Framework of the Architecture of the Communication Process Within Industry 4.0 Oriented Production System

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Abstract. Implementation of the Industry 4.0 concept requires changes on many levels. Implementation of technical solutions (ICT technologies, automation, robotization, AI) entails changes in the organization of processes, as well as in management and communication patterns. The article presents the concept of the IT system architecture supporting communication between the production planner and the production system in the enterprise. The aim was to develop a solution supporting and improving communication between a man and a machine. This area is important for the effectiveness, completeness and quality of information flow and the quality of decisions made on the basis of interpreted feedback. The solution presented in the article was developed as part of the study work on the preparation of the concept of reorganization of the company's production system during the preparation for the implementation of the Industry 4.0 concept. The analyzed enterprise manufactures single large-size machines. The technologies used include casting, machining and assembly. The analyzed production unit was the machining department, as it was selected as a pilot department for the implementation of Industry 4.0. The developed solution will be exemplary and will be the best practice to be used at the next stages of the implementation of Industry 4.0 in the enterprise.

Keywords: production planning, man-machine communication, Industry 4.0.

1 Introduction

1.1 Industry 4.0

Industry 4.0 is the term broadly referred to, for some companies still something to strive form, for the others the step already taken on the path to Industry 5.0 and further future developments. Interest of both academic and business environments, cognitive and utilitarian aspects of the concept, result in growing number of publications in the field. The dynamics of the growth is distinctive and presented in the Figure 1a. The concept is multidisciplinary which brings representatives of many disciplines to discussing various aspects of Industry 4.0, as presented in the Figure 1b.

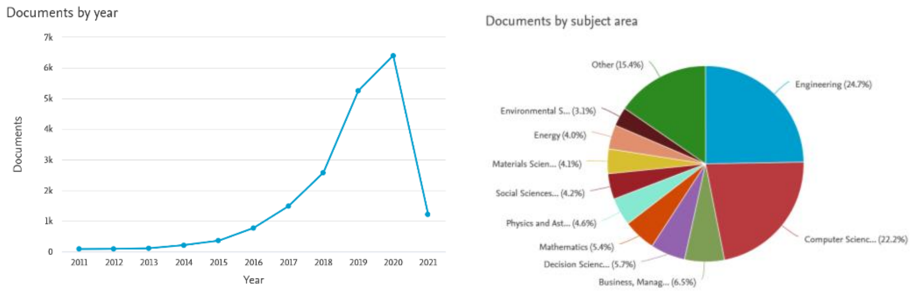

Fig. 1. a. Publications on Industry 4.0 (Scopus database, extracted 26 March 2021) b. Disciplines referred to in publications on Industry 4.0 (Scopus database, extracted 26 March 2021)

The publications originating from 2011 – year in which the Industrie 4.0 program was announced in Germany - refer to definitions [Culot et al 2020, Nosalska et al 2019, Piccarozzi et al 2018], scopes [Piccarozzi et al 2018, Vaidya et al 2018], pillars [Bai et al 2020], tools [Frank et al 2019, Dalenogare et al 2018, Chiarello et al 2018] that can be used to upgrade a company to Industry 4.0 level, benefits [Tupa et al 2017, Davies et al 2017], difficulties and challenges connected with Industry 4.0 implementation [Thames et al 2017, Masood et al 2020], case studies, literature surveys and comparative studies [Pacchini et al 2019, Davies et al 2017, Strandhagen et al 2017, Grieco et al 2017]. Industry 4.0 as broadly defined set of methods, techniques and tools implemented to increase manufacturing efficiency has for ten years been in the center of attention. Development of methods and tools enabling digitization [Bai et al 2020], Internet of Things [Bai et al 2020, Frank et al 2018], Big Data Analysis [Chiarello et al 2018], Cloud Computing [Thames et al 2017], augmented reality [Tupa et al 2017], additive manufacturing [Davies et al 2017] opened new fields for scientific research. Consequently, interest of academic society is stimulated by interest of business environment all over the world and actively contributes to dissemination of the concept worldwide, proven by numerous reports by independent and governments institutions [Grieco et al 2017, Schumacher et al 2016]. Countries and regions develop their original, yet Industry 4.0 based, programs stimulating entrepreneurs and economies [Piccarozzi et al 2020, Dalenogare et al 2018, Davies et al 2017] to improve their performance. Benchmarks and best practices published all over the world confirm universality of the concept – it can be implemented in many sectors of industry – and its positive impact on individual companies and entire economies. Recognition of potential benefits inspired one of large Polish companies to initiate processes striving for its adjustment to Industry 4.0 requirements.

