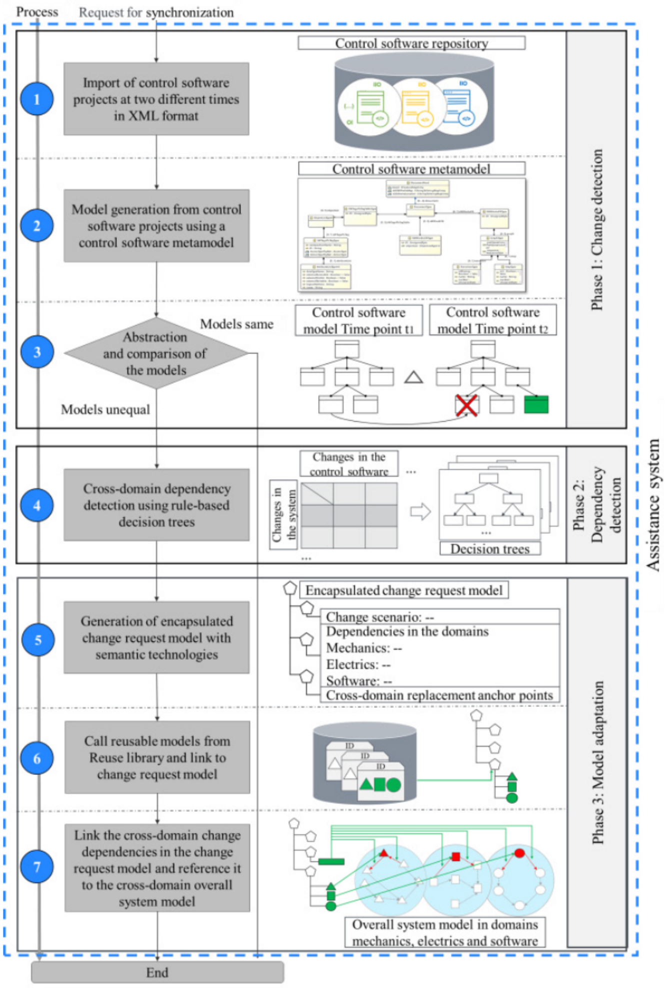

Fig. 1: Seven steps of the anchor-point method divided in three phases

To categorize the changes and create these rules, a wide technical knowledge of changes in automated systems must be combined within the knowledge of mechanical, electrical and software engineers. In the Anchor-Point-Method, these rules are collected from a detailed investigation of frequently occurring changes in the automated systems. The rule table contains a number of change scenarios that can occur in an automated system and how they can be detected within the PLC code. This rule table is described in detail in [2]. After changes and dependencies in the real system have been identified, the models of the corresponding Digital Twin need to be adjusted. For this purpose, steps five, six and seven, which form phase three "model adaptation", describe an automated generation of encapsulated Change-Request-Models (CRM) based on engineering change management approaches using semantic technologies. In the fifth step, an CRM is created using a semantic technology within the integrated models of the Digital Twin. To CRMs, semantic technologies such as technologies to integrate the models of the DT during engineering must be used, so that the created change request models are readable for cross-domain tools used in the engineering of the DT of the system. This allows the responsible designers of the respective models within the overall system model to easily open and adapt these change request models in their tools. By analyzing the detected anchor points from the fourth step, the unique ID of the modified component is identified. This unique ID is used in the sixth step to read all reusable models of the asset from a component library and encapsulate them in the change request model. In the last step of the Anchor-Point-Method, step seven, the detected cross-domain dependencies of the changes in the overall system model are merged into the CRM, and the entire encapsulated CRM with its information and models is referenced at the changed anchor points of the overall system model. The entire process steps one to seven of the Anchor-Point-Method can be performed automatically in an assistance system, which enables the synchronization of the models of the Digital Twin. In this study, an assistance system based on the Anchor-Point-Method was realized, which is described in the next section. Finally, the adaptation of the models of the Digital Twin has to be performed by the responsible engineers for the affected components using reusable models and information within the CRM, which are referenced directly to the affected anchor points.

