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Digital twin: revealing potentials of real-time autonomous decisions at a manufacturing company

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Abstract

Complexity and constant increasing volumes of the data combined with daily disruptions such as changing production capacity and/or new customer orders lead to an expanding number of adjustments of production plans and to boosting stock levels. In order to resolve those issues for a manufacturing company, we created the assembly digital twin i.e. "real-time digital replica" with the ability to update production orders as the reaction to changes in relevant internal and external data. The over two years study demonstrates how a digital twin can be integrated into existing IT architecture and based on simulation modeling quantifies the potentials of the real-time decisions.

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Keywords: Digital twin; Self-adaptive manufacturing; Real-time scheduling.

1. Introduction

One of the most meaningful factors of well-functioning companies is the capability of fast reaction to disruptions and changes, which is the main prerequisite for a long-term endurance for companies regardless of their size.[1] Within the context of manufacturing, changeability characterizes the efficiency of a system in modifying from one state to another, ranging from the strategic level down to the shop-floor level. [2] In order to react rapidly to unforeseen situations without centralized re-planning, production systems should be developed into autonomous systems with the ability to accomplish their assignments without human supervision. Knowing their modeled capabilities and a current state, autonomous systems can choose from a set of alternative actions and orchestrate events, at the same time they require access to precise models of the current state of the environment and processes in real-time – known as the "Digital Twin". [3]

The purpose of this paper is to solve the problem of centralized re-planning of assembly orders and allow a mid-sized manufacturing company reacts to new customer orders as well as changes in production capacities in real-time modus, at the same time increasing changeability of the company. Several authors (Rosen [3], Brenner [4], Uhlemann [5], Rajhans [6]) have already described different concepts of a Digital Twin underlining its importance for production and logistics, however a real-life proven concept of a Digital Twin with the ability to take autonomous decisions without human control was so far untried.

2. Digital Transformation in Manufacturing Industry

Concept of a "Digital Twin" exists for over 20 years [4], it started with the NASA's Apollo program, when in order to be able to mirror the flight conditions of a space vehicle in the middle of a mission and support the astronauts in dangerous circumstances, the identical vehicle on Earth, the "Twin", was operated. A similar example for a twin is Iron Bird from

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Airbus “a ground-based engineering tool used in aircraft industries to incorporate, optimize and validate vital aircraft systems”[3]. However, virtual models are more and more replacing the “hardware” components in the Iron Bird, allowing to start a simulation even when physical components are unavailable. In that context, a prototype created to simulate real conditions can be referred to as a “Twin” and a complete digital model of a physical system can be called a “Digital Twin”. Rosen et al. argue that Digital Twin is “the next wave in modeling, simulation, and optimization technology” and therefore is “the core enabler of autonomy” allowing to achieve “new level of flexibility in automation system”[3].

In order to decide how to build a Digital Twin of production processes, we need to understand the current state of the digitalization. For several years researchers, as well as practitioners, are working on digital solutions and receive support on an international level, with a broad variety of initiatives:

- Industrial Internet of Things (IIoT), USA
- Industry 4.0 in Germany
- Industry 2025 in Switzerland
- InternetPlus and Made in China 2025
- Society 5.0 in Japan

Under different names, those initiatives have a similar purpose to support the application of digital technologies in pursuance of increase of competitiveness under global market conditions[7]–[9]. Both Internet of Things and Industry 4.0 concepts based on application of Cyber-Physical Systems (CPS), which “are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its ongoing processes, providing and using, at the same time, data-accessing and data processing services available on the internet” [10]. Data-gathering and communication with each other as well as with the environment or an IT system is enabled through sensors and actuators [11].

Monostori [10] indicates increased transparency as well as higher robustness of operation processes through faster identification of the probable disruptions by use of cyber-physical solutions. Verdouw [12] illustrates such an increase of transparency on the example of food supply chains in general and fish distribution in particular. Furthermore, companies can achieve robustness and competitiveness by the implementation of an adaptive and IoT-based solution where decisions made by machine-intelligence will be aligned with high-level decisions taken by humans as explained in the mathematical programming model from Rezaei et al [13].

