Consistency check to synchronize the Digital Twin of Manufacturing automation based on anchor points

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Abstract

Increasing product variety and the shortening of product lifecycles require a fast and inexpensive reconfiguration of existing manufacturing automation systems. To face this challenge one solution is a Digital Twin, which can be used to reduce the complexity and time of reconfiguration by early detection of design or process sequence errors of the system with a cross-domain simulation. For engineering the Digital Twin and systemically synchronizing the data of mechatronic components in the interdisciplinary engineering models of a Digital Twin during the life cycle of manufacturing automation systems, this paper presents a concept for the engineering of a Digital Twin based on model integration in a PLM IT-Platform and an Anchor-Point method to systematically detect variances of the mechatronic data structure between the digital models and the physical system. The data of a mechatronic component from interdisciplinary domains, developed by the corresponding engineering tools are referred to as anchor points. This paper analyses domain-specific challenges in automation software-code to develop an assistance system for rule-based consistency check and for synchronizing the engineering models of the Digital Twin of the manufacturing automation system based on the Anchor-Point method.

Keywords: Digital Twin; Manufacturing systems; Mechatronic design process; Assistance system; Change management.

1. Introduction

The automotive industry is an example for advanced manufacturing automation. Nowadays, automotive manufacturers are participating in a global competition characterized by growing customization demands and the need for increased product variety [1].

Increased reconfigurability and flexibility of corresponding production systems is thus aspired to meet these demands [2]. In response to occurring industrial challenges and motivated by the need for increased efficiency in production, the concept of Industry 4.0 emerged [3]. Within this concept, production systems can be equipped with connectivity features and are to be engineered and operated in a way that would enable them to benefit from intelligent services. These services can access and use available information about the production system to provide assistance functions during operation and optimize the system's performance [2, 4].

Using concepts of Industrie 4.0 to achieve a dynamically reconfigurable production system that can promptly respond to actual market demands and changing requirements is therefore necessary for automotive manufacturers to keep pace with global competition. One of the Industrie 4.0 concepts to enable this is the Digital Twin [5].

1.1. The Digital Twin

The Digital Twin is a virtual model of a physical asset capable of fully mirroring its characteristics and functionalities during its entire lifecycle. It is an approach to manage all generated digital data of a component or system along its lifecycle and retrieve them as needed by simulation or optimization functions to address any occurring challenges. The concept of the Digital Twin as applied on an industrial system can be associated with the concept of Product Lifecycle Management, where a model in a virtual space was described that is created in parallel to a physical system and gradually enriched with information [6]. Other terms within this concept have been mentioned, such as a 'mirrored spaces model' or an 'information mirroring model' by the same author [6]. The term Digital Twin as such, was mentioned in a NASA report containing their future strategies for modeling and simulation (NASA Technology Roadmap, 2010 and 2012) [7]. Within the concept of Industrie 4.0, the Digital Twin has gained more momentum in the industry sectors as a method for managing increasing system's complexities and as a link to the digital world, thus facilitating applying intelligent functions and services to the physical systems [5].

1.2. A cross-domain simulation with the Digital Twin

For the Digital Twin to contain all generated data along a system's lifecycle and be used during its lifecycle, its development and connection to the physical system should be considered at an early lifecycle phase.

