Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 118 (2023) 229–234

www.elsevier.com/locate/procedia

16th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME ‘22, Italy

Development of a Dynamic TCP-Positioning Method for a Collaborative Robot Using an Intelligent, Self-Aware Workpiece Carrier

Adrian Burkart[a,]*, Jeremy Askin[b]

[a]ESB-Business School, Reutlingen University, Alteburgstraße 150, Reutlingen, BW 72762, Germany
[b]School of Engineering Technology, Purdue University, West Lafayette, IN 47907, USA

* Corresponding author. Tel.: +49 176 81327461; *E-mail address:* Adrian.Burkart@gmx.de

Abstract

The Industry 4.0 paradigm requires concepts for integrating intelligent/ smart IoT Solutions into manufacturing. Such intelligent solutions are envisioned to increase flexibility and adaptability in smart factories. Especially autonomous cobots capable of adapting to changing conditions are a key enabler for changeable factory concepts. However, identifying the requirements and solution scenarios incorporating intelligent products challenges the manufacturing industry, especially in the SME sector. In pick and place scenarios, changing coordinate systems of workpiece carriers cause placing process errors. Using the IPIDS framework, this paper describes the development of a tool-center-point positioning method to improve the process stability of a collaborative robot in a changeable assembly workstation. Applying the framework identifies the requirement for an intelligent workpiece carrier as a part of the solution. Implementing and evaluating the solution within a changeable factory validates the IPIDS framework.

Keywords: TCP-positioning; Intelligent products; Collaborative robots; IPIDS framework

1. Introduction

Industry 4.0 requires the development of flexible and decentralized manufacturing systems to cope with the challenge of manufacturing products with a high variety, a short lead-time to market, and short product lifecycles [1, 2]. In the field of decentralized autonomy for dynamic manufacturing systems, intelligent products are structural elements to enable Cyber-Physical Systems (CPSs) and IoT technologies.

Smart/intelligent products have various fields of application, such as product lifecycle management and information management in the product's use phase. Hence, product-driven manufacturing represents a key application field for intelligent products [3]. In addition to the bidirectional communication between machines (Machine to Machine or M2M), intelligent products represent another communication partner providing additional valuable information [4]. By making full use of such advanced information, the interconnected and intelligent manufacturing scenario aims to optimize production [2]. Therefore, intelligent and self-aware products are required to sense, interconnect, and interact with each other and automatically carry out manufacturing logic in decentralized systems. Bertelsmeier et al. [5], for instance, have developed an intelligent candle carrier to analyze its behavior, physical coupling, and interfaces depending on product variance [5].

However, enterprises, especially SMEs, strive to allocate and develop promising intelligent product applications. Whereas existing approaches focus on a distinct aspect of either defining [6], analyzing [7], or developing [5, 8] intelligent products, the IPIDS approach encourages a holistic method to integrate intelligent products into manufacturing systems.

10.1016/j.procir.2023.06.040

Therefore, this paper demonstrates the identification, design, development, and implementation of a novel intelligent product application. The accordingly introduced intelligent workpiece carrier communicates with a cobot to dynamically adapt the placing position in a pick and place sequence.

The remainder of this paper is structured into five sections. Section 2 defines and classifies intelligent products in the manufacturing environment. In addition, it describes the structure of the intelligent-product initiation decision-support (IPIDS) framework. Section 3 applies the IPIDS framework to a specific use case in a learning factory to develop a dynamic TCP-positioning method for a collaborative robot. The practicability and the process stability of the solution is analyzed compared to the initial situation in section 4.

2. Background and related work

Identifying requirements and solution scenarios of intelligent products challenges the manufacturing industry, especially in the SME sector [6]. The IPIDS framework provides a holistic method for analyzing the existing manufacturing resources and integrating enhanced product capabilities. The framework's key investigation considers the value-adding aspect of product capability enhancements for the individual manufacturing problem. Therefore, section 2 describes the general definition and relevance of intelligent products and refers to the IPIDS framework.