As a summary, it can be proposed to build a Digital Twin in manufacturing in accordance to the concept of Industry 4.0 or Internet of Things applying a set of Cyber-Physical Systems in order to create a precise digital replica of processes and material movements within the assembly.

3. Research Design

3.1. Research Motivation

Expanding the number of product varieties, shorter product life cycles in combination with increasing demand for fast deliveries cause tremendous complexity in production planning and monitoring, pushing companies to search for new concepts for their production systems [14]. In order to deal with high complexity, we decided to develop and test under real-life conditions decentralized system, a Digital Twin of assembly processes with the capability to take autonomous decisions in real-time modus. Within this autonomous assembly system, each assembly cell will act as an independent Cyber-Physical System, providing the workers with the information needed for the efficient performance and able to react to changes in the availability of resources as well as increase or decrease of demand.

3.2. OTD-NET

The Assembly Digital Twin was developed on the basis of the adapted version of OTD-NET, which was initially developed by Fraunhofer-Institute of Material Flow and Logistics (IML) as a simulation tool [15]. This tool was already successfully implemented for the production network of Daimler AG, VW and other projects where information and material flows are deeply interconnected [16]. Furthermore, OTD-NET allows to perform simulation and record the data for further analysis in a sufficient way. For the proper data exchange the tool offers independently executable programs in addition to the usual XML-interface, thus, allowing independent control of a simulation from other separated program segments [16].

The quality of the OTD-NET was acknowledged by the “Rockwell Automation”, where it was awarded as the best simulation software in comparison to well-known tools such as Quest, Witness, Extend, FlexSim, Enterprise Dynamics and Anylogic. The most innovative part of the software is the ability to connect the process of order fulfillment with the entire supply chain, which in a combination of highly-detailed modeling tools enables very efficient programming of real-life processes [15].

For the above reasons, the OTD-NET met the requirements of a Digital Twin especially in terms of detailed mapping of processes in combination with the ability to store the simulation results and flexible interfaces for the users and was chosen as a main tool for the project. Furthermore, in last year’s at University of Applied Sciences in Hamburg OTD-NET was modified for the use as an embedded real-time system for the implementation of Cyber-Physical Systems at small and mid-sized companies, giving them the opportunity to improve their often deficient IT systems.

3.3. Data Collection

Data collection is a central component of a Digital Twin and can be divided into two types: volatile and nonvolatile data [5]. While nonvolatile data was collected mostly during workshops with employees of the company and consists of warehouse layouts, specifications of assembly cells and bills of material, volatile data, which display the current status of material movements, customer orders, etc. were collected directly from the enterprise IT systems. Thereby the decisions taken by the Digital Twin of assembly can take decisions based on current, so-called “real-time” data.

4. Concept of a Digital Twin with Real-Time Autonomous Decisions

4.1. Project Details

Company X* is a mid-sized international manufacturing company in the area of electronic engineering with head office and production facility in Hamburg. In order to remain a clear focus during the cooperation between the University and the Company, the following project goals were agreed:

- Reduction of the Order-Lead-Time
- Increase the flexibility of order processing

In order to keep the project manageable, we focused only on one product group of filter fans with over 250 product variations and separate assembly area with six assembly cells. Filter fans are assembled in equipped cells from several components, one share of which consists of plastic grids can be produced at the same production facility and the other, such as screws, filter sponges must be purchased from different suppliers. Since raw materials, required for the production, have very high-security stock due to transportation from Asia in combination with high-volume minimum order quantity, purchasing orders for them are completely left out-of-scope. Details on existing processes as well as a first draft for the new processes were presented at Hamburg International Conference on Logistics in 2017 [17], however, the implementation of the concept as well as validation of the simulation of the Assembly Digital Twin took further one and a half years.