3. Realization of the Anchor-Point-Method via an assistance system

An assistance system is an expert system that is developed to support users with a specific function in dealing with complex problems by providing information or recommendations for action [16], [17]. It has the ability to store knowledge, possibly rule-based [18], to process the user input. The output of the assistance system is then derived from the knowledge base and the input data, which support the user in a target application. An assistance system can also have interfaces to higher-level IT systems [18]. In the context of the realization of the Anchor-Point-Method to synchronize the models of the Digital Twin, an assistance system is implemented in this work. The developed assistance system is an integration of three software systems for the realization of the change detection, dependency detection and model adaptation phases. The assistance system was implemented as a Java application, which runs on all standard computer. Fig. 2 gives an overview of the software architecture and the interfaces of the assistance system.

One component of the assistance system is the graphical user interface, GUI. Via the GUI, the user can load two PLC codes from different points in time into the assistance system. In addition, the GUI is used to obtain the user credentials for logging onto the data backbone and the address of the data backbone, which includes the models of the system's Digital Twin.

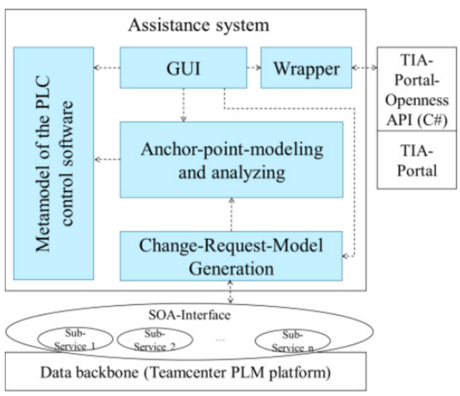

Fig. 2: Assistance system software architecture

Thus, the assistance system can log on to the data backbone, in this case, a PLM system, via its interface and automatically generate change request models to the anchor points of the Digital Twin. A "wrapper" as a further component was implemented in the assistance system to call external software for generating XML files from the PLC code. For the creation of the PLC code, the software TIA-Portal was used in this work. TIA-Portal-Openness is an integrated API of the TIA Portal software, which allows to generate XML data from the elements of the PLC code stored in the TIA Portal format. Since the TIA-Openness interface is only available in C# language, the wrapper is used to translate the commands from the assistance system written in Java to C# for the TIA-Openness API. For the realization of the formalization concept of the Anchor-Point-Method, a component called "Metamodel of the PLC control software" is implemented in the assistance system, whereby two standardized instance object models will be generated from XML. The assistance system contains another component called "Anchor point modeling and analysis". This component is of essential importance for the change detection by abstraction of the generated control software instance object models as well as the analysis of the contained anchor points by decision trees. The anchor point model is based on the abstraction concept of the Anchor-Point-Method, which only contains the necessary data and relations for rule-based analysis. This component consists of a Java class called "Compare", which contains all rules of the Anchor-Point-Method's decision tree. It is used to compare the two anchor point models of the PLC control software to complete the cross-domain changes in the real automated system. The result of the captured changes is stored in the change detection results of the “Anchor Point Modeling and Analysis” component. On the one hand, the GUI can access the results of the change detection and visualize them for the users; on the other hand, their contents are made available to the implemented component "Change Request Model Generation". The Java classes within this component interact with the services of the data backbone, here Teamcenter PLM Platform, using the SOA client library and perform the steps of the Anchor-Point-Method to generate the CRMs and reference them at the anchor points of the overall system model in the data backbone.

4. A use case scenario in ARENA2036

The ARENA2036, Active Research Environment for the Next Generation of Automobile, is a research campus that deals with the next generation of automobiles, the design of agile and flexible production and intelligent lightweight construction. In this work, a flexible intelligent warehouse (iWarehouse) is physically and digitally designed and assembled in a flexible production plant in the Arena 2036. This system is used to evaluate the assistance system and give a qualitative and quantitative evaluation of the benefits using a synchronized Digital Twin for reconfiguring an automation system based on an industry-orientated use-case.