2.1. Product intelligence

Intelligent manufacturing has emerged as a compelling topic for researchers and industries, achieving superior results to traditional manufacturing systems [7]. Therefore, intelligent objects create value through the connection and integration of manufacturing and service systems. Using communication tools and objects enables machines and products to interact and achieve predefined targets. One major goal of Industrial IoT is to develop self-aware products and machines capable of seeing and sensing their environment [3].

The paper closely follows Dörner's definition of operational intelligence [8]. Concretly, Dörner defines operational intelligence as the ability to solve complex problems. Typical attributes of complex problems are complexity, opacity, high connectivity, dynamics of the situation, and polytely. The complexity of the problem situation is represented by the number of variables and the number of possible interventions. High complexity leads to opacity about the involved variables and their current values. In addition, high connectivity describes the phenomenon that variables do not remain isolated and have mutual dependencies between the involved variables. The situation's dynamic reflects the role of time and developments within the system. The attribute of polytely expresses an actor who needs to optimize multiple and contradictory objectives [8].

2.2. IPIDS framework

The development of a dynamic TCP-positioning (Tool Center Point) method for collaborative robots is based on the IPIDS framework [9]. The framework contributes toward defining, analyzing, and designing intelligent objects within the context of flexible manufacturing. Figure 1 shows the process of the IPIDS framework.

The unique characteristic of the conceptual framework for applicants is the holistic aspect of mapping the capabilities of the current manufacturing resources and deriving improvements by increasing the product-intelligence level. The classification and potential to integrate intelligent products into manufacturing have been recognized several times [10–12] by providing intelligent classes and concepts for different product intelligence categories in various use cases. The focus was not on the guided holistic approach from defining to developing an intelligent product or carrier. For instance, Bertelsmeier et al. [5] focused on the design and development of intelligent products, whereas Ostgathe et al. [12] and Meyer et al. [11] defined, classified, and designed use cases for intelligent products without any development and implementation.

The guideline for the integration process of intelligent-product structures is divided into the four stages definition, analysis and evaluation, design, and execution. The first stage defines the production process and resources in the manufacturing environment. The product and additional resources are classified according to their existing capabilities. Besides defining the existing environmental conditions in the

