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A Concept of an SME Focused Edge Computing Self-managing Cyber-physical System

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