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A digital twin for production planning based on cyber-physical systems: A Case Study for a Cyber-Physical System-Based Creation of a Digital Twin

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Abstract

The increasing change of production leads to differences between the current shop floor and the state of planning. This difference causes significant challenges for production planners while integrating new products into existing production systems. To tackle this issue, this paper presents a concept for the automated creation of a digital twin of a body-in-white production system based on current resources, products as well as process information from the cyber-physical system. The paper focuses on the different data sources and information in cyber-physical systems necessary for integration planning. Furthermore, major parts of the concept are evaluated in a real body-in-white production system. The resulting digital twin enables faster product integration and Industry 4.0 concepts.

Keywords: Digital twin; Body-in-white production systems; Cyber-physical system; Production planning; Integration planning

1. Introduction

The increasing electrification in the automotive industry [1] leads to an increasing number of vehicle variants which have to be integrated into existing body-in-white (BIW) production systems. This integration represents a big challenge for production planners because there can be differences between the real production system and the state of planning. Westkämper [2] describes these differences between the real shop floor and the planning models as one of the most significant weaknesses of today's information systems. A production system underlies a continuous optimization process during the life-cycle of the production. These optimizations cause differences between the planning models and the real production system. The basis for an expedited and low-cost integration of new products would be an always current digital image of the production system known as the digital twin. To keep this digital image up to date, it is essential that all the information from the real factory is transferred back to the digital model [3] [4].

In section 2, the state of the art, the technical issue as well as the research gap are described. Section 3 presents the concept for creating a digital twin based on cyber-physical systems. In section 4, information on the cyber-physical system from a case study in a BIW production system is illustrated and evaluated. The conclusion and further work follow in section 5.

2. Motivation and State of the Art

In this chapter, the technical issues in the production planning in the automotive industry are presented. In addition the state-of-the-art and the research gap for the automated creation of a digital twin of a BIW production system are discussed.

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2.1. Problem Statement

In the following, the technical problem and the research gap will be discussed. Figure 1 represents a simplified description of the issues in the automotive industry for integration planning of new products and shows the need of an automatic update of a digital twin for the BIW production system as a current planning project.
The digital factory enables an early parallelization of product development and production planning [5]. On the upper left side of the figure, the planning and building process are divided into *rough planning*, *detail planning*, and *engineering* as well as *implementing and building*. The rough planning takes place by the automotive original equipment manufacturer (OEM) itself [6]. Following cost work with different facility suppliers, the internal rough planning state of the OEM has the best quality. The OEM instructs an external facility supplier to build the assembly line. The facility supplier does the detailed planning and engineering after receiving instructions [6] [7]. At this time, there are differences between the internal rough planning and the external detail planning project (issue 1). According to the detailed planning and engineering, the production system is built by the facility supplier. At the installation of the assembly line, there are also some differences between detail planning (simulation and offline programming) and the reality. These differences will be fixed directly during installation and do not lead back to the original rough planning state (issue 2). After the start of production (SoP), the lot of the production system transfers to serial production and the production planners are working on new projects. During the production life cycle, there are cycle time and production optimizations which change the production system. Further possible triggers for changes are new products, changing requirements and new technologies [8]. Through these changes in the production system, the quality of the digital image decreases primarily through the model update (issue 3). A manual inventory list made by planners would take much time and is cost intensive. The difference between the real production system and the digital model is a great challenge for production planners when integrating new products. To solve this challange, an on-demand, automatically created digital twin is required. This digital twin would increase the quality of the digital image. Through a current digital twin, the integration time for new product variants into the existing BIW production system could be reduced (Figure 1) as well as costs for manual documentation saved. Furthermore, product development can develop the product under consideration of production-relevant aspects.

However, there is no public industrial concept for an on-demand created digital twin of a BIW production system.

2.2. State of the Art

One of the first public definitions of a digital twin is given by Shafto et al. [9] in 2010. He defined the digital twin as an integrated multi-physics, multi-scale, probabilistic simulation of a system which uses the best available physical model [9]. Since 2010, the digital twin has been created in production, especially in the simulation and the virtual commissioning. It is described as a software model for the development and testing of different configurations. [10]

However, the simulation aspect is just one of many digital twin concepts [11]. Exact digital twin models are also used for power flow optimization and energy optimization in BIW production systems [12]. Nowadays, the digital twin is defined as a realistic model on a current state of the process and behavior of real objects with its structure and elements that are connected to it [10]. In the review from Negri [13] in 2017, the roles of digital twins in cyber-physical systems-based production systems have been described. However, there is no concept of an automated created digital twin of BIW production systems with the use case of integration planning.
In this paper, a concept of an automatically created digital twin of BIW production systems will be discussed and partly evaluated in a real BIW production system.