1.2 Experience of Polish companies in implementation of Industry 4.0

According to Global Entrepreneurship Monitor (GEM) Poland has been included in the efficiency economies with the aspirations to join the group of innovation-oriented countries in recent years. Polish companies to be competitive need to follow the trends and solution recognized worldwide. However, the study conducted by Siemens and Millward Brown on Smart Industry in 2016 [Siemens 2016] showed that only 25%

representatives of Polish production companies were familiar with the concept of Smart Industry. At the same time, a significantly higher number of people declared that their organizations used technologies and solutions characteristic for smart factories. This proved, that there is a gap in knowledge on modern management and industry concepts.

The study conducted by Siemens and Millward Brown on Smart Industry in 2017 [Siemens 2017] proved some progress, showing large interest in innovativeness. The results of the survey show that the technologies that give the greatest competitive advantage are the automation and robotization of production. The most commonly used solution supporting innovativeness was automation with the use of individual machines - in 48.6 percent of companies have already been implemented, and 10.4 percent of enterprises had plans for implementation. In turn, the robotization of the entire production line took place in 14.3 percent, and is planned in 3.6 percent of companies.

The survey Smart Industry 2018 [Siemens 2018] was conducted on a nationwide sample of 200 companies from the industrial or production sector with the number of employees up to 249 employees, conducting production activity in Poland, i.e. having a production plant or plants operating in Poland. The analysis of the results takes into account the specificity of the heavy and light industry sector.

Smart Industry 2018 Report concludes that 60% of entrepreneurs have not heard of the Industry 4.0 concept. However, this is not synonymous with the non-use of modern technologies by these companies. It has already been proved by findings from previous reports 2016 and 2017.

2 Theoretical background

2.1 Production system in Industry 4.0 context

The elements that constitute the production system in the conditions of Industry 4.0 can be roughly divided based on their nature into four interrelated groups (layers). Brief characteristics of the layers covers the nature of elements and processes performed within them: 1) physical layer - it is made up of production and auxiliary machines and devices, implementing and supporting physical processes of material transformation: production processes. The term ‘supporting’ used above should be understood in a narrow sense - as the implementation of physical processes ensuring the continuity and proper course of the basic process, which is transformation of work objects (materials) in terms of shape, size, appearance, physical or chemical composition or properties. These processes are the so-called auxiliary and service processes and include transport and storage in the production process, production quality control, replacement of tools and workshop aids, and maintenance; 2) IT layer - devices (computers) and software controlling elements of the physical layer and creating a virtual copy of physical reality and supporting people in collecting and visualizing information relevant to decision-making. The task of this layer is also to make some decisions (in predefined scope, based on functionalities available); 3) Social layer - people working in the production system, both on operational and managerial level, communicating and cooperating with its various layers; 4) Communication layer - Internet ensuring the flow of information between individual layers and their elements.

The layers are not isolated, they make an open system of elements cooperating in achieving the predefined goal (production task) and link to environment with material and information flow. In Industry 4.0 context the physical layer will be strongly related or even integrated with IT layer as it will consist of cyber-physical systems. Cyber-physical systems operation control, according to the views dominating in the literature on the subject, will be based on the technology of embedded systems. These are special-purpose computer systems that are an integral part of the hardware they operate. Each embedded system is based on a microprocessor (or microcontroller) programmed to perform a limited number of tasks. The challenge seems to be integration of social and communication layer so that the production system benefited from synergy.