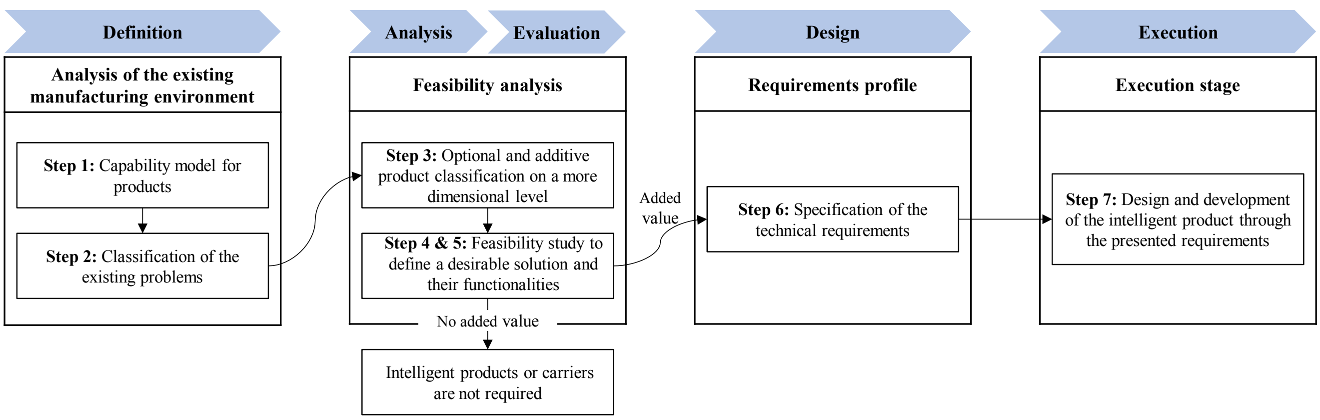


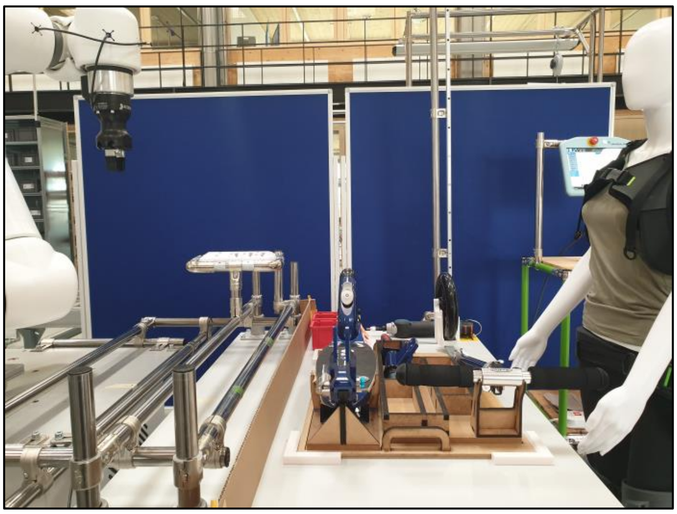
Fig. 1. The structure of the IPIDS framework.

manufacturing system, the classification of the existing problems is examined at stage one. At stage two, the current intelligence levels of the resources are compared with more advanced solutions. The user compares different scenarios by increasing the respective levels to identify potential benefits. Stage two aims to establish whether an enhancement of the intelligence level improves the existing assembly problems. If the defined problem can be improved or even eliminated, the third step examines the design and technical requirements of the intelligent-product structures. Based on the selected intelligent-product levels and mixture of levels, a list of requirements is provided. The final stage comprises designing and developing the intelligent object or carrier in the manufacturing environment. At stage 4, a crucial decision about the aggregation level is needed to define whether the desired product solution requires intrinsic product intelligence to manage information and decisions about itself or if a proxy is a more suitable solution.

3. Use case: Dynamic TCP-positioning method for collaborative robots

3.1. The initial situation at the learning factory

The scope of the investigation is on picking and placing screws on the footboard of a pedal scooter, as shown in figure 2. The workstation consists of a UR10e and a workbench, which are rigidly connected to each other to ensure the correct execution of the robot program. The UR10e is connected to the local network via its ethernet connection. Additionally, there is a mount for screws, where the UR10e picks the screws. Subsequently, the cobot places them in the holes in the footboard. The workpiece carrier and its inlay for the footboard are placed manually on the workbench by the operator. There are 90-degree angle brackets mounted on the workbench, which enclose the workpiece carrier and thus ensure the correct position according to the Poka-Yoke method [13].



Fig, 2. Assembly station.

3.2. Definition phase

After describing the existing assembly process, the resources are classified according to the generic capability model of the IPIDS framework. The collaborative robot UR10e is categorized into class 4, as it represents all functionalities of memorization, communication, processing, and sensor actuation. The current workpiece carrier acts as a transport aid, which carries components from one assembly station to another. Besides, the carrier has individual inlays that can be exchanged for the respective product variants. However, the carrier does not provide intelligent capabilities and consequently is not classifiable into any of the four capability levels.

The second step of the IPIDS framework consists of a brief problem description of the processes at the assembly station. The current situation does not allow information exchange between the workpiece carrier and the UR10e to communicate the current state or position. In addition, the workbench is inflexible, as it is rigidly designed for only one position and sequence by using mounting brackets on the table. The main problem faces the additional manual handling effort from the conveyor system to the workbench because it cannot be assembled on the conveyor system. Currently, the consistent position of the workpiece carrier is only ensured by the 90-degree angle brackets, which do not apply to the roller conveyor system. These problems are classified as complicated because formulae, recipes, and expertise are required to solve them [14]. Table 1 lists the problems as well as their urgency and visibility level. The preliminary analysis shows that the actual position of the workpiece carrier is the basis for dynamically adjusting the TCP position of the UR10e, which aims to solve the defined problems.