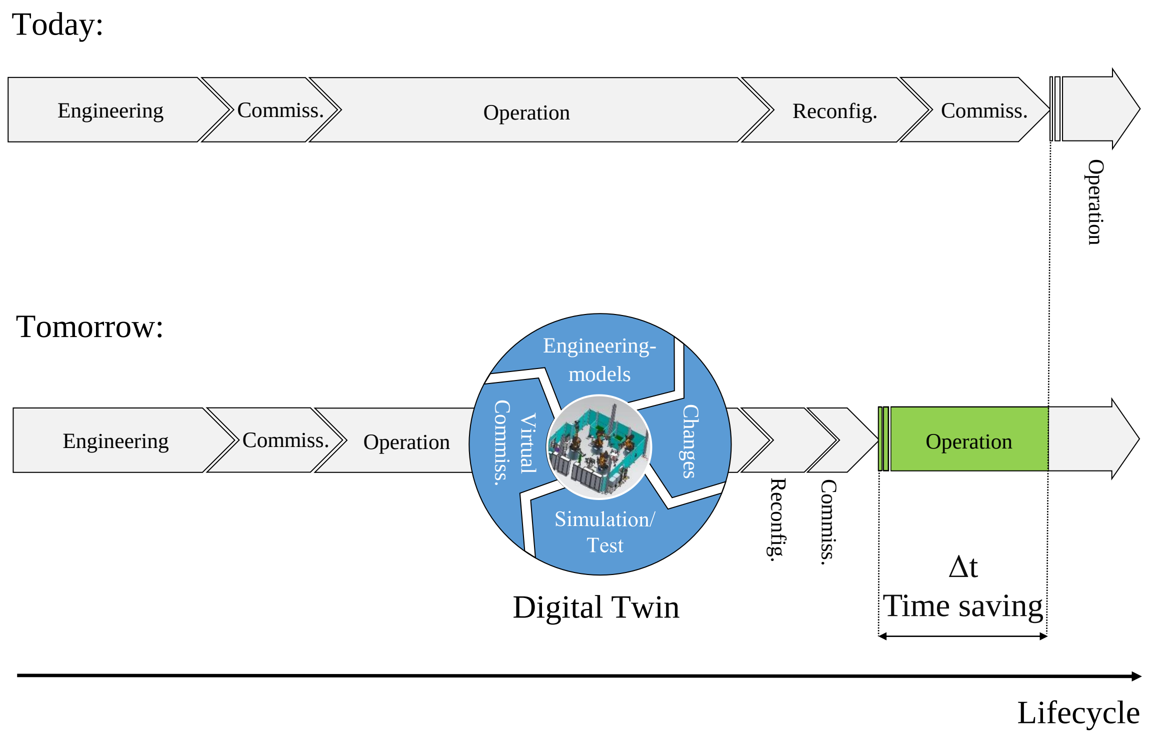

Fig. 1: Digital Twin and life cycle of manufacturing automation.

Manufacturing automation in the context of this paper is an example automotive manufacturing cell. Such an automated manufacturing cell consists of mechatronic components linked together and controlled centrally via a programmable logic controller, PLC. These components cover a wide variety of sensors, actuators, such as industrial robots as well as conveyors etc. An automated cell can be referred to as a mechatronic system. To implement the concept of the Digital Twin on the mechatronic system, it is important to get an overview of its engineering process and the used software tools.

In the engineering of a mechatronic system, first a concept for product and production is created, upon which the system is designed. Correspondingly, a concept for the infrastructure of the Digital Twin is created in parallel. The Digital Twin concept at this stage includes the creation of a digital container, where created data with a specific transfer mechanism can flow into. The design and engineering of a mechatronic systems involves several domains such as mechanical, e.g. geometry and physical component selection, electric, e.g. sensor lists and circuit plan as well as software design e.g. PLC control code. Each of the domains have specific software tools, with which models can be created [8]. Simulation and modelling of each domain is state of the art, as it helps showing design flaws and improves operation [9]. The domain-specific model generation is sequential as the mechanic model precedes the electric model and the software model. Iterations to improve any design change in the sequential process are therefore time consuming [8]. Furthermore, with increasing complexity and functionality of the mechatronic system, more domains are involved with stronger dependencies, making a variable cross-domain simulation necessary. At this phase, the Digital Twin is enriched with the developed multi-domain models, which are integrated and semantically referenced together. References between models are achieved by using software tools that allow model integration and data exchange across different domains. This enables a cross-domain simulation of different aspects and the system behavior [7].

A cross-domain simulation during engineering supports a rising tendency for parallelizing the engineering process, therefore reducing engineering time and supporting multi-domain collaboration. After system commissioning, the gained value from the Digital Twin increases as it closes the gap between engineering and operation in the cell's lifecycle by making the models created during engineering also useable during operation [7]. These models can be used for simulations while making reconfigurations for example. This way, reconfiguration is done more time efficiently without the need of testing the physical system repeatedly and mainly relying on domain experts [10]. Furthermore, being connected to the manufacturing cell, the Digital Twin receives updated status information, which are used to optimize the system's performance and detect any failures. Changes occurring in the manufacturing cell, such as the exchange, deletion, addition of a mechatronic component must be updated on the Digital Twin as well to avoid a gap between the digital model and the physical asset. The Digital Twin then becomes a system's byproduct and addresses the challenge of increased system complexity as well as abrupt market requirement changes, Fig. 1.

1.3. Challenges

The vision of the Digital Twin for a manufacturing cell as previously described is currently challenging to realize [7]. With growing multi-domain models, a growing need for consistency and model integration to a single source of information arises. To address this issue; two important aspects must be considered.

- Integration of multi-domain engineering models into a consistent Digital Twin.
- Synchronization of physical changes on the Digital Twin.