2.2 Integrated physical and IT layer structure and functions.

According to the literature on the subject, the CPS layer will cover five levels, as presented in the figure 2:

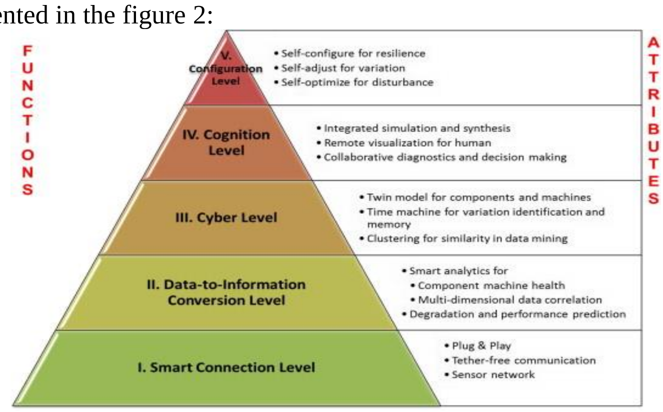

Fig. 2. 5C architecture for implementation of Cyber-Physical System Source [Lee at al. 2015].

The architecture presented covers mostly IT structure issues but it links them to physical layer through implemented technical solutions, mostly located at level I (smart connection level), data interpretation schemes, located at levels II and III, the upper levels are linked to social and communication layers as they support decisions making (level IV) and resilience of the system (V): Smart Connection level - it consists of data collecting devices - sensors (sensors) installed on machines and devices whose task is to capture signals from the surrounding environment, recognize and record them, and a network that amplifies the signals and transmits them over long distances, further processing using digital techniques and computers and remembering it. Data-to-information Conversion level - this level consists of a set of programs collecting and processing data collected by the layer of data collecting devices. These programs can be located on one central computer, on several computers or in the "cloud". The tasks of this level are: diagnosing the condition of machines, devices and work environment, predicting failures of machines and devices and environmental hazards and their potential impact on the operation of the system, analysis of collected data in terms of

searching for their temporal, spatial and causal relationships for the needs of system and environment diagnostics.
Some of the tasks of this level can also be performed by embedded systems, which are elements of the physical layer. The division of tasks in terms of transforming data into information between the elements of the physical layer and the IT layer is not clearly defined. It is difficult to indicate the criteria for this division. It seems that the main criterion should be to maximize the operational reliability of the entire production system. **Cyber level** - consists of a set of programs collecting and processing information collected by the layer transforming data into information. The tasks of this level are: modeling the behavior of machines, devices, changes in resource availability over time, analysis of the distribution (statistics) of events, activities, system states in time to forecast their frequency and duration, grouping of collected information for similarity for analysis using Big Data Analysis techniques. **Cognition leve**l - the level that recognizes (diagnoses) the operation of the system - consists of a set of programs collecting and processing information collected by the layer that analyzes information. It also organizes communication in the system by controlling the flow of data and information between individual layers. The tasks of this level are: preparation of information and data visualization for the needs of computer-human communication, simulation and information integration for resource demand forecasting, organization of cooperation in the field of joint (human-computer system) assessment of the situation and joint decision-making. **Configuration level** – the highest level that stabilizes the system providing resilient control, supervisory control and actions. The level is based on self-learning mechanisms and auto-regulations and its tasks are: Self-configuration, Self-adjustment, Self-optimization.
The structure is internally linked and related with other layers, which requires multi-level communication. The framework of communication schemes and architecture for the communication processes not only enabling but supporting the communication developed for a large machining industry company is presented in the next chapters of the paper.

3 Problem definition

The problem to be solved is designing interface (communication scheme) between man and machine to support information flow and decision making process in complex environment striving for increased automation and digitization of processes. The information flow in the analyzed production department is based on the blueprints system. The production planner fills in the relevant documents, analyzes the situation and makes appropriate decisions based on the reports from the workstation service. The approach is based on manual approach, planner’s knowledge and experience.
In Industry 4.0 environment such approach is insufficient and inefficient. Communication needs to be improved and potential of IT support, imminent element of Industry 4.0 concept, should be exploited. The problem was defined for a specific production environment, as a part of a dedicated project striving for adjusting the production system to Industry 4.0 level.

Yet, we believe that communication process and its improvement are problems that many companies face, disregarding their technical and technological advancement, automation and robotization level. Hence, though referred to the specific company, the problem is universal in nature.