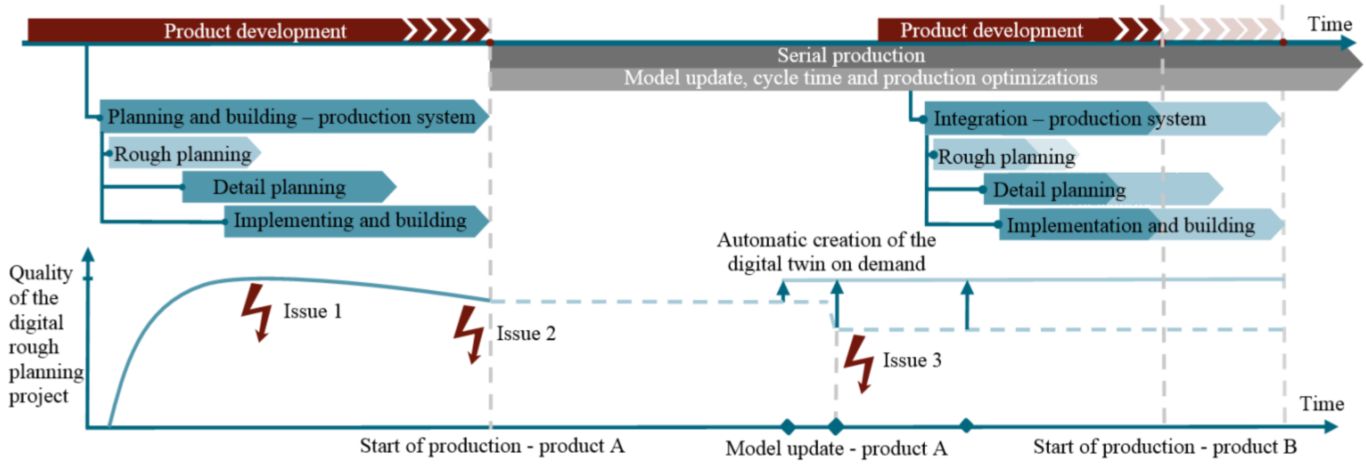

Fig. 1: Simplified description of the industrial issue and research gap.

3. Approaches for a Digital Twin in Body-in-White Production Systems

Astari et al. [14] describe the digital twin as a system which consists of data and information about each asset in the real world, different models as well as different granularities. In the concept of an automatically created digital twin of the BIW production systems in this paper, the data and information about each asset come from the cyber-physical system on the shop floor. The cyber-physical system (CPS) is a set of embedded systems which communicate and interact with each other in a communication network [15] [16]. In the context of production technologies, the CPS is called cyber-physical production system (CPPS) [17].

3.1. Digital Twin Requirements for Integration Planning

In the following, a digital twin of BIW production systems for the use of integration planning is discussed. The requirements for the digital twin have been identified in different interviews and discussions with experts of the digital factory as well as planners and a manager from the internal rough planning department. A fundamental requirement for a time reduction in integration planning is a current bill of resources which includes the planning object identification numbers as well as the current position of each resource in the digital twin model [18]. However, there is some more information in addition to the resource information which is essential for the planning department by integrating new vehicles. A digital twin of BIW production systems should contain the knowledge of the current cycle times of each station and production line. Furthermore, the idle time of each robot, as well as the different cycle times of each process, are essential information for a digital twin. Moreover, a joining element distribution to each robot and station is helpful for the integration. Also, the different variant distributions and load levels of the joining points about the robots are essential information. Based on all these information bottlenecks as well as free capacity for the integration can be identified. Furthermore, a significant data analysis of each process cycle time can be used to optimize the planning cycle times for future projects. Thus, in the future, a great deal of additional money can be saved.