Table 1. Problem classification,

Problem statement	Urgency	Visibility
Additional manual handling of the workpiece carrier to a workbench	High because of the manual handling effort	High
Inflexible workbench	Medium	Medium
No information exchange between the resources	Less urgent as process is stable	Low

3.3. Analysis and evaluation phase

The following step consists of analyzing and evaluating the intelligent workpiece carrier in terms of feasibility. The feasibility analysis requires the definition of the focus area, the SMART goals, and the desired solution.

- Focus area: The additional manual handling effort from the conveyor system to the workbench requires a lot of process time. In addition, the inflexible positioning of the workpiece carrier by the 90-degree angle brackets reflects a potential source of error and damage. The manual handling effort is also a physical strain for the operator, as parts and subassemblies of the footboard and handlebar are already on it, which results in a heavy carrier.

- SMART goals: Position determination of the workpiece carrier on the workstation and dynamic adjustment of the TCP-position of the UR10e. The position adjustment is based on the difference between the current position and the actual target position of the workpiece carrier. The workpiece carrier executes the measurement of the distances and calculation of the position adjustment. The project's goal is to design and implement the prototypical system in a budget below 100€ per workpiece carrier. The design and implementation time is ought to be roughly about two to four weeks.
- Desirable solution: The position determination should use distance sensors with an accuracy range of +/-3 mm and a ranging frequency up to 50 Hz. The mounting of the sensors is on the workpiece carrier. The raw data processing takes place on the carrier to communicate the adjusted waypoints to the UR10e.

Step 5 of the IPIDS framework defines the required target functionalities to achieve the desirable TCP-positioning method for the UR10e. The focus lies on the self-awareness of the workpiece carrier, as the UR10 already has the highest capability level. For measuring and storing the distances from the workpiece carrier to the side rails of the workbench or conveyor system, the workpiece carrier requires the ability to read and write information. For calculating the rotation and translation adjustment of the actual position and the target position, the workpiece carrier requires data processing capabilities to enable the use of trigonometric formulae. The communication of the adjusted picking position to the UR10e requires data-oriented communication capabilities. Therefore, the capabilities of the target solution represent a capability upgrade to level 2. The final step of the feasibility study requires a statement regarding the value-adding of the desired solution.

In the case of the TCP-positioning method, the benefits of the intelligent workpiece carrier include reduced processing time, establishing communication between the manufacturing resources, and improved process flexibility. Implementing the dynamic TCP positioning method on the workpiece carrier requires no further operator handling. Therefore, it enables a fast production process and a shorter assembly lead time per product. Regarding the communication aspect, the intelligent workpiece carrier is able to interact with different entities, such as the workstation, other carriers, or the conveyor system. Every carrier also stores organizational data, such as the unique production ID, required or completed process stations, or delivery priority. Process flexibility is defined as the ability of a manufacturing system to produce a set of parts without major setups [15]. The intelligent workpiece carrier requires a new setup to install the distance sensors and electronics. After completing the installation, there is a change-level shift, as it has the potential to increase the availability and utilization of the workstation [16].

3.4. Design of the intelligent workpiece carrier for flexible pedal scooter production

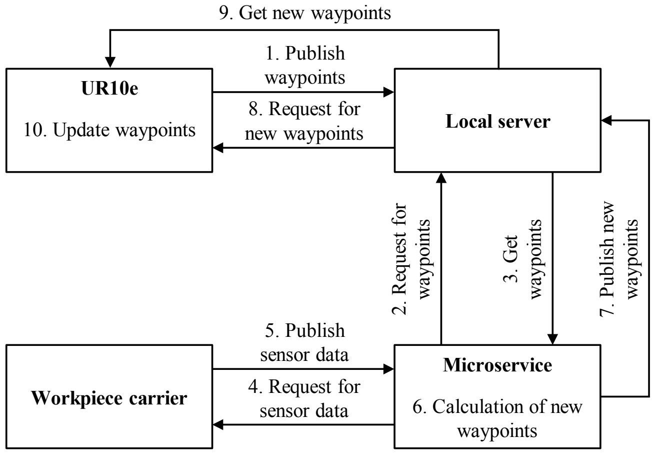


Fig. 3. Flow diagram for dynamic TCP-positioning.

