Lecture Notes in Mechanical Engineering

Vitalii Ivanov · Justyna Trojanowska · Ivan Pavlenko · Erwin Rauch · Ján Piteľ *Editors*

Advances in Design, Simulation and Manufacturing VII

Proceedings of the 7th International Conference on Design, Simulation, Manufacturing: The Innovation Exchange, DSMIE-2024, June 4–7, 2024, Pilsen, Czech Republic - Volume 1: Manufacturing Engineering

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Editors
Vitalii Ivanov
Department of Manufacturing Engineering, Machines and Tools
Sumy State University
Sumy, Ukraine

Ivan Pavlenko
Department of Computational Mechanics Named After V. Martsynkovskyy
Sumy State University
Sumy, Ukraine

Ján Pitel'
Faculty of Manufacturing Technologies with a Seat in Prešov
Technical University of Košice
Prešov, Slovakia

Justyna Trojanowska
Faculty of Mechanical Engineering
Poznań University of Technology
Poznań, Poland

Erwin Rauch
Faculty of Engineering
Free University of Bozen-Bolzano
Bolzano, Italy

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Preface

This volume of Lecture Notes in Mechanical Engineering contains selected papers presented at the 7th International Conference on Design, Simulation, Manufacturing: The Innovation Exchange (DSMIE-2024), held in Pilsen, Czech Republic, on June 4–7, 2024. The conference was organized by the Sumy State University, University of West Bohemia, and International Association for Technological Development and Innovations in partnership with Poznan University of Technology (Poland), Technical University of Kosice (Slovak Republic), Kielce University of Technology (Poland), Association for Promoting Innovative Technologies – Innovative FET (Croatia), and Society for Robotics of Bosnia and Herzegovina (Bosnia and Herzegovina).

DSMIE Conference Series is the international forum for fundamental and applied research and industrial applications in engineering. The conference focuses on research challenges in the fields of Manufacturing Engineering, Materials Engineering, and Mechanical Engineering, addressing current and future trends in design approaches, simulation techniques, and manufacturing technologies, highlighting the growing role of smart manufacturing systems, artificial intelligence, standards-based integration, and innovations implementation to the transition to sustainable, human-centric, and resilient engineering solutions. DSMIE brings together researchers from academic institutions, leading industrial companies, and government laboratories worldwide to promote and popularize the scientific fundamentals of engineering.

DSMIE-2024 received 148 contributions from 33 countries around the world. After a two-stage single-blind review, the Program Committee accepted 83 papers written by 324 authors from 28 countries. Thank you very much to the authors for their contribution. These papers are published in the present book, achieving an acceptance rate of about 56%. Extended versions of selected best papers will be published in scientific journals: Management and Production Engineering Review (Poland), Journal of Engineering Sciences (Ukraine), Advances in Thermal Processes and Energy Transformation (Slovak Republic), Assembly Techniques and Technology (Poland), special issue of Machines (Switzerland) "Innovations in the Design, Simulation, and Manufacturing of Production Systems", and a special issue of Materials (Switzerland) "Novel Approaches in the Design, Simulation, and Manufacturing for Processes and Systems".

We would like to thank members of the Program Committee and invited external reviewers for their efforts and expertise in contributing to reviewing, without which it would be impossible to maintain the high standards of peer-reviewed papers. About 97 Program Committee members and 13 invited external reviewers devoted their time and energy to peer-reviewing manuscripts. Our reviewers come from around the world, representing 21 countries, and are affiliated with 39 institutions.

Thank you very much to the keynote speakers: Prof. Arkadiusz Gola (Lublin University of Technology, Poland), Dr. Foivos Psarommatis (University of Oslo, Norway & ZerOfect Company, Switzerland), Prof. Jinyang Xu (Shanghai Jiao Tong University, China), Prof. Francisco J.G. Silva (Polytechnic of Porto, Portugal), and Prof. Andre Batako (Liverpool John Moores University, UK).

We sincerely appreciate the invited speakers of the DSMIE Workshops: Dr. Bohdan Haidabrus (Riga Technical University, Latvia) and Prof. Katarzyna Antosz (Rzeszow University of Technology, Poland).

The book "Advances in Design, Simulation and Manufacturing VII" was organized in two LNME volumes according to the main conference topics: Volume 1—Manufacturing Engineering and Volume 2—Mechanical and Materials Engineering. Each volume is devoted to research in design, simulation, and manufacturing within the main conference areas.

The first volume consists of six parts. The first part includes recent developments in smart and sustainable manufacturing. It presents research works in designing cyber-physical production systems, implementing the technological capabilities of modern laboratories, and studies on streamlining processes for Industry 4.0. Additionally, this part includes studies on laser technologies, sustainable design, and advanced circular economy. Moreover, recent developments in simulation-driven evaluation of reward systems for activity-based manufacturing environments are presented in this part. Problems of an industrial data collection application are also discussed.