3.2. The Digital Twin Data Concept

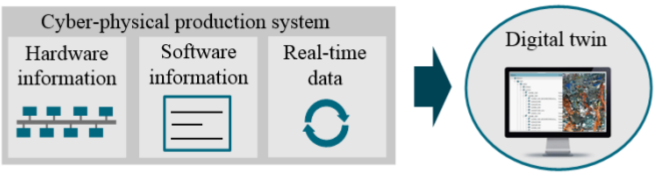

Fig. 2: Cyber-physical production system as data source for a digital twin of a BIW production system.

The CPPS contains a lot of hardware information about each electrical and mechatronics device. In addition to the hardware information, the CPPS contains software information as well as real-time data as illustrated in Figure 2. This information can be used to create a digital twin for production planning. In the following, different methods to acquire the current resource, product, as well as process information from the CPPS by analyzing the hardware configuration, parsing the software and measuring real-time information are illustrated and discussed.

3.3. The Cyber-Physical Production Systems as Information Source of the Digital Twin

In the automation system of BIW production, the primary devices are programmable logic controllers (PLC) as well as robots. The PLC controls robots, devices as well as sensors and actors. Each robot also controls different devices. A device can control sensors and actuators. In the following, three methods to access the information in the CPPS are discussed.

One way to acquire the resource information of the CPPS is a network scan. Another way to acquire resource information of a CPPS in a BIW production system is the combination of offline hardware configurations of the robot and PLC which are located on backup servers. The results are information about all the electronic and mechatronic devices [19].

OEMs use the backup servers to save current software and hardware configurations of PLCs and robots. So the backup server can also be used to parse the PLC and robot software to generate information for the digital twin. By parsing the software, there is additional information about pure mechanical equipment. In the software of the PLC, there is information about the different variants which are built as well as cycle times of the station and production line. In the software of the robot, there is information about the different variants as well as information about the joining point distributions and the load level. Hence, the software of the CPPS in the BIW production system offers a great deal of product information for the digital twin.

In 2014, Bauernhansl et al. [20] described the integration of real-time information as one of the most significant challenges of Industry 4.0. The implementation of the Manufacturing Service Bus (MSB) in automotive BIW production systems has solved this major challenge of Industry 4.0. The MSB is a special kind of enterprise service bus for production systems which links data between the data source and data user [21]. For data transfer, the MSB uses the Message Queue Telemetry Transport (MQTT) protocol. MQTT was invented in 1999 as a lightweight and straightforward messaging protocol which is designed for constrained devices and low bandwidth for high-latency networks and low-reliability needs [22]. The MSB can deliver different information through MQTT, for example in JavaScript Object Notation (JSON) format, which is easy to read and parse. Through the implementation of MSB, it is possible to send different information from each device in the CPPS to a client such as the digital twin. Contents of JSON files can be information about the hardware, real-time data as well as whole parts of the software of a device. The processing time of each process can be calculated through the time difference between the time stamps of two event-triggered JSON files ─ one at the start and one at the end of each software program. Through this method, the latency time in a production network can be neglected.

Table 1: Information access and sources in the CPPS.

	Hardware information	Software information	Real-time data
Network scan	x		
Offline configuration (backup server)	x	x	
Real-time system (Manufacturing Service Bus)	x	x	x

In table 1, the discussed data sources as well as the three different access methods in a BIW production system are compared. This comparison shows that the MSB enables the best access to the information in the CPPS compared to the other methods.

4. Case Study: Cyber-Physical System Information for the Digital Twin

This case study focuses on the current information in the CPPS of a BIW production system which is needed to create the digital twin. In the following, the information for the digital twin in PLCs and robots is analyzed and parsed in a real production system.

4.1. Application BIW Production System

In Figure 3, a very simplified image of a BIW production system is shown. It consists of different robot modules for joining and handling as well as different stations.

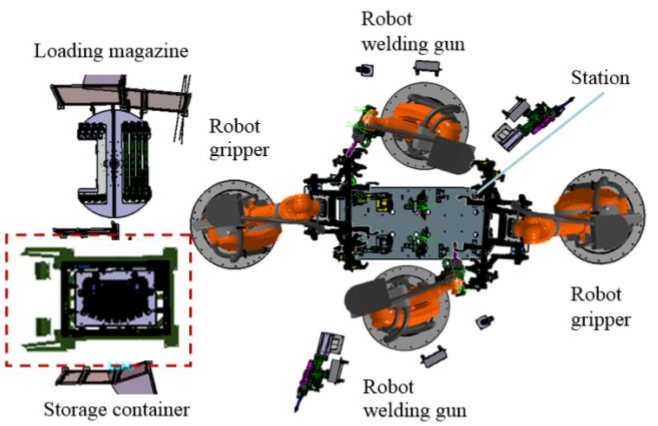

Fig. 3: Simplified description of a body-in-white production system.