4 Problem solution

4.1 Structure of communication process

For the problem defined in the section 3 the following solution framework was designed. The proposed communication is based on availability of database extracting data from sensors and covering three data sets (S, P, D):
S - a set of workstations within a given production unit
The elements of the set s_i, i = {1, .., n} are divided into groups distinguished according to: **Group size** - this parameter is identified by the number of workstations of a given type in the production unit: Location - this parameter is distinguished by the location of a given station in the production process in a given production unit, it is possible to classify the station into three groups in terms of significance: 1) initial, stations performing initial operations in the processes performed in a given unit, 2) intermediate, positions that perform intermediate (middle) operations in the processes performed in a given unit, final, stations carrying out finishing operations in the processes performed in a given unit, **Availability** - this parameter is determined in relation to the planning horizon, on the basis of the load plan for a given workstation from the workstation system, each time unit is assigned the status: 1) available, 2) busy, 3) damaged, based on reports
P - a set of items performed in a given production unit in a given planning horizon. The elements of the set p_j, j = {1, m} are divided into categories according to the following criteria: 1) advancement - it is defined as the relation of the planned start-up date to the current date, according to this criterion it is possible to classify a given subject into the following groups: pending - the launch date is a future date in relation to the current date; delayed - the launch date is the one that has already passed; in progress - split into three categories: a) in progress as planned - in the 'information' part, the execution of at least one technological operation has been registered, the date of completion of the last registered completed operation corresponds to that planned in the MES, b) in progress and pending - in the 'information' part, the execution of at least one technological operation has been registered, the deadline, the planned date of launching the next scheduled operation has already expired, c) in progress, in processing - in the 'information' part, the start of any technological operation is registered, there is no information about its completion, the planned completion date has not yet expired, d) in progress, interrupted in the 'information' part, the start of any technological operation is registered, there is no information about its completion, the planned completion date of the registered operation has already expired; e) completed - split into two categories: completed as planned - in the 'information' part, the execution of the last technological operation was recorded, the date of execution of this operation is earlier or equal to the planned completion date, completed delayed - in the 'information' part, the execution

of the last technological operation has been registered, the date of performing this operation is later than the planned completion date, 2) importance - this category determines the significance of a given assortment item from the point of view of the production process carried out in a given production unit, according to this criterion it is possible to classify a given item into the following groups (including a given assortment item in a specific group is done using the expert method): a) key, b) significant, c) supplementary; 3) quantity - this category can be referred to as the planned quantity of a given item of assortment ratio to the quantity available after a given operation, according to this criterion, it is possible to classify a given item into the following groups: a) launched according to the plan - if the quantity included in a given operation corresponds to the planned quantity, b) completed according to the plan - if the quantity completing a given operation corresponds to the quantity planned, c) insufficient - if the quantity that starts or ends a given operation is smaller than the quantity planned.
D - a set of data assigned to a given set of positions and the set of objects performed on it in a given planning horizon. Each data saved in this set has two versions: 1) planned value - imported from the MES system, 2) actual value - saved as information from sensors or embedded systems installed on the workstations.
Data $d_{(i, l)}$ where i = {1,., N} and l = {1,., P} relating to workstations are of the following scope: availability of the position, the date of launching a given operation on the workstation, completion date of a given operation on the workstation. The suggested structure of the process is dedicated to the specific problem defined in the section 3, nevertheless we designed it to be as universal and flexible as possible to enable its implementation in any production systems which deals with similar problems.

4.2 Communication process realization

Communication between a production planner and the systems is based on continuous interactions. The system produces the following reports: 1) damaged positions and available positions, each report is prepared according to the categories of initial, intermediate and final positions; 2) completed items divided into the categories of scheduled completion and delayed completed, the reported items are divided into the categories of key, material and supplementary items, 3) items waiting to be launched with a breakdown into the categories of pending and pending delayed, the reported items are divided into categories of key, significant and supplementary items, 4) report on the number of completed assortment items from the insufficient category, broken down into the categories of key, significant and supplementary items.

The system collects data from embedded systems, sensors and sensors on an ongoing basis. The incoming data is continuously used to update the reports. After each update, two versions of reports - the one before the update and the one after the update are compared by the experimental system. If the differences between the reports are considered significant, the information about it, together with the version of the report, is provided to the production planner after updating. In addition to this information, the scheduler also has access to all subsequent versions of the reports.