The second part includes studies in information management systems, particularly the development of IT systems in warehouse management. Application of AI in delivery management and agile digital projects are also presented. Finally, this part proposes improvements in information resources management at industrial companies.

The third part of manufacturing technologies is devoted to increasing the vibration resistance of finishing and boring machines, ensuring tool run-in during milling, and improving metal cutting tools using data-based failure rate assessment methodology. It presents studies on applying ANFIS systems to predict spindle vibrations for CNC machining centers and enhancing service life and machine parts' durability. This part also includes recent developments in designing technological schemes for rolled metal production, increasing the efficiency of rolling rolls and grinding processes, and preventing cracks formation. Moreover, issues regarding the sustainable machining of automotive parts, evaluating the stiffness of underpinning supports for fixtures, and developing flexible fixtures for fork-type parts are presented. Studies on surface hardness improvement of tool steel, wear behavior of coated tools during milling, adaptive fluid jet support technique for end milling, surface morphology and microstructural features of superalloys, and heat treatment are also discussed in this part. Moreover, the third part proposes ways to improve the profile accuracy of large-pitch tapered threads and the power parameters of forming the screw spirals. Finally, it includes research on the statistical comparison of manual and automatic enterprise sampling.

The fourth part considers studies on quality assurance, including problems in assembly technology and machined surface integrity. Statistical analysis and machine learning techniques are also presented in this part. Moreover, it discusses issues of metrological support in defectoscopy and reliability control for mechanical products depending on the tool's accuracy.

The fifth part aims to discuss modern challenges in supply chain and transportation. It includes risk assessment using fuzzy logic and external supply risk assessment.

The problems of designing green logistics systems and real-time driver detection using transfer learning are also added to this part. Finally, it consists of research on process optimization and supply chain.

The sixth part regarding engineering education is based on studies in designing the educational content for the Industry 4.0 competency model and implementing eco-oriented pedagogical technologies. The model for professional competence development of educators at engineering colleges is also proposed in this part. Finally, it discusses motivation principles of self-management in the professional training of engineers to form creative competencies.

We appreciate the partnership with Springer Nature, iThenticate, EasyChair, International Innovation Foundation, and our sponsors for their essential support during the preparation of DSMIE-2024.

Thank you very much to the DSMIE Team. Their outstanding involvement and hard work were crucial to the success of the conference.

DSMIE's motto is *"Together we can do more for science, technology, engineering, and education"*.

June 2024

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Contents

Smart and Sustainable Manufacturing

Cyber-Physical Production System Design Decomposition for Internal Disruption Avoidance

Tanel Aruväli[1], Matteo De Marchi[1], Erwin Rauch[1](✉), and Dominik T. Matt[1,2]

[1] Industrial Engineering and Automation (IEA), Free University of Bozen-Bolzano, 1, Piazza Università, 39100 Bolzano, Italy
erwin.rauch@unibz.it

[2] Innovation Engineering Center, Fraunhofer Research Italia, 13 A, Via A. Volta, 39100 Bolzano, Italy

Abstract. A growing number of manufacturing companies are undergoing digital transformation and moving towards Cyber-Physical Production Systems (CPPS). To ensure the long-term resilience of CPPS by avoiding internal disruptions, the starting point is the proper design of a functional digital shadow. Therefore, the goal was to provide decomposed design guidelines for the digital shadow implementation. The Axiomatic Design (AD) method was applied to discard systems-based categorization and decompose design parameters from functional requirements, which guided a novel approach covering digital shadow design guidelines. Through the zigzagging process, we elaborated collectively exhaustive and mutually exclusive conceptual design parameters. The received results were applied to a cyber-physical demonstrator. The practical value of the received design parameters guided towards alternative digital solutions, and based on AD axioms, the selection of digital solutions was implemented on the demonstrator. Such an approach enabled us to cover the full concerned functionality while avoiding decoupling and overlapping in implemented solutions.

Keywords: Digital Shadow · Axiomatic Design · Resilience · Industrial Growth

1 Introduction

The last four years of multiple external disruptions have led a growing number of manufacturing companies to adopt digital technologies to their processes [1] and deploy principles of Cyber-Physical Production Systems (CPPS). Many of these companies have seen the possibility of maintaining competitiveness and increasing resilience against disruptions in this step. Disruption management starts from the internal processes to ensure the quality of manufacturing processes. Digital Twin (DT), as an enabler for real-time optimization of the processes [2], only adds value when its input data is reliable. This requires real-time knowledge about physical phenomena taking place on the shop floor. Thus, the design of digital shadow influences the efficiency of higher-level manufacturing control. It stands for mirroring the physical changes in a digital space and the reliable representation of the acquired data.