In the BIW production system, robots handle parts of different variants between the fixtures, where the parts are joined by different joining robots [23]. Hence, a robot has the information where it collects a vehicle component and where the component is deposited. So it is possible to parse the position of a loading magazine and station to the robot by parsing the robot's software. In the robot software, there are two different information sources about the robots position. On one side, the robot has the information about the position to the equipment with which it is working. On the other side, there is the so-called "base position" which describes the robot position to the vehicle 0 point at the station with which it is working. In addition, the software offers information about pure mechanical equipment such as a storage container (Figure 3 marked red). A gripper also has information about the component flow which can be used to create a predecessor to successor relation for the stations in the BIW production system. This is important information for future autonomous planning assistant algorithms [23]. A robot has all the information about the device which is controlled by it, such as the technology controller of a gripper or a welding gun as well as type of welding gun. As Figure 3 illustrates, the code of each main program contains information about the variants and loading level of the products with which the robot is working. Also, there is some information about current joining points defined in subprograms of the robot.

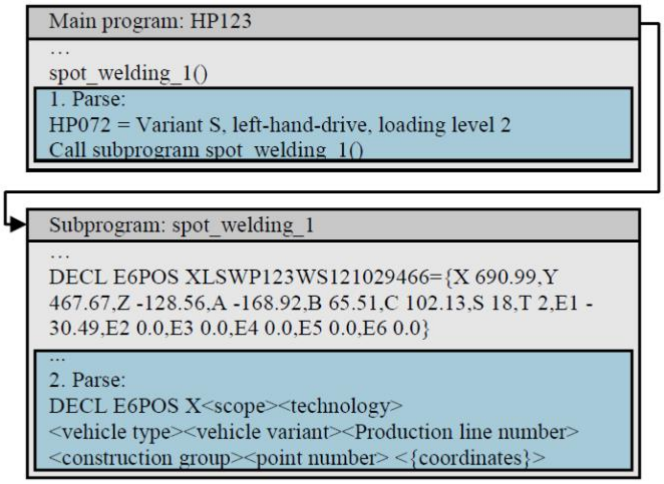

Fig. 4: Simplified parsing example of joining points in the robot software.

Through parsing the software, it is possible to acquire this product information. The logic of the developed parser is illustrated by example in Figure 4. This parser identifies different variants, joining point numbers, and coordinates a joining point for each robot. To always acquire the current joining points, the parser checks if the main program calls the subprogram joining. Furthermore, it is possible to access information about the contact pressure of a welding gun, its process time and material thickness. However nowadays, whole program parts of the software can also be transferred by the MSB. Hence, parsing of this software is also possible by using a real-time system. In addition, through the implementation of real-time systems in the BIW production system, it is possible to calculate the current cycle-time of each process. This can be realized by triggering the start and the end of each specific program of the robot. Figure 5 illustrates two JSON files which it can acquire from the robot through the MSB. The first JSON file in Figure 5 is event triggered by the start of the subprogram spot_welding_1 of the robot. The second JSON file is event triggered by the end of the subprogram. These JSON files contain information about the robot as well as the program number, the load data, and a time stamp. By calculating the different time between the two JSON files, it is possible to evaluate the cycle time of spot welding for this robot. In the example in Figure 5, the process cycle time of the robot's spot welding program would be approximately 18.398 seconds.

```
JSON file 1 – triggered by program start
{
  "CYCLETIME":{
   "@Name":" /D/XBO/JSON/ /0500/h901-02…
        "RobotName":"UB50_020RB_400",
        "Serial":"636408",
        "PNDeviceName":"h901-020rb-400-kf106.m050g7sub50plc1",
        "Pro_state1":"#P_ACTIVE",
        "Appl_Run":"TRUE",
        "Pgno":"72",
        "sLast":"2",
        "TimeStamp":"1523274444427",
        "TimeStamp2":"2018-04-09T11:47:24.4270229Z"
    }
}
JSON file 2 – triggered by program end
{
  "CYCLETIME":{
        "@Name":" /D/XBO/JSON//0500/h901-02…
        "RobotName":"UB50_020RB_400",
        "Serial":"636408",
        "PNDeviceName":"h901-020rb-400-kf106.m050g7sub50plc1",
        "Pro_state1":"#P_END",
        "Appl_Run":"FALSE",
        "Pgno":"0",
        "sLast":"2",
        "TimeStamp":"1523274462825",
        "TimeStamp2":"2018-04-09T11:47:42.8253545Z"
    }
}
```