Step 6 consists of the design and the technical requirements to upgrade the workpiece carrier to intelligence level 2. The first aspect of the design requirements includes the flow diagram, presented in figure 3.

The flow diagram includes four objects, the UR10e, the local server, the microservice, and the workpiece carrier. The operator approves the process start on the UR10e teaching pendant, thereby initiating the dynamic TCP-positioning method. For calculating the actual waypoints, the microservices requires the sensor data of the workpiece carrier and the initial waypoints of the UR10e to calculate the adjusted waypoints. The sensor measures the distances in x- and y-direction between the workpiece carrier and the side rails of the workbench. The published waypoints of the UR10e define the programmed waypoints for picking the screws. These positions refer to the fixed position of the workpiece carrier, which has been achieved by the 90-degree angle brackets on the workbench. After the microservice calculates the new waypoints, it publishes the values to the UR10e via the server to update the initial waypoints with the actual ones. In the next step, the pick and place process of the screws with the updated waypoints is carried out. The flow diagram shows that the central unit is the microservice as it requires the raw sensor data and the initial waypoints, using the trigonometric calculation for determining the actual waypoints. Based on the developed design of the dynamic TCP-positioning method, the technical requirements for intelligence level 2 need to be fulfilled by a microcontroller, WIFI module, and distance sensors. Comparing the technical requirements for intelligence levels 2 from step 1 of the IPIDS framework with the components confirms whether the design is sufficient. To achieve the first capability of memorization, the microcontroller reads and writes data from a storage. Providing reading and writing capabilities on the microcontroller already achieves the data-oriented communication requirement. The microcontroller provides a data-processing capability for collecting, synthesizing, and managing the data to enable the TCP-positioning of the actual waypoints. A battery pack powers the microcontroller.

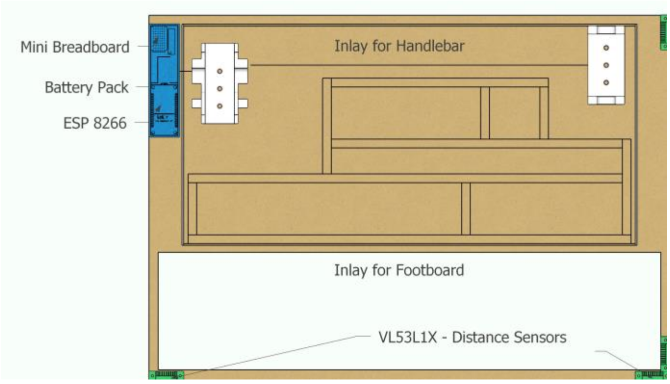


Figure 5. Intelligent workpiece carrier - CAD model

3.5. Development of the flexible assembly station

The last step of the IPIDS framework focuses on executing and designing the intelligent workpiece carrier complying with the defined requirements. Accordingly, figure 4 displays the CAD model of the intelligent workpiece carrier.

The requirements for the intelligent capability classes of the workpiece carrier are mainly realized by the ESP 8266 microcontroller board and the four VL53L1X distance sensors.

The IPIDS framework identifies several scenarios to achieve the dynamic TCP-positioning method. The first scenario investigates an intelligent pedal scooter with level 2 capabilities. Considering the manufactured product as intelligent requires a local integration of the capabilities into the product. In the case of the pedal scooter, own product intelligence is characterized as non-value adding for the customer. In scenario 2 the intelligent capabilities are on the workbench to determine and communicate the actual position of the workpiece carrier. This alternative is rejected, because the solution should be also practicable on the conveyor system to create a self-aware product. The target scenario 3 equips the workpiece carrier with the required capabilities, which means that the pedal scooter has no or low product intelligence after manufacturing. Besides the goal of multiple applications, the self-awareness of the workpiece carrier supports the adaptability of the manufacturing system, which is defined as the ability to adapt a system with low effort to unknown changes for actively countering dynamic changes [16]. In comparison to the position determination on the workbench, the method on the workpiece carrier has mobility and universality, as it can be used in other manufacturing stations.