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The paper aims to provide decomposed design guidelines for the digital mirroring of physical manufacturing through the realization of digital shadow to decrease the occurrence of internal disruptions in cyber-physical shop floors. The research aims to decompose design guidelines for CPPS. More specifically, the Axiomatic Design (AD) method is deployed to the design of a DT for daily manufacturing, focused on achieving reliable digital shadow. The study is limited to the functions of digital shadow to minimize the number of internal disruptions. It does not involve post-disruption management actions of a DT to adapt to disruptions and recover performance.

2 Literature Review

Napoleone et al. [3] divided CPS characteristics into five groups relating to the data: integration, intelligence/smartness, cooperation/collaboration, reconfigurability/adaptability, and predictability. The initial parameter in designing a successful CPS system is accurate and reliable data from the shop floor [4]. This is achieved through a 3-layer architecture: perception, transmission, and application [5]. Having static data about manufacturing parameters enables the creation of a digital model. A digital shadow is created when this data is dynamic, meaning constant near real-time updates from a physical shop floor. The digital shadow does not require the representation of real-time digitally animated movements. The basics of the digital shadow are having the data at a sufficient level of actuality to make knowledge-based decisions. The next level is the DT [6], which enables bidirectional secured communication [7] between cyber and physical space [8, 9]. None of the outputs can have a higher accuracy than the input. Therefore, managing data structures and their communication is essential for applying a structured method of digitalizing manufacturing systems [10]- DT.

Before the introduction of CPPS, Manufacturing System Design Decomposition (MSDD) for various competitive environments using AD and lean approach was applied to manufacturing systems by Cochran et al. [11]. The branch managing disruptions is called “Deliver products on time, “one of the quality production characteristics. The branch lower-level functional requirements (FRs) manage DPs for disruption minimization, identification, and rapid resolution. Later, Cochran et al. [12] expanded the problem with a sustainability dimension and applied a Collective System Design to ensure takt times and efficiency of the manufacturing systems. Lately, Cochran et al. [13] introduced an elaborated version of MSDD called MSDD 10.0, where the study is focused on Industry 4.0 manufacturing processes. Vickery et al. [14] applied the AD method to decompose smart data analytics for small and medium enterprises. They devised an FR, “use available real-time data for prediction needs,” and its following level FR, “gather real-time data from production”. They also highlighted the need for connectivity and data visualization. Aruväli et al. [15] started the decomposition of resilient CPPS by dividing the required functions into two main branches according to a resilience metric Penalty of Change (POC) previously selected as the most practically usable resilience metric for manufacturing companies.

The reviewed AD studies approached the disruption minimization from different digitalization levels. They focused on the internal processes and solutions to improve the quality of the production process and related data. Nevertheless, a solution-neutral approach for detecting design parameters specifically for digital shadow has yet to be carried out. This is a research gap that needs a further structured approach.

3 Research Methodology

AD, as the primary method, was used for deriving the most inevitable DPs of CPPS to reduce occurrences of internal disruptions. AD is a system engineering methodology that uses matrix methods to analyze the translation of customer systematically needs into FRs and DPs. This methodology is suitable for the design of products, processes, projects, and systems. Suh's axioms [16]: (i) maintain the independence of the FRs and (ii) minimize the information content – were followed in the decoupling and decomposing process. The main characteristics and functions of CPPS were considered to increase the level of resilience in the assurance of quality manufacturing processes. The approach was not subsystems-based but rather functions-based to increase solution neutrality. For instance, a monitoring system was not considered as a DP. Instead, sub-functions and sub-components of the monitoring system were distributed all over the decomposition where needed. The resilience metric POC defined the first-level requirements and thus derivated the two main branches. Through zigzagging, the FRs, with their functional requirement metrics, were decoupled, and related DPs were found. Coupled design was avoided and checked through the design matrices.

3.1 Resilient Manufacturing System Main Branches

The decomposition of resilient CPPS in [15] was considered the starting point for quality manufacturing process decomposition. According to this approach, the resilient manufacturing system has two DPs: avoidance of disruptions occurrence and preparedness for changes caused by disruptions. These parameters were achieved from the resilience metric POC [17] by translating the metric components into FRs. In the second level, the FRs of both branches were divided between external and internal disruptions. In the lower levels, we focused on branch 1.2 with FR "Minimize the occurrence of internal disruptions", functional requirement metric "No of internal disruptions", and DP "Quality manufacturing process".

3.2 Minimize the Occurrence of Internal Disruptions

The decomposition of quality manufacturing was modified compared to [15]. The current approach (Fig. 1) considers CPPS's main characteristics: physical and cyber (digital) manufacturing. This ensures the focus on CPPS needs and strengthens the design. Thus, the quality manufacturing of CPPS is a combination of physical manufacturing processes, digital information, and communication between physical and digital domains to merge them into a seamlessly functioning flexible system.