The first aspect deals with how the multi-domain engineering models are integrated and referenced on the Digital Twin to optimize the cross-model collaboration. The second aspect raises the question of how physical changes in the manufacturing cell are detected and synchronized on the Digital Twin to continuously keep it updated with the current cell status, while maintaining model dependencies consistent. Currently, there are no optimized methods to seamlessly integrate the different engineering models on the Digital Twin. There are data transfer mechanisms between domain specific engineering tools. Besides technical reasons, a cross- domain collaboration also has a challenge of employing modularization methods as a multi-domain mechatronic system can be viewed from a physically-oriented, a device-oriented or a function-oriented perspective [11].

The Anchor-Point method [12] is a method for systematically synchronizing the Digital Twin with the physical manufacturing cell by detecting changes in anchor points of mechatronic components in the different developed models by corresponding tools and synchronize these models during whole life cycle of the system. Anchor points are identified characteristic model information with interfaces to other domain models. After detecting changes, a consistency check between models is conducted to maintain their dependencies.

2. State of the art

The state of the art discusses methodologies for multi-domain model integration on a single IT system by exchanging data between domain specific engineering tools for creating a complete cross domain project.

2.1. Exchanging data between domain specific tools

This approach discusses methods for transferring data generated in a specific domain with a corresponding software tool to another domain specific software tool in order to reduce the engineering effort of the repeated generation of the same data [8]. For this purpose, data exchange between software tools can be achieved either with a point to point transfer mechanism, in a structured or semi-structured way or with the use of semantic models.

- A point to point data transfer is a direct exchange method. This method is restricted for data transfer within a specific domain. The direct data exchange is on the basis of transformation rules denoted in a standard. An example for point to point data transfer is PLCOpen, a standard enabling data exchange between vendor-different programmable logic controllers.
- A structured approach to exchange data of different domain database elements is by managing heterogonous database formats and elements with a meta-database on a single IT-system. Two library elements of different domain databases with different structures belonging to the same mechatronic component can then be joined together [13].
- A semi-structured approach uses neutral data formats for the data exchange. An XML-file is an example of this approach, it contains model data, as well as data describing their format, called metadata. With information contained in XML-files, different software tools can extract and the exchanged data from the xml file by parsing its elements and attributes [14].
- Semantic technologies can be applied for data exchange between software tools to support their interoperability. To achieve this, not only data should be known and exchanged, but among other its syntax and semantics. This can be achieved by adding global identifiers to data [15] or through using an object-oriented approach by identifying objects and their attributes as well as relations to other objects [16].

2.2. Scientific deficit

The discussed approach for data exchange with its different methodologies shows deficiencies when applying them to model integration and referencing on the Digital Twin. The exchange methods listed are applicable during the detail phase of the engineering process. The Digital Twin is to be synchronized with the actual state of the manufacturing cell. In order to achieve this synchronization, each engineering domain has to be updated. For this reason, knowing how domain models are related to each other is necessary. This requirement is not provided by the current approaches. Furthermore, the mentioned data exchange approaches discuss the engineering phase of a system and do not address the challenge of systematically updating the multi-domain models in case a physical change occurs.

Facing these deficits this paper presents an engineering approach for the integration of the multi-domain engineering models on the Digital Twin based on anchor points during the detail design phase. After introducing the structure and basic ideas of the engineering approach, special attention is paid to the Anchor-Point method [12] to synchronize the disciplines engineering models of manufacturing automation during their whole lifecycle. The anchor point method has been firstly introduced and developed by the same authors and is based on determining specific identifiers for each domain-specific engineering model to enable a cross domain collaboration [12].

3. Digital Twin based on model integration in PLM IT-Platform

A Product Lifecycle Management (PLM) system holds and maintains the integrity of the product data produced throughout its entire lifecycle. To build a Digital Twin of a manufacturing automation, a metamodel in the PLM system during engineering must be created. This metamodel is necessary, as it semantically references and stores data of domain-specific models, which have been created by different domain specific tools. As an example, this metamodel can be a higher-level production structure hierarchically organizing data of mechatronic components from different domains. The production structure coordinates data belonging to the same mechatronic component in a conceptual shell. This shell has a unique Item-ID or symbolic name to uniquely identify the mechatronic component along its lifecycle. The shell encapsulates mechatronic data from different engineering models and has interfaces to the domains via the corresponding engineering tools, with which the models are developed. These data in the shell of a mechatronic component from interdisciplinary domains are referred to as anchor points. As an example, Fig. 2 shows a production structure in the PLM-IT Platform. A shell of a conveyer in station 1 references and encapsulates conveyor data, for example 3D-geometry, electrical circuits and PLC function blocks from different models developed by different tools.