4.1. Physical implementation of the intelligent warehouse

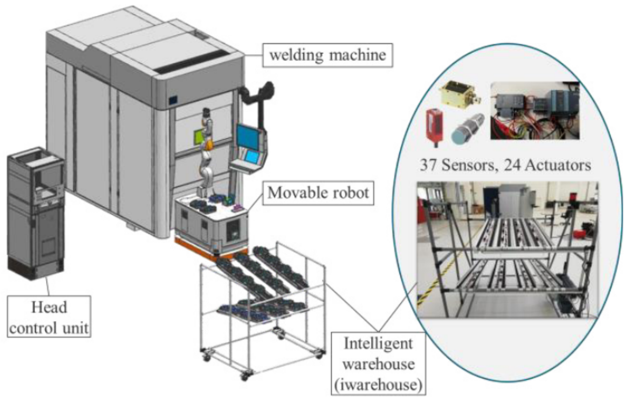

Fig. 3: Components of the flexible production system in the ARENA2036

The flexible production plant in the lab of the ARENA2036 consists of three automated systems (welding machine, movable robot and iWarehouse) with decentralized control (head control unit), which produce a model car from four sheet metal parts. Fig. 3 shows the components of the flexible production plant. The automated systems are not arranged in a fixed, conventional line linkage, but are connected by the movable robot as a driverless transport vehicle. This enables a variable and easily modifiable production process. Here, the iWarehouse is used as a storage facility for the prefabricated sheet metal parts in the workpiece carriers. The position of the iWarehouse is flexible due to its mobile structure and the robot can detect its position by communication via WLAN. The iWarehouse consists of 37 sensors, 24 actuators, a PLC (S7-1500) and a WLAN module for communication between the decentralized peripheral components with the head control unit. In addition to the real iWarehouse's structure, its Digital Twin was also realized with engineering tools.

4.2. Digital Twin of the iWarehouse

A common approach in the industry to create a Digital Twin of the automated system with cross-domain models during engineering process is applying a PLM system. This approach is based on a structured data exchange between different domains, which makes it possible to integrate and manage heterogeneous models in a single IT system. Fig. 4 shows the usage of the iWarehouse with its Digital Twin and the tools.

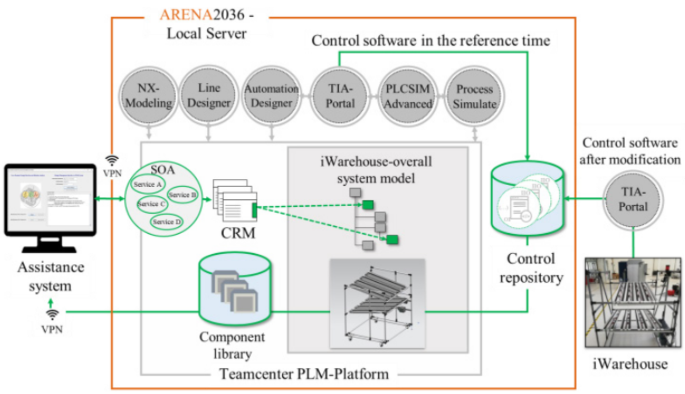

Fig. 4: Usage of the assistance system with the DT of the iWarehouse

Such single IT systems are able to integrate numerous tools and their created models in the context of engineering, management and service through their extensive functionalities, workflows and interfaces. The Digital Twin of the iWarehouse is built on the installed Teamcenter PLM platform as data backbone on the server of ARENA2036. The iWarehouse's models are created using NX-Modeling, Line Designer, Automation Designer, TIA-Portal, PLCSIM Advanced in an engineering process. Furthermore, the Digital Twin of the other automated systems within the flexible production plant such as welding machine, movable robot and head control cabinet were created by the industrial partners using the same engineering tools. Finally, the entire model car production process was simulated and validated in a virtual commissioning with the tools Process Simulate, PLCSIM Advanced and TIA Portal. After validation of the entire system by a virtual commissioning, the PLC control software of the iWarehouse was stored on a control repository with the label "reference time". During the operation of the flexible production plant, the iWarehouse had to be continuously adapted or optimized, e.g. through maintenance, replacement of components, optimization of the entire process flow, etc. After these changes, the control software was saved to the repository with a time label. The developed assistance system automatically detected changes in the system by calling up and analyzing two PLC codes from this repository. In this way CRMs could be created to the changed anchor points of the Digital Twin from the iWarehouse in Teamcenter.