Quality Manufacturing Process. A design parameter in standardized physical manufacturing processes (DP1.2.1) stands for the efficiency of manufacturing processes while ensuring safety in workplaces. Efficiency functions are related to Overall Equipment Effectiveness (OEE), which has three main components: availability, performance, and quality. These components, together with safety, are translated into FRs.

While supporting manufacturing with digital information, analytics, and control, the accuracy of the information must be guaranteed. Therefore, the DT of daily manufacturing is proposed as the DP1.2.2. It is crucial to differentiate between daily manufacturing, which must ensure the avoidance of disruptions, and adaptation measures after the occurrence of any disruption. While the DT of daily manufacturing is represented in the branch, which stands for the avoidance of disruptions occurrence (the currently analyzed branch), the DT resolving of disruption consequences is related to the other main branch that minimizes the cost of changes caused by disruptions.

A digital communication infrastructure is needed to provide communication between physical manufacturing, digital space, and humans (DP1.2.3). As in the current branch, the physical manufacturing is mirrored in a digital space, and communication is built according to the needs of the physical and digital spaces, and decoupled design is achieved at the third level (Eq. 1).

$$\begin{Bmatrix} FR1.2.1 \\ FR1.2.2 \\ FR1.2.3 \end{Bmatrix} = \begin{vmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{vmatrix} \begin{Bmatrix} DP1.2.1 \\ DP1.2.2 \\ DP1.2.3 \end{Bmatrix} \tag{1}$$

DT of Daily Manufacturing. The DT of daily manufacturing is foreseen to coordinate the daily manufacturing and ensure a seamless production flow in a disruption-free environment. Therefore, it consists of a manufacturing controlling unit (DP1.2.2.1). Digital shadow (DP1.2.2.2) stands for mirroring physical phenomena taking place on the physical shop floor. Strategies comparison and evaluation system (DP1.2.2.3) takes into consideration the mirrored data from the physical shop floor and information systems to simulate and analyze for optimization purposes. Optimization vectors may consider performance, delivery times, throughput, energy usage, customer satisfaction, etc. Such a system can comprise machine learning and artificial intelligence as input for decision-making. The production planning system (DP1.2.2.4) stands for implementing the chosen strategy. As the manufacturing controlling unit coordinates the manufacturing and the DT, it is a prerequisite for other same-level DPs. Information on the digital shadow is needed to select the proper manufacturing strategy and for subsequent planning and scheduling. Therefore, the DPs are decoupled (Eq. 2).

$$\begin{Bmatrix} FR1.2.2.1 \\ FR1.2.2.2 \\ FR1.2.2.3 \\ FR1.2.2.4 \end{Bmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & X & X & 0 \\ X & X & X & X \end{vmatrix} \begin{Bmatrix} DP1.2.2.1 \\ DP1.2.2.2 \\ DP1.2.2.3 \\ DP1.2.2.4 \end{Bmatrix} \tag{2}$$

Digital Communication Infrastructure. Communication occurs between various entities on a shop floor and supporting digital systems. Various digital management systems have gained popularity recently (Enterprise Resource Planning (ERP), Product Lifecycle Management, Warehouse Management System, Customer Relationships Management, etc.). This has led to the data being partially duplicated between different

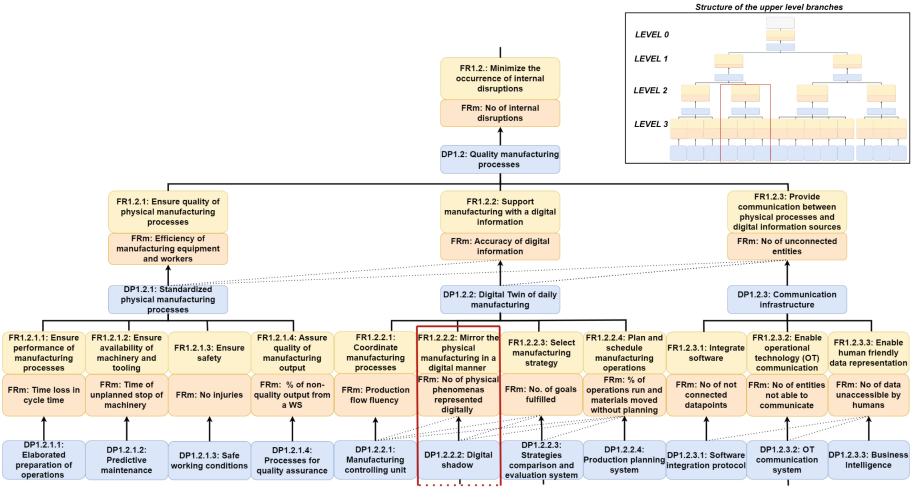

Fig. 1. Main branches of the design decomposition of quality manufacturing processes.

software. Although implementing central management systems has lowered the number of separate locally stored documents (mainly spreadsheets), data still needs to be corrected. If earlier duplication often existed between workers in the same department, then management systems have eliminated that duplication level. Hence, without integrating different digital systems, duplication exists mainly between different (sub)departments, continuously creating data misalignments. To overcome this challenge, a single source of truth must exist at the data level. This requires connecting the existing data points.