4.2. Process Analysis

In general, all operations can be divided in material flow, which starts by arrival of ordered raw materials and parts at the warehouse moving to production of assembly components towards outbound of assembled finished goods ordered by a customer, and information flow, which is triggered with every new customer order (as shown in Fig.1).

At the start of the project was not clear which part(s) of the processes should be digitalized. For that reason, the first step was to analyze all processes and to define the potentials for the increase of transparency and/or flexibility. Purchasing department buys, in general only three types of products:

- Spare parts for the assembly, such as screws and other rather small-sized parts
- Plastic granules for the production of the plastic grids for the assembly of filter fans
- Packaging materials

The processes in purchasing are strictly defined by longstanding contracts, according to which small-sized parts are delivered by principles of vendor-managed-inventory (orders are released automatically making the process already automated), plastic granules are bought in high-volumes (up to 4 months demand) in Asia due to agreed minimum order quantity, packaging materials have already low stocks since the products are quite standard and the supplier located not far from the company. Consequently, any changes in the existing process will not bring high impact, so the purchasing processes were excluded from digital twin (except data on current stocks level and consumption).

Production processes which include production planning and monitoring of plastic molding machines as well as retooling process, that can take up to three hours and must be communicated in advance. Although the trend goes to small batch production, it would be economically inefficient to produce small batches of a product for one hour and then have several hours of retooling. Therefore the production processes were taken only partially into consideration by the design of the Digital Twin.

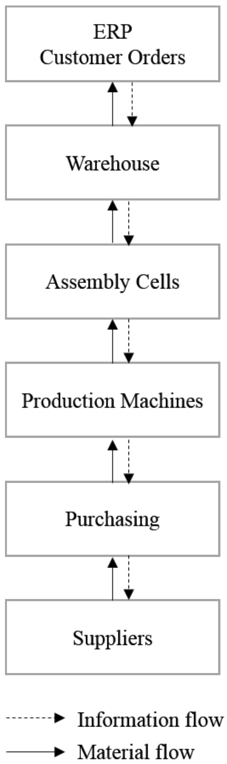

Fig 1. Material- and information flow.

* following will be referred to as “the company”

The processes in the assembly are on one hand, the most flexible: the capacity can vary from one to two people per assembly cell, the products can be assembled in one or three shifts (8 or 24 hours per day); on the other hand, all calculations such as assembly planning for the next weeks are made with help of Excel-based reports and workers get a paper-based version of the production plan for one assembly cell at the start of the day, which make the process non-transparent and rigid. Thus the assembly processes including two planning departments were defined as the most appropriate for the mapping with a Digital Twin in order to make the whole supply chain faster and more flexible.

Customer orders, as well as data concerning the level of stocks in different warehouses, are available in the ERP system with the automatic updates within minutes after the change happened, consequently, both parts are used in Assembly Twin without restrictions.

4.3. Order-Triggered Assembly Planning

In order to be able to define all the data and decision logic of the future process, the concept of the Order-Triggered Assembly Planning was created (s. Fig. 2). Although the logic seems to be quite simple, the volume of daily date is remarkable. For example, in one day the company receives hundreds of orders, which contain tens of order lines.

As the first step, the Digital Twin performs availability check per each order line (since it contains information about ordered volume per product). If the product is available in warehouse, it should be delivered from stock, in which case the Digital Twin will provide respective information to the ERP system.