Furthermore, the ESP 8266 is equipped with a WIFI module, enabling the ability to communicate and interact with local controllers and manufacturing cells. In addition, a 2.200 mAh battery pack ensures the power supply. The mini breadboard allows the connection to the distance sensors. Except for the sensors, all components are installed in one housing, colored blue in figure 4. The distance sensors use time of flight laser pulses to measure absolute distances. The total costs for one ESP8266, the VL53L1X distance sensors, one mini breadboard, one power bank, and the 3D printed parts are approximately 70€, below the target of 100€.

4. Analyzing the practicability of the TCP-positioning method

After applying the IPIDS framework for the use case-specific TCP-positioning method, the practicability and relevance of the intelligent workpiece carrier are analyzed. Therefore, one aspect of the analysis is comparing the initial situation and the situation using the dynamic TCP-positioning method. The number of correctly placed screws on the footboard is observed in both systems. The study aims to clarify whether there is a difference between the number of correctly placed screws in the initial situation and the situation using the TCP-positioning method. The comparison of the situations allows a statement regarding the relevance of the use case, which relates to the IPIDS framework as the framework derived the use case.

4.1. Testing conditions

In the design, there are two features, each with two expressions. The first feature distinguishes between the initial situation A and deploying an intelligent workpiece carrier in situation B. Therefore, the first feature expresses the capability level of the workpiece carrier, with no capabilities in situation A and level 2 capabilities in situation B. The second feature between 0 and 1 express whether the screw has been correctly placed on the footboard. The dataset consists of 588 records, unequally distributed among the initial situation's 255 records and the adapted situation's 333 records. The criterion for a correctly placed screw is that the tip of the screw inserts into the screw-hole, and the screw's body does not fall horizontally onto the footboard. Therefore, a tilted screw with an angle counts as correctly placed because the following screwing process is conducted by the operator, who can correct the screw with small additional effort.

4.2. Relationship between the variables of capability level and number of correctly placed screws

A statistical investigation using the Chi-Square test is conducted to explain the relationship between the two features [17]. The test procedure of the Chi-Square test is appropriate, as the following conditions are met:

- The study aims to investigate a differential question of whether there is a difference between the two situations.
- The two categorical features are at the nominal level in the use case. The data in the cells counts frequencies of whether the screw is correctly placed or not.
- The expected frequency count for each contingency table cell is a minimum of 5 in at least 80% of the cells. In the use case, the minimum expected frequency is 17.8.
- The study groups are independent, which is ensured that there are two different situations. The measured values of situation A are independent of situation B.

Table 1 displays correctly and incorrectly placed screws in the two situations. In addition, the expected values for each cell are provided in brackets.

Table 2. 2x2 Contingency table of observed and expected values.

	0 (No)	1 (Yes)	Σ
Initial situation (A)	11 (17.8)	244 (237.2)	255
Dynamic TCP positioning (B)	30 (23.2)	303 (309.8)	333
Σ	41	547	588

4.3. Interpretation of the results

With the data in the table form, the calculation of the Chi-Square test according to Pearson is selected without any correction. The chi-square test of independence shows a score of 4.91 with a p-value of 0.027. The null hypothesis is rejected because the p-value of 0.027 is smaller than the significance level of $\alpha = 0.05$. In addition, the rejection is supported by the higher Chi-square value of 4.91 compared to the critical Chi-Square value of 3.84, with $\alpha = 0.05$ and $df = 1$. It is essential to mention that the result is highly significant and close to the significance level of $\alpha = 0.025$. Therefore, the null hypothesis is unlikely, and the alternative hypothesis is assumed. There is evidence that there is an association between capability level and the placing accuracy of the UR10e at 5% significance level.