3.3 Digital Shadow Decomposition

Digital shadow mirrors the physical world in the best possible manner. For this reason, it must track the status of manufacturing and, at the same time, ensure the quality of data (Fig. 2). The DPs are uncoupled (Eq. 3).

$$\begin{Bmatrix} FR1.2.2.2.1 \\ FR1.2.2.2.2 \end{Bmatrix} = \begin{vmatrix} X & 0 \\ 0 & X \end{vmatrix} \begin{Bmatrix} DP1.2.2.2.1 \\ DP1.2.2.2.2 \end{Bmatrix} \tag{3}$$

For data reliability, each data type must have one single source (DP1.2.2.2.1). The data can be divided into operational data that tracks traditional manufacturing-related parameters such as the movement of parts, machines and operators' status, production orders, and big data for predictive decisions. ERP (DP1.2.2.2.1.1) is a type of software that stores and makes connections between different departments in a single system. It comprises modules for sales, manufacturing, warehouse, quality management, logistics, and bookkeeping. Relational database (1.2.2.2.1.2), on the other hand, is a good option for larger datasets. High-frequency sensor measurements cannot be recorded in ERP; therefore, an additional structured database is needed. After data management in the

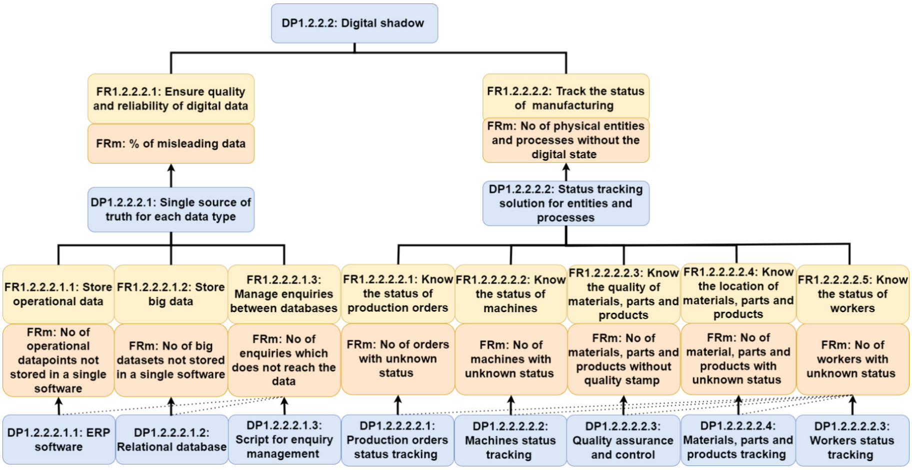

Fig. 2. Decomposition of the digital shadow.

storage systems, a script for inquiry management leads inquiries to a specific single data source (Eq. 4).

$$\begin{Bmatrix} FR1.2.2.2.1.1 \\ FR1.2.2.2.1.2 \\ FR1.2.2.2.1.3 \end{Bmatrix} = \begin{vmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & X & X \end{vmatrix} \begin{Bmatrix} DP1.2.2.2.1.1 \\ DP1.2.2.2.1.2 \\ DP1.2.2.2.1.3 \end{Bmatrix} \tag{4}$$

However, the central function of digital shadow is tracking manufacturing status, which comprises entities and processes. Therefore, the status tracking solution for entities and processes (DP1.2.2.2.2) plays the central role in data acquisition. The most crucial daily manufacturing operative information is achieved through manufacturing orders output tracking (DP1.2.2.2.2.1), machines status tracking (DP1.2.2.2.2.2), quality assurance and control (DP1.2.2.2.2.3), materials, parts and components tracking (DP1.2.2.2.2.4), and indirect operators status tracking (DP1.2.2.2.2.5). The tracking systems are partly uncoupled as operators' status tracking should be deployed indirectly using the data of other tracking systems to lower the stress level of operators (Eq. 5).

$$\begin{Bmatrix} FR1.2.2.2.2.1 \\ FR1.2.2.2.2.2 \\ FR1.2.2.2.2.3 \\ FR1.2.2.2.2.4 \\ FR1.2.2.2.2.5 \end{Bmatrix} = \begin{vmatrix} X & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & X & 0 \\ X & X & X & X & X \end{vmatrix} \begin{Bmatrix} DP1.2.2.2.2.1 \\ DP1.2.2.2.2.2 \\ DP1.2.2.2.2.3 \\ DP1.2.2.2.2.4 \\ DP1.2.2.2.2.5 \end{Bmatrix} \tag{5}$$

4 Results and Discussion

AD-based decomposition of FRs for resilient CPPS led to the specification of conceptual DPs to avoid internal disruptions. The results were implemented in a cyber-physical flexible manufacturing cell demonstrator.