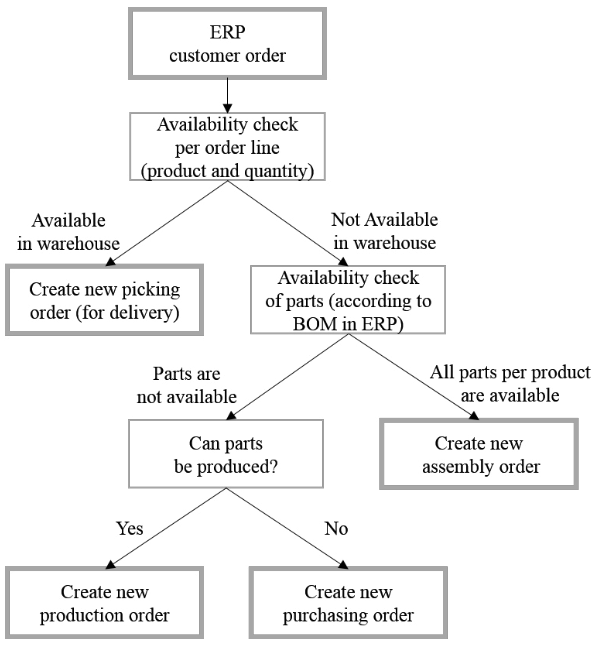

Fig 2. Order-triggered assembly planning.

If the demanded amount is not available at stock, another availability check will be started, this time it will be based on so-called Bill of Materials (from ERP), which contains information on all needed spare parts. Should some of the required parts be not available, then the inquiry will be sent to the purchasing department or to the production department (if missing parts can be produced). The main focus lies on the situations in which all of the demanded spare parts are available and the assembly should start manufacturing them. In real life, hundreds of orders per day result in thousands of assembly orders, thousands of production and purchasing orders and tens of thousands of different checks and inquires, which is hard to manage for a person with an excel-sheet as an only available tool. Furthermore, in such Excel-based tools, the planning is done for weeks and showing the sum of the demand per product, which is highly ambiguous, especially after orders change ordered volume or delivery date.

4.4. Embedding the Digital Twin into existing IT Architecture

After the presentation of the possible scenario of the Assembly Digital Twin in front of responsible managers of the company and agreement on the flexible, but autonomous solution without human control the concept was extended further. As shown in Fig. 3 the Digital Twin consists of CPS on different levels:

- One central CPS Assembly Controller is designed to analyze the open orders (new orders + not fulfilled orders) and assign them to one of the Assembly Cell CPS. At the end of the day or shift, the central CPS should “report” the relevant data back to the ERP and PPS systems, i.e. total produced volume per product, total production time, not fulfilled orders etc. The data will be used for the calculation of the available stocks, long-term analysis of production KPIs, and calculation of open orders for the next day or shift.
- Each Assembly Cell will act as own CPS in order to gather the data on material movements (produced products, material consumption) as well as exchange the information with other cells.

The model structure is the same for all six of Assembly Cell CPS, it contains a databank with a copy of the relevant bill of materials from the ERP, capacity information from the production system and other relevant data, specific for each cell (since each cell is equipped to build defined product range). Synchronization module triggers a re-planning of the assembly orders if necessary or forwards the acquired data to the CPS Assembly Controller. In order to ensure the data acquisition, each cell has a scanner which collects data on produced products, as an alternative, some data, such as available manpower can be calculated based on manually added data. For example, if a worker starts his shift he logs in himself in a system, letting the system know that there will be available capacity for the next shift. Outer Interfaces, on one

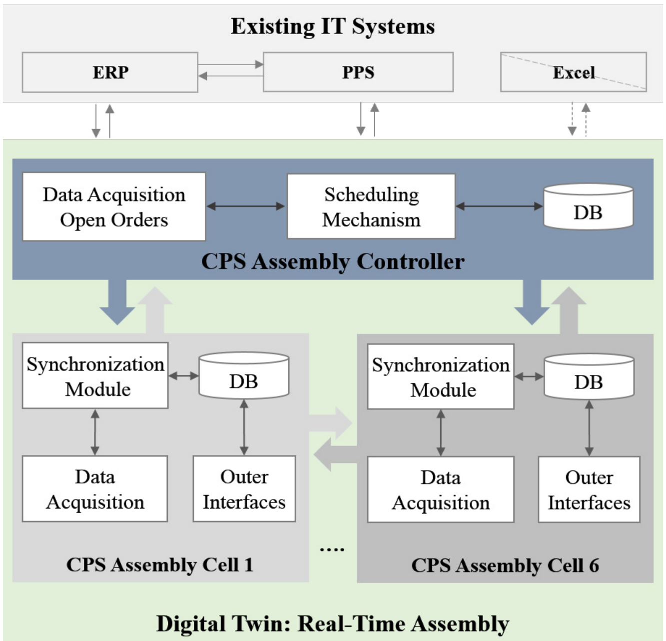

Fig 3. Architecture of assembly digital twin.