The anchor points of mechatronic components in the different models are developed and maintained by the corresponding engineering tools. For data of interdisciplinary models to be encapsulated by the shell, it is necessary for the corresponding engineering tools to support an interface to the shell for semantically data exchange. Besides engineering models, a shell of a mechatronic component can also include other data and information relevant to it during its entire lifecycle, such as maintenance and service data as well as information from the office floor level, Fig. 3.

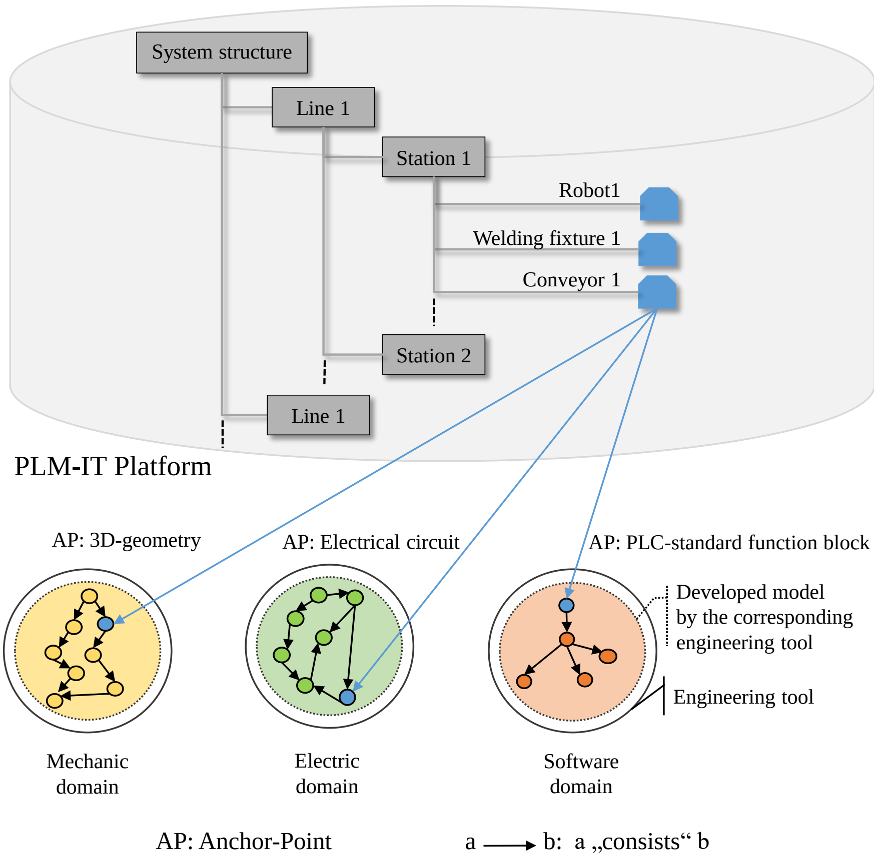

Fig. 2: Exchange data of different domain database elements is by managing heterogonous database formats with a meta-database on a single A PLM-IT Platform.

Having a metamodel fulfils the requirement of the Digital Twin to contain data of heterogeneous sources. Another requirement is to manage this data, to enable synchronization along the lifecycle of mechatronic component.

This requirement is fulfilled by integrating the metamodel on a Product Lifecycle Management IT-Platform, referred to as PLM IT-Platform. This metamodel must be managed via a PLM IT-Platform. A PLM IT-Platform is an open data backbone, which integrates the metamodel and has available tools and services, which can manage it and make its data accessible with different detail levels to different actors along the lifecycle.