4.1 Results

DPs for internal disruption avoidance in CPPS were identified. More deeply, the analysis was applied to receive the DPs of digital shadow, which is a prerequisite for the DT of daily manufacturing. Additionally, related digital communication means were studied sufficiently to deploy the communication measures. The following DPs for digital shadow were detected: ERP software, relational database, a script for inquiry management, production orders output tracking, machine status tracking, quality assurance and control, materials, parts, and products tracking, and workers status tracking. The following DPs were identified for communication infrastructure: software integration protocol, operational technology communication system, and business intelligence.

4.2 Results Implementation and Discussion in a Use Case: CPPS Demonstrator Design for Minimizing Internal Disruptions

Based on the results, minimizing internal disruptions in a resilient CPPS was applied to a didactic demonstrator. The digital solutions were found based on the conceptual DPs (Table 1). This cyber-physical demonstrator was built in the learning factory 'Smart Mini Factory' at the Free University of Bozen-Bolzano.

Table 1. Digital solutions for minimizing the occurrence of internal disruptions.

Branch of DPs	Conceptual DPs	Digital solutions
Digital shadow (data structures)	ERP	Microsoft Business Central
	Relational DB	PostgreSQL
	Script for inquiry management	Python
Digital shadow (status tracking)	Production orders status tracking	Automatic reporting through IoT weighing scales system
	Machines status tracking	Event logs
	Quality assurance and control	Quality control station
	Materials, parts, and products tracking	ERP extensions (optional)
	Workers' status tracking	Mix of the tracking information
Communication infrastructure	Software integration protocol	Rest API
	OT communication system	MQTT (+ middleware)
	Business intelligence	Grafana

The flexible manufacturing cell demonstrator consists of the following machinery (Fig. 3): a Montrac transfer line with three shuttles for cell-wide transportation; a Universal Robot UR10 collaborative robotic arm for loading components and products between the warehouse and the shuttles; a Universal Robot UR5 collaborative robotic arm for loading components and products between the shuttles and a manual workstation; a 3D-printer/laser work center; a manual workstation with a cognitive assistance system; quality control station; and a warehouse rack. The manufacturing cell is used to manufacture mechanical components for USB flash drives and assemble the product. The components are moved on blisters (specific bins for storing up to six different components). Each shuttle can carry three blisters at a time.

It needs to be noted that CPPS does not mean full automation and the exclusion of operators. Resilient CPPS must find the best ratio between automation's efficiency and human flexibility [18]. Therefore, the system accommodates the workplace for a human operator. The worker is possibly instructed by a cognitive assistance system integrated into the workstation and can provide step-by-step work tasks.

Digital Shadow Data Structures. Digital shadow data structures must provide a single source of truth. Otherwise, the system's liability suffers. Two different data storage software are used because the data collected from a shop floor may have different data structures.

An implemented ERP system, Microsoft Business Central (BC), covers operational manufacturing data that contains information regarding production scheduling, work centers, products, raw materials, components, production calendars, bill of materials, etc. It covers and links data of other departments. An alternative ERP system Monitor was considered for implementation. Although the Monitor is suitable for smaller enterprises and partly covers the functions of the Manufacturing Execution System (MES), the BC was selected. This ERP is mainly used in mid-size companies. Still, considering the cost and close-by dedicated technical support needed for specific extensions, the selection favored BC. In addition, BC can be integrated easily with Advanced Planning and Scheduling (APS) software Etagis, which is used for production scheduling and is comparable with MES functionality.