hand, provide workers with current information on open orders and on the other hand allow to add data manually if needed. CPS Assembly Controller is built with similar logic, but have additional "responsibility" of monitoring the Assembly Cell CPSs, accumulated their data at the end of shift/ day and forwards it to the ERP or PPS.

Since the assembly process is basically the same in each cell and only products are assigned to one cell (in order to reduce space needed for the storage of spare parts), information exchange between cells allow identification of available capacities and as a result transfer of free workers to another cell with high-volume on open orders. For example, if on day X the Cell Nr.1 have open orders for only 3 hours and the cell Nr. 2 have open orders for 10 hours, the cell Nr. 3 do not need to work in a second shift, instead, it can communicate the request for additional manpower to other cells. Additionally, as it often happens in times of flue, workers do not always show up in the morning as planned and since humans cannot be substituted immediately, it is helpful to have a tool which can consider real available manpower and re-calculate the assembly orders based on given priorities within minutes or even seconds. Consequently, the assembly processes will not only be able to react in real-time modus to the changes in the environment but as well optimize the use of resources by leveling out peaks in demand or lack of manpower.

5. Discussion of Results

Monostori [10] defines two ways of robustness as a way of consistent performance despite changes in a system:

- Through the efficient allocation of physical or time reserves
- By operating a reactive scheduling technique.

In the case of a Real-Time Digital Twin of Assembly both ways were achieved: reactive autonomous scheduling of assembly orders allowed the best use of available resources within the area. This way, not only customers can receive ordered goods within a shorter period of time, but a company could detect potentials for better resource planning.

Successful simulation rounds in real-time modus of re-planning of assembly orders persuaded management of the company that a properly developed system brings huge value through cutting the time effort for the planning processes by over 90% while providing detailed information for the workers in assembly cells and collecting data on material movements in real-time modus. Thus, allowing the company to deliver the products not within three weeks as it was in the original process [17], but in the week of order or latest in the following week. Other researchers came to a similar conclusion, even naming simulations "one of the pillars for the Industry 4.0 revolution" [18].

6. Conclusions

This paper illustrates a slightly different approach to the concept of a digital twin, which do not include direct visualization of the manufacturing entities with CAD or similar tools, still consider all necessary data, allowing each assembly cell to be directly connected to the customer orders in ERP system and thus, react to the changes in it, as well as to communicate changes in own capacities to other cells and if necessary back to the ERP.

In comparison to often used automated systems, which are able to perform fixed sets of actions, the autonomous systems act on knowledge of the current state of the process, machine or environment. This way an autonomous system is able to respond to various situations without human control or reconfiguration, which transforms it into a key enabler for the changeability and robustness demanded by today's economy [3]. Although it can be expected that the complexity of manufacturing systems will increase due to growing customer expectations, technical opportunities for the creation of autonomous systems with real-time decisions are expanding as well [10]. Additionally, assembly planning in real-time modus instead of planning weeks upfront allows a company better allocation of resources, shorter order-lead time with less effort invested in planning processes.

This paper provides a detailed description for a real-time digital twin of production processes which can serve as a blueprint for a manufacturing company looking for more robustness of own processes in times of high complexity and same day deliveries.

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References

[1] L. Monostori *et al.*, ‘Towards adaptive and digital manufacturing’, *Annu. Rev. Control*, vol. 34, no. 1, pp. 118–128, Apr. 2010.