An interpretation of the screw placing accuracies between the two conditions shows that there is a minor deviation in the correctly placed screws of 4.7% between the product's capabilities in the initial situation and the situation using the TCP-positioning method. In the initial situation, 95.7% of the screws are placed correctly, compared to 91% in the adapted system. The statistical comparison shows that the practicability of the TCP-positioning method is provided, due to the minor placing deviation.

5. Conclusion and Outlook

The article presents a holistic analysis and evaluation framework for resources in manufacturing, which was evaluated by a prototypical implementation and validation. The results show that the intelligent workpiece carrier is improves the process stability of a collaborative robot in a changeable assembly workstation. Thereby, the outcome shows that the IPIDS framework for the holistic implementation intelligent product structures is both valid and relevant for use within manufacturing practice and research.

The study's main limitation is that the IPIDS framework was applied to only one application area. In addition, the data from the position determination was gathered from a single source. Implementing further use cases and gathering more data from multiple sources in different manufacturing enterprises will assist in the validation of the conceptual framework. Therefore, not all possible factors have been incorporated. Further research that focuses on qualitative analysis of various users of the IPIDS framework supports the better verification of the framework.

References

[1] Shou, Y., Li, Y., Park, Y.W., Kang, M. The impact of product complexity and variety on supply chain integration, 2017, 47:297–317.

[2] Y. Zhong, R., Xu, X., Klotz, E., Newman, S.T. Intelligent Manufacturing in the Context of Industry 4.0: A Review, 2017, 3:616–30.

[3] Filho, M.F., Liao, Y., Loures, E.R., Canciglieri, O. Self-Aware Smart Products: Systematic Literature Review, Conceptual Design and Prototype Implementation, 2017, 11:1471–80.

[4] Främling, K., Holmström, J., Loukkola, J., Nyman, J. et al. Sustainable PLM through Intelligent Products, 2013, 26:789–99.

[5] Bertelsmeier, F., Schone, S., Trächtler, A. Development and design of intelligent product carriers for flexible networked control of distributed manufacturing processes, in 24th Mediterranean Conference on Control and Automation (MED), 2016:755–60.

[6] Leitão, P., Rodrigues, N., Barbosa, J., Turrin, C. et al. Intelligent products: The grace experience, 2015, 42:95–105.

[7] Liang, S., Rajora, M., Liu, X., Yue, C. et al. Intelligent manufacturing systems A review, 2018, 7:324–30.

[8] Dörner, D. Diagnosis of operative intelligence, 1986, 32.

[9] Burkart, A., Bitsch, G., de Kock, I. Framework for integrating Intelligent Product Structures into a Flexible Manufacturing System (forthcoming), 2022;

[10] McFarlane, D., Sarma, S., Chirn, J.L., Wong, C.Y. et al. The Intelligent Product in Manufacturing Control and Management, 2002, 35:49–54.

[11] G. Meyer, G., Främling, K., Holmström, J. Intelligent Products: A survey, 2009, 60:137–48.

[12] Ostgathe, M., Zaeh, M.F. System for product-based control of production processes, in IEEE Symposium on Computational:138–44.

[13] Burlikowska, M.D., Szewieczek, D. The Poka-Yoke method as an improving quality tool of operations in the process, 2009, 36:95–102.

[14] Glouberman, S., Zimmerman, B. Complicated and Complex Systems: What Would Successful Reform of Medicare Look Like?: Changing Health Care in Canada, 2002:21–53.

[15] Parker, R.P., Wirth, A. Manufacturing flexibility: Measures and relationships, 1999, 118:429–49.

[16] VDI. 5201 Part 1 - Adaptability - Description and measurement of the adaptability of manufacturing companies - Medical device industry, ICS 03.100.50, 11.020.99, 2017;

[17] McHugh, M. The Chi-square test of independence, 2013, 23:143–9.