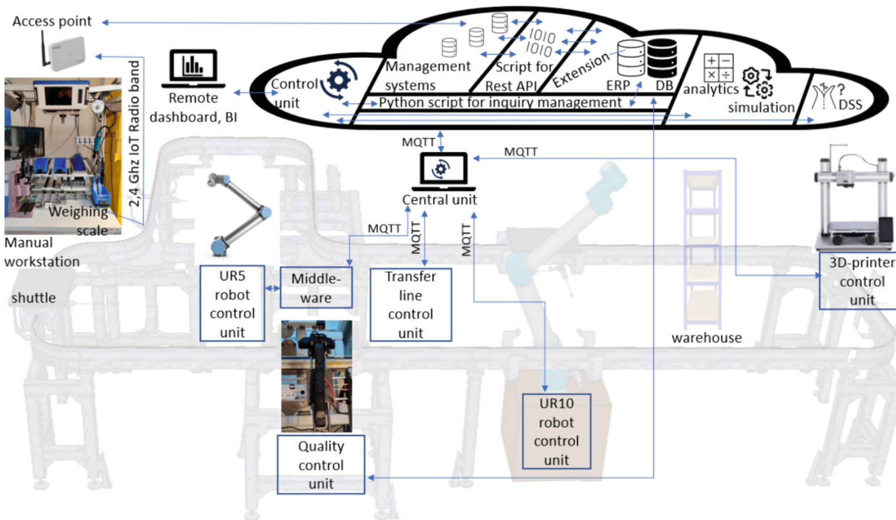

Fig. 3. Digital design solutions in the cyber-physical demonstrator. DB – database, ERP – enterprise resource planning, DSS – decision support system, UR – Universal Robot, API – application programming interface, IoT – Internet of Things.

The relational database covers data structures that are unsuitable or unreasonable for the ERP. The relational database PostgreSQL is deployed to store quality assurance-related data. The quality control unit can directly access the database to compare inspection camera data with previously trained data structures. Python script is adapted to manage the principle of a single source of truth and directs the inquiries to the related data source: BC ERP or PostgreSQL DB. My SQL DB was considered as an alternative. PostgreSQL was chosen because it performs complex queries faster and does not have that tight space constraints compared to My SQL.

Having one single data source, such as a relational database, would eliminate the need for the extra inquiry management layer, but the consequence was losing the links in standardized manufacturing information and scheduling, as well as the links to other departments' data. ERP functions could be theoretically replicated to a single DB in a perfect scenario. Nevertheless, this choice is unfavorable considering small but frequent changes in regulations and related IT management.

Digital Shadow Status Tracking. Tracking for a digital shadow can be divided into five main parts: production orders output tracking, machine status tracking, quality assurance and control, materials, parts, and products tracking, and workers status tracking. Automatic reporting of produced goods eliminates postproduction manual counting by an operator. Manual reporting, even if the results are entered digitally, is often time-consuming and prone to errors. Implemented weighing scales allow the detection of manufactured quantities of goods by measuring the weight of a bin. The measuring is activated by vibration when placing the goods, and results are delivered wirelessly using 2,4 GHz IoT protocol to the access point. Further, the data is delivered to a cloud-scale provider provider management system.

Although ERP systems provide a wide scale of functionality, there is still sometimes a need for customer-specific extensions. In the demonstrator, the system difficulty lies in the description of internal logistics applied untraditionally. The system consists of two-level warehousing: the static warehouse and movable blisters. In the BC, AL language was used to add extra features in the system description to enable tracking of movements. The blisters were defined as micro bins, and the warehouse and workstations were defined as macro bins. This specification allows tracking the location of a specific component and the related blister with other components on it. In addition, the extension allows reservation of workstations and a place on the shuttle when the movement of components starts to avoid scheduling conflicts.

Event logs for machinery status tracking are recorded when the components are moved between workstations and the warehouse. When needed components are delivered to a specific workstation, the production order operation is stated as in progress. Consequently, the event of machine occupation is recorded in the system. After machining, the central unit is informed to organize the pick-up of the parts and change the status. The alternative option would be to use sensors for real-time measuring the machinery vibrations, acoustics, or current to define its status. This demonstrator enables tracking of shuttles and components and communication between operational technology. Therefore, a more data-capacious alternative with sensors was discarded.

A quality control station was built that uses a camera sensor to detect incorrectly assembled products. Additionally, in-process quality assurance is applied to the cognitive assistance system, which launches quality control steps during assembly processes to ensure quality during manufacturing. The operator's status is tracked indirectly, using a combination of assistance system output, materials tracking, and finished product output tracking.

Communication Infrastructure. A Rest Application Programming Interface (API) was applied to communicate between ERP as a central operational information system and other supporting management systems such as Etagis APS and weighing scale system. The data format used in the communication between different software was json. Python script was launched to manage the requests and connect the endpoints in the Rest API format to deliver the payloads. Rest API protocol and payloads in the JSON format were the only options that complied with all the used software. Therefore, other alternatives, such as Soap API, were not considered.

The IoT communication protocol MQTT was launched for operational technology and Central Unit communication. This protocol enables the sending and receiving messages according to each entity's subscription to topics. Alternative OT protocols are, for instance, Zigbee, Lora, and LwM2M. The benefit of MQTT is the ability to communicate to the cloud. Many gateway protocols, such as Lora and Zigbee, are still converted into MQTT protocol in the case of device-cloud communication. MQTT protocol was designed for IoT devices; therefore, it is designed to be lightweight and reliable in a shop floor environment. Protocol conversion is needed for disparate devices to integrate into the network (in our case, UR5). Grafana, as a business intelligence application, was launched to provide easy-to-catch charts for humans. Alternatively, the ThingsBoard application was considered, but the selection was made due to Grafana's compatibility with containerization technology.