[2] J. Fisel, N. Duffie, E. Moser, and G. Lanza, ‘Changeability - a frequency perspective’, *Procedia CIRP*, vol. 79, pp. 186–191, 2019.

[3] R. Rosen, G. von Wichert, G. Lo, and K. D. Bettenhausen, ‘About The Importance of Autonomy and Digital Twins for the Future of Manufacturing’, *IFAC-Pap.*, vol. 48, no. 3, pp. 567–572, 2015.

[4] B. Brenner and V. Hummel, ‘Digital Twin as Enabler for an Innovative Digital Shopfloor Management System in the ESB Logistics Learning Factory at Reutlingen - University’, *Procedia Manuf.*, vol. 9, pp. 198–205, 2017.

[5] T. H.-J. Uhlemann, C. Schock, C. Lehmann, S. Freiberger, and R. Steinhilper, ‘The Digital Twin: Demonstrating the Potential of Real Time Data Acquisition in Production Systems’, *Procedia Manuf.*, vol. 9, pp. 113–120, 2017.

[6] A. Rajhans and D. Lluch, ‘A Digital Twin Approach to Online Monitoring in Industrial Internet of Things Applications’, p. 2.

[7] B. Rylands, T. Böhme, R. Gorkin, J. Fan, and T. Birtchnell, ‘The adoption process and impact of additive manufacturing on manufacturing systems’, *J. Manuf. Technol. Manag.*, vol. 27, no. 7, pp. 969–989, Sep. 2016.

[8] F. Tao, Q. Qi, A. Liu, and A. Kusiak, ‘Data-driven smart manufacturing’, *J. Manuf. Syst.*, Jan. 2018.

[9] B. Tjahjono, C. Esplugues, E. Ares, and G. Pelaez, ‘What does Industry 4.0 mean to Supply Chain?’, *Procedia Manuf.*, vol. 13, pp. 1175–1182, 2017.

[10] J. Monostori, ‘Supply chains robustness: Challenges and opportunities’, *Procedia CIRP*, vol. 67, 2018.

[11] D. Kolberg, C. Berger, B.-C. Pirvu, M. Franke, and J. Michniewicz, ‘CyProF – Insights from a Framework for Designing Cyber-Physical Systems in Production Environments’, *Procedia CIRP*, vol. 57, pp. 32–37, 2016.

[12] C. N. Verdouw, J. Wolfert, A. J. M. Beulens, and A. Rialland, ‘Virtualization of food supply chains with the internet of things’, *J. Food Eng.*, vol. 176, pp. 128–136, May 2016.

[13] M. Rezaei, M. Akbarpour Shirazi, and B. Karimi, ‘IoT-based framework for performance measurement: A real-time supply chain decision alignment’, *Ind. Manag. Data Syst.*, vol. 117, no. 4, pp. 688–712, May 2017.

[14] L. Kiefer, P. Voit, C. Richter, and G. Reinhart, ‘Attribute-based identification processes for autonomous manufacturing systems – an approach for the integration in factory planning methods’, *Procedia CIRP*, vol. 79, pp. 204–209, 2019.

[15] M. Motta, A. Wagenitz, B. Hellingrath, and R. Weller, ‘Gestaltung logistischer Netzwerke– ein Praxisbericht’, p. 10.

[16] C. Li and D. Fang, ‘OTD-NET based simulation evaluation of (R, Q) inventory policies for complex distribution systems’, in *2012 International Conference on Information Management, Innovation Management and Industrial Engineering*, Sanya, China, 2012, pp. 470–474.

[17] J. Wagner and H. Kontny, ‘Use case of self-organizing adaptive supply chain’, *epubli*, Oct. 2017.

[18] G. Lugaresi and A. Matta, ‘Real-time simulation in manufacturing systems: challenges and research directions’, in *2018 Winter Simulation Conference (WSC)*, Gothenburg, Sweden, 2018, pp. 3319–3330.