5. Qualitative and quantitative evaluation

To evaluate the Anchor-Point-Method and reconfiguration using DT, a reconfiguration of the iWarehouse was carried out in two different ways in a case study within a student research project. The first approach involves the synchronization of the Digital Twin models with the developed assistance system and the reconfiguration of the iWarehouse using the DT. The second approach, which was raised in a survey, involves reconfiguring the iWarehouse according to a common industrial rebuilding process without the support of the Digital Twin. Therefore, the potential of the Digital Twin cannot be used for reconfiguration, such as model-based system engineering, cross-domain, reusable component libraries, what-if simulations, virtual commissioning and the resulting benefits. A survey was conducted in ARENA2036 to determine the sequence and duration of the reconfiguration process in this approach. A questionnaire was designed to collect comparative data and filled out by eleven different experts from the fields of plant construction and reconfiguration. The interviewees were development engineers, project managers and PLC programmers with professional experience in real automated systems as well as scientific employees who are researching in the field of reconfiguration. The survey was conducted exclusively with regard to the iWarehouse by showing the respondents its real structure and describing the basic functionality of the system. The existing models and the changes occurring in the system were mentioned without specifying their exact content. With this prior knowledge, the survey participants were asked to answer the questionnaire.

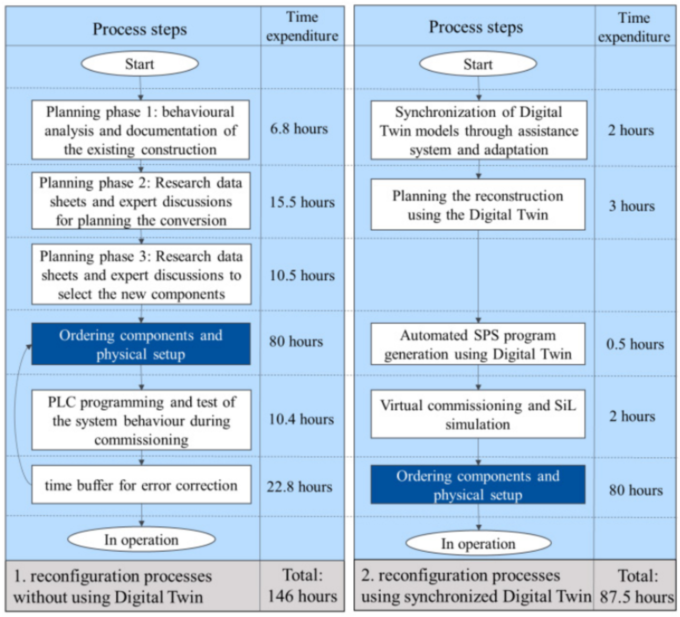

Fig. 5: Reconfiguration steps of the iWarehouse with and without DT

The steps of the most frequently mentioned methods and their sequence were combined to calculate the average processing time of the individual steps. Fig. 5 outlines the sequence and the average time of the process steps of the reconfiguration without using the DT as well as the results of the actual reconfiguration of the iWarehouse using the DT synchronized by the Anchor-Point-Method. The process without the DT begins with research into the behavior of the system and detection of the components. This is followed by an expert discussion about the necessary modifications and components in the system to meet the customer requirements. The corresponding components are then ordered and the iWarehouse is converted. 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 test period. If no errors occur in the system, the iWarehouse is put into operation. According to the survey's answers, it can happen in practice that an error is detected during the buffer time in the system and the rebuild process is repeated accordingly. In the reconfiguration approach using the Digital Twin, the first step is to carry out change detection with the help of the assistance system. In about two minutes, the assistance system has successfully completed the analysis of the PLC control software at the reference time and the current status. In this time, it also identified all changes occurring in the iWarehouse and their dependencies during operation. Furthermore, correct CRMs were sent to the