Fig. 5: Example of the cycle time calculation of a spot-welding program.

The PLC device also offers resource information about all the connected devices, sensors and actuators as well as robots. Devices which are controlled by the PLC are fixtures, robots and loading magazines, for example. There is some product information such as the variant type, which is based on the production system. Furthermore, there is also process information about current cycle times of the production line via triggering the start and the end of each specific program as illustrated for the robot in Figure 5.

4.2. Evaluation

The application of the developed software parser for generating detailed information from the robot software has shown that the method forms a key part of a current digital twin. The software of the devices in the CPPS is an essential data source which contains a great deal of information about resources, products and processes in the BIW production system.

Furthermore, the application part has shown that it is possible to calculate the individual process time by implementing time stamps into the real-time message. With this method, the issue of latency time in a production system could be solved, and it was possible to calculate the exact cycle time of the robot's spot welding process.

In table 2, the different data for the automated creation of a digital twin is summarized. The application of the concepts has shown that it is possible to acquire resource, product and process information via the hardware, software and real-time data of the CPPS. Hence, this current information of the CPPS is the foundation for creating a digital twin of BIW production systems which connects resources, products, and processes with each other.

Table 2: Overview of CPPS information on the BIW production systems.

Source	Information type	Information
PLC	Resource	Electronic and mechatronic devices that are controlled by the PLC
	Product	Vehicle components, variant type (cabriolet, coupé, sedan / right-hand-drive, left-hand-drive), load level
	Process	Cycle time of the production line
Robot	Resource	Electronic and mechatronic devices that are controlled by the robot
	Product	Joining points, variant type (cabriolet, coupé, sedan/right-hand-drive, left-hand-drive), load level, material thickness, contact pressure (welding gun), weld time
	Process	Cycle time of each process (handling, joining)

5. Conclusions and Further Work

5.1. Conclusions

In this paper, a concept for the automatic creation of a digital twin has been discussed. The production planning department needs a digital twin for time reduction during the integration process of a new vehicle. However, there is no method for the automated creation of a digital twin for BIW production systems for the planning department at present.

This case study has shown that the CPPS can offer a great deal of information that planners and autonomous planning assistents [23] need from a digital twin for integration planning. In the CPPS, a joining element distribution to station and robot, a classification of different variants and types to station and robot can be parsed. Moreover, the current cycle times of individual processes and production lines can be calculated. The most significant insights of the case study can be summarized in the following points.

- A use case for the automated creation of a digital twin for BIW production systems is elaborated. The planning department needs a current digital twin for time reduction during the integration process of new vehicles.
- The implementation of a real-time system into the production system enables the access of current resources, products and process information that planners need for product integration into existing BIW production systems.
- The software of a device contains a great deal of product, process and resource information. Hence, a software parser is a primary tool in order to obtain data for a digital twin based on the CPPS.
- The implementation of time stamps into the process triggers real-time messages and enables calculation of exact cycle times for individual processes. These current process cycle times can be used to optimize the estimated planning cycle times.

- The comparison of the current information from CPPS compared to the information in the digital model points to changes in the production system.

This insights of the case study can also be transferred to other sections and issues if the CPPS in the production system has a similar structure to BIW production systems.

5.2. Further Work

The digital twin with information access and sources of CPPS might offer further options of an automated or semi-automated integration planning via production-product mapping. The case study has shown different data sources to calculate for the robot's position to other equipment in the production system. Hence, further research will be automatic repositioning of robots and equipment based on this information. Furthermore, the digital twin of BIW production systems which consists of current resources, products, and processes can also offer detailed information about changes in production. Consequently, the implementation of an automated creation of the digital twin could also be used to track optimization processes and create transparency of information in the event of reconstructions.

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