5 Conclusions

The AD approach was deployed to CPPS to decouple its FRs and decompose its DPs to launch a digital shadow to support the avoidance of internal disruptions. The delivered DPs were converted into digital solutions implemented in the cyber-physical demonstrator. An interesting result is a guideline for separate data storage for operational and enormous datasets, ERP, and relational DB controlled by the custom script for inquiry management. Although the digital twin solutions mainly use one or another data storage infrastructure [20, 21]. Such diversification enables the integration of management systems and big data into the existing operational data infrastructure, thus creating dedicated spaces for various types of data manipulation and integration. Additionally, the proposed design process helps specify if customized ERP developments are needed, such as for items tracking in the demonstrator. The demonstrator still needs additional effort to launch the proposed solutions for each single entity in the system. The next step will be decomposing DT functionality to lower the cost of changes related to the adaptation to disruptions.

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References

1. Arica, E., Powell, D.: Digitalization in manufacturing: trends, drivers, challenges, and research areas in Norway. In: Dolgui, A., Bernard, A., Lemoine, D., von Cieminski, G., Romero, Da. (eds.) Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems: IFIP WG 5.7 International Conference, APMS 2021, Nantes, France, September 5–9, 2021, Proceedings, Part III, pp. 118–125. Springer International Publishing, Cham (2021). https://doi.org/10.1007/978-3-030-85906-0_14
2. Papacharalampopoulos, A., Michail, C.K., Stavropoulos, P.: Manufacturing resilience and agility through processes digital twin: design and testing applied in the LPBF case. Proc. CIRP **103**, 164–169 (2021). https://doi.org/10.1016/j.procir.2021.10.026
3. Napoleone, A., Macchi, M., Pozzetti, A.: A review on the characteristics of cyber-physical systems for the future smart factories. J. Manuf. Syst. **54**, 305–335 (2020). https://doi.org/10.1016/j.jmsy.2020.01.007
4. Sony, M.: Design of cyber physical system architecture for industry 4.0 through lean six sigma: conceptual foundations and research issues. Product. Manufac. Res. **8**(1), 158−181 (2020). https://doi.org/10.1080/21693277.2020.1774814
5. Yaacoub, J.A., Salman, O., Noura, H.N., Kaaniche, N., Chehab, A., Malli, M.: Cyber-physical systems security: limitations, issues and future trends. Microprocess. Microsyst. **77**, 103201 (2020). https://doi.org/10.1016/j.micpro.2020.103201
6. Magalhães, L.C., Magalhães, L.C., Ramos, J.B., et al.: Conceiving a digital twin for a flexible manufacturing system. Appl. Sci. **12**(19), 9864 (2022). https://doi.org/10.3390/app12199864
7. Lydia, M., Edwin Prem Kumar, G., Immanuel Selvakumar, A.: Securing the cyber-physical system: a review. Cyber-Phys. Syst. **9**(3), 193−223 (2023). https://doi.org/10.1080/23335777.2022.2104378
8. Segovia, M., Garcia-Alfaro, J.: Design, modeling and implementation of digital twins. Sensors **22**(14), 5396 (2022). https://doi.org/10.3390/s22145396
9. Attaran, M., Celik, B.G.: Digital twin: benefits, use cases, challenges, and opportunities. Dec. Anal. J. **6**, 100165 (2023). https://doi.org/10.1016/j.dajour.2023.100165
10. Pizoń, J., Gola, A., Świć, A.: The role and meaning of the digital twin technology in the process of implementing intelligent collaborative robots. In: Gapiński, B., Ciszak, O., Ivanov, V. (eds.) Advances in Manufacturing III: Volume 1 - Mechanical Engineering: Research and Technology Innovations, Industry 4.0, pp. 39–49. Springer International Publishing, Cham (2022). https://doi.org/10.1007/978-3-031-00805-4_4
11. Cochran, D.S., Arinez, J.F., Duda, J.W., Linck, J.: A decomposition approach for manufacturing system design. J. Manuf. Syst. **20**, 371–389 (2001). https://doi.org/10.1016/S0278-6125(01)80058-3
12. Cochran, D.S., Hendricks, S., Barnes, J., Bi, Z.: Extension of manufacturing system design decomposition to implement manufacturing systems that are sustainable. J. Manufac. Sci. Eng. **138**(10) (2016). https://doi.org/10.1115/1.4034303
13. Cochran, D.S., Smith J., Fitch, J.: MSDD 10.0: a design pattern for sustainable manufacturing systems. Product. Manufac. Res. **10**(1), 964−989 (2022). https://doi.org/10.1080/21693277.2022.2153184