anchor points of the iWarehouse on the PLM platform. However, the detection of the exact mechanical localizations of the changes is a challenge that cannot be solved automatically with the Anchor-Point-Method alone and inevitably requires the cooperation of a systems engineer. The exact location of the changes in the models can be adjusted in a few hours, depending on the scope of the changes. In the case of iWarehouse, the changes could be implemented in just under two hours. The further steps to reconfigure the iWarehouse are shown in Fig. 5.

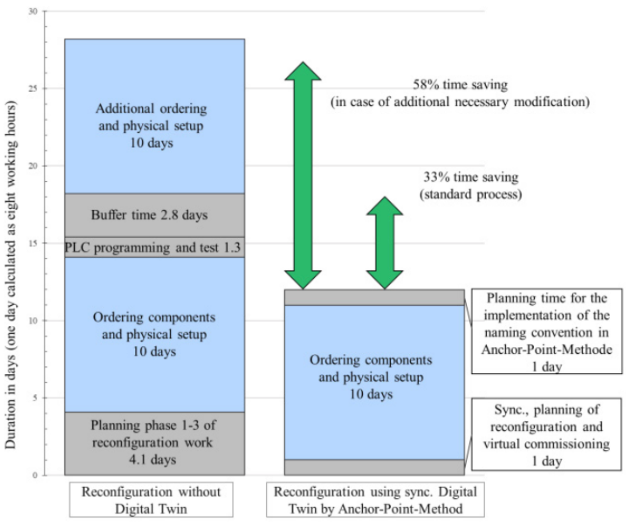

Fig. 6: Time evaluation of the reconfiguration process with and without DT

The results of the survey on reconfiguration without a DT and the calculated times using a DT synchronized with the Anchor-Point-Method serve as an evaluation of the benefits of reconfiguring an automated system using Digital Twins. Fig. 6 compares the time of both reconfiguration processes. Due to the lack of simulation, it is expected that the reconfiguration without DT will not be completely successful at the first attempt. For this reason, the reconfiguration process without the use of a DT is expected to involve an additional ordering process and a new reconfiguration phase for ten days. Furthermore, for a correct evaluation of both approaches, the additional time required for the planning of the anchor points (consideration of the naming convention) in the engineering process was included in the total duration. With regard to the quantitative evaluation use of a synchronized DT shortened the reconfiguration process and the downtime of the iWarehouse by about 33 percent in the standard process and 58 percent for an additionally required rebuild. The physical test operation of the system can be omitted, since this has already been carried out virtually. In the context of a qualitative assessment, the completeness of the test results by simulating several possible production scenarios, reconfiguration using the Digital Twin reduces the production risk after commissioning.

6. Summary

The described Anchor-Point-Method enables automatic updates of the DT and is presented as a solution to synchronize the DT based on PLC code analyzes. Using an assistance system as implementation of the Anchor-point-Method, the benefits of an up-to-date DT were evaluated. A reconfiguration of an automated system using an approach based on its DT synchronized with the Anchor-Point-Method and an industrial standard approach without using the DT was carried out. The result shows significant time saving.

The presented method for the synchronization of the DT detect and transfer changes, which can be detected inside the PLC code. The exact mechanical position of a new component and pure mechanical or electrical modifications cannot be synchronized automatically, but need to be done manually. It could be quite difficult to find such modifications of large machines by hand. This approach could be combined with other data sources like the process data or data from a real-time locating system. Analyzing them could allow to identify the mechanical changes, enable automatic synchronization of these and therefor increase the benefits of the DT in late phases.

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