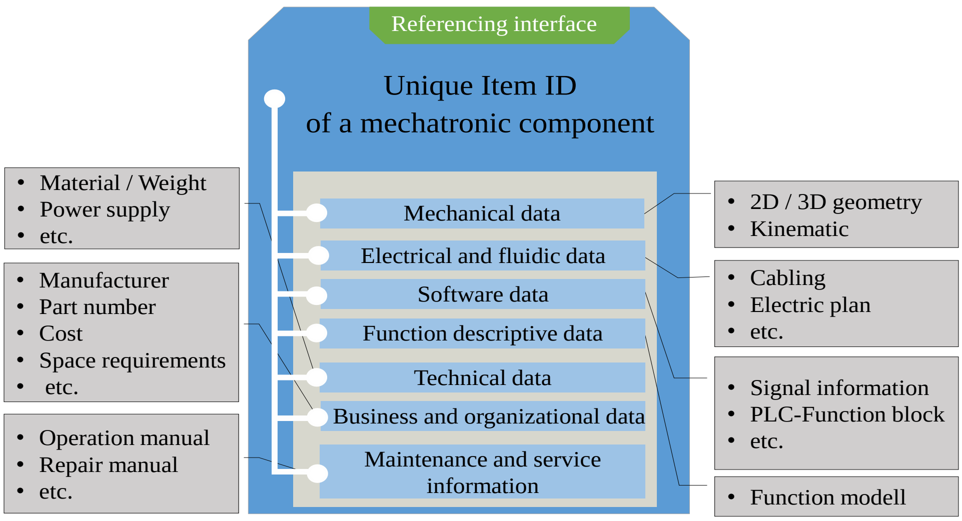

Fig. 3: A shell for encapsulating the information and anchor points of a mechatronic component.

4. Anchor-Point method to synchronize the Digital Twin

As previously mentioned, the anchor points of a mechatronic component in its shell are derived from engineering models developed by different tools.

For a successful synchronization, first the anchor points of a mechatronic component must be identified from a data source of a manufacturing cell, where its actual status is reflected. Then, any occurring changes must be adjusted to the shell of a mechatronic component in the production structure on the PLM-IT platform. The data source reflecting the physical cell's status can be the software code of the distributed automation system, such as the actual PLC code or robot codes in this cell. For future reference in this paper, both will be referred to as software code. The synchronization based on the detected changes of identified anchor points must undergo a rule-based consistency check between different models corresponding engineering tools. This analysis must be based on a categorization of different change scenarios in the automation system during commissioning and operation. Using this analysis, relations of mechatronic components in different models in the corresponding tools can be kept consistent.

4.1. Rule-based consistency check based on a decision tree

For the synchronisation of the Digital Twin it is not only necessary to detect anchor points of a mechatronic component in different tools models but also the relations of this component to other components in interdisciplinary domains are necessary to have a consistent Digital Twin of the manufacturing cell. For example, if a new sensor is added to the conveyor, not only its related 3D-geometriy, electric circuit as well as its PLC function block should be considered, but also the relations this added component has to other components, such as the cable connecting it to other mechatronic components or its signal as a transition condition for affecting the behaviour of another component. To model these relations, a decision tree has been created, where change scenarios such as the addition or removal of a component and the affected interdisciplinary relations in engineering models are described. For these consistency check, it is necessary to categorize all possible and frequently occurring changes in the physical manufacturing cell at the commissioning time and during operation. These can be modeled rule-based in a decision tree. With the aid of this rule-based consistency check based on a decision tree software codes from distributed automation systems in manufacturing cells can be analyzed at different times. Moreover, this decision tree can always be expanded for detection of further change scenarios in the real world as well as for better analysis of the software codes.

4.2. Assistance system with interface integrated on PLM IT system

The proposed assistance system is a system responsible for synchronizing the Digital Twin after detecting changes with the aid of anchor points. Fig. 4 shows the structure the assistance system as used in the anchor point method. It has multiple interfaces to the PLM -IT platform. One interface is with the repository, where the software code of the distributed automated system at the time of commissioning is stored. This code is retrieved as an input to the assistance system. The other input is the actual software code retrieved from the running manufacturing cell. The code retrieval from the running manufacturing cell can be save periodically in the software code repository integrated on the PLM-IT Platform. Both software codes have been exported in XML format as a neutral data format. As the schema describing the exported XML document is the same, an increasing complexity of the software code only results expanding the analysis to all existing components and functions and is not expected to increase the computing effort drastically. The assistance system then compares and analyses both textual files based on an embedded decision tree. After this step, software anchor points of the changed, removed or added mechatronic component are detected. Furthermore, the affected component's unique Item-ID is detected. With the Item-ID, the assistance system can call the specific mechatronic component's shell from the reuse library. The reuse library contains unique Item-ID's of mechatronic components from different suppliers and is integrated on the PLM-IT system. This ID must be supplied in a standardized way with other data describing the component, such as mechanic and electric anchor points as well as material and organizational data. In the final step, the assistance system has the detected software anchor points from the inputted software codes and the electric and mechanical anchor points from the reuse library.