The set of reports generated by the system has been supplemented with a mechanism for comparing and tracking the compliance of the production flow between the planned, and the actual flow. The concept of the applied mechanism was based on the method of analyzing the process capability. It is a computational procedure for assessing whether the process is running correctly and meets the requirements. A modified capability index model was used. The indicator used to track the compliance of the production flow between the planned amount and the actual flow was built on the basis of the process capability index C_p used in the process capability analysis method. In the original version, this indicator is a measure of the precision of the process. It measures the width of the actual process scatter relative to the width of the tolerance field. Data from control charts are used in the process capability analysis. Control limits are the numerical values within which the process is to run. These are usually the minimum (lower limit) and maximum (upper limit) allowable values of certain process parameters. The boundaries are defined at the design stage of the process.

In the applied solution, the lower and upper limits of the process were adopted arbitrarily. The value of the lower control limit was assumed to be $S_l = 0$. The value of the upper control limit was assumed to be $S_u = 1$. The production system was divided into three channels: 1) initial channel including positions qualified as initial, 2) an indirect channel including positions classified as intermediate, 3) end channel including positions qualified as ending.

For each of the distinguished channels, it was assumed that a separate control chart was developed and that the proposed U_f flow uniformity index was calculated separately.

The values of the analyzed process will be marked on the control card at the beginning and end of the technological operation. These values will be adopted depending on whether the commencement or completion of a given technological operation at a specific position took place as planned, was delayed or was faster than planned: a) in the case when the commencement or termination of a given operation took place on the scheduled date, the process value x = 0.5 entered on the control card, b) if the start or end of a given operation was delayed compared to the scheduled date, the process value $x = 1 + \alpha$ entered on the control card, where α is the delay value; c) in the case when the commencement or completion of a given technological operation took place before the scheduled date, the process value x = 1 entered on the control card.

The flow uniformity index U_f is calculated at the end of each shift for each channel separately according to the formula similar to the coefficient C_p.

$$U_f = 1 / 3\delta \quad (1)$$

where:

U_f - flow uniformity index

T = 1 - tolerance range, the difference between the upper and lower control limit

σ - standard deviation.

With the adopted method of determining the value of the process applied on the control card, in a situation when all technological operations are started and completed on time, the U_f coefficient takes the value of zero. The value of the coefficient decreases in the case of earlier commencement or termination of technological operations, and it decreases significantly in the case of delays.

After collecting a specific set of empirical data, the authors intend to check whether the specific U_f value can be assigned to specific states of the production process.

It is possible to modify the structure or the flow of the communication process to adjust and adapt it to the specific conditions of any other company dealing with the communication problem in manufacturing process.

5 Conclusion

Work on the development of the communication scheme presented in this article is in progress. The analysis of the production system led to an update of the system concept. It turned out that due to the specific quality requirements of some of the elements produced in the production system, the data on the course of their production process must be extended, stored in separate files and made available to external stakeholders on request. It was decided that this data would come from the communication system between the production planner and the production system, and collected, stored and made available by the IT system operating at the level of the entire enterprise. This requires designing an interface between the communication system between the production planner and the production system and the information system operating at the enterprise level.

The developed solution was pre-evaluated during the presentation for the company. Basic assumptions were presented and explained, conclusions were discussed and as a result some improvements to initial idea were introduced (they are included in the conceptual solution presented in the paper). The implementation is on-going and after it is completed the system will be evaluated with the set of qualitative and quantitative measures including: cohesion rate (information flow vs material flow), muda size (for time, errors, and activity mudas), cost of information flow (prior to implementation and after that). The results of evaluation will be the basis for improvement, we assume periodic evaluation to control growing maturity of the solution.

The team of automation and IT specialists operating in the company is currently working on the concept of selecting embedded systems and sensors, connecting them into a network and selecting software. The expected results from the communication system implementation will consist in qualitative and quantitative improvement of information flow expressed by: number of errors, number of unnecessary actions and decisions taken, lead-time for information flow and material flow, flexibility of manufacturing system and the cost of information flow. The evaluation measures for evaluation of the system were selected to identify the expected benefits and enable continuous improvement of the solution

Acknowledgment: The research was financed from Faculty of Engineering Management project fund nr 0812/SBAD/4185

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