The assistance system can then output a shell containing all anchor points to the production structure. Based on the change scenario, the changed anchor points are adjusted to the models developed on the different engineering tools.

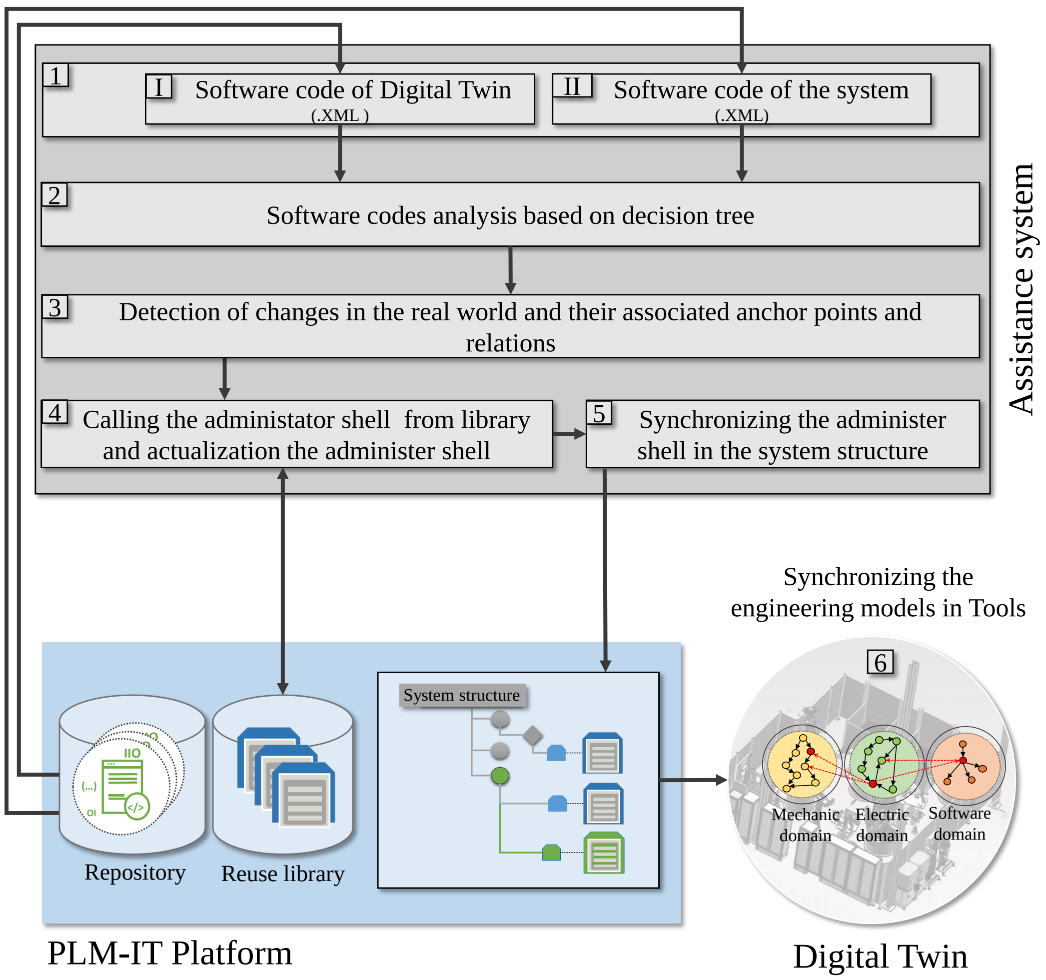

Fig. 4: An assistance system to synchronize the Digital Twin of manufacturing automation based on anchor points.

5. Summary

This paper presents an engineering approach to integrate multi-domain engineering models on the Digital Twin based on anchor points of mechatronic components and PLM IT-Platform during the engineering phase.

After introducing the structure and basic ideas of the engineering approach and the shell of mechatronic components in the digital world special attention was paid to the Anchor-Point method to detect anchor points of mechatronic component in the physical system and systemically synchronize them in the hierarchical production structure in PLM IT- Platform. The implementation of the assistance system is planned to take place on an automotive manufacturing cell, which is controlled by a Siemens PLC STEP 7. For the preliminary prototypical implementation and validation, a Festo Modular Production System is being used. With the aid of this assistant system based on the Anchor-Point method it is possible to maintain a Digital Twin during the entire lifecycle of a manufacturing automation system.

Having a Digital Twin enables performing further analysis on the system, like definition of test cases for the whole system. This safeguards a reconfiguration process and thereby contributes to reducing of expensive errors occurring during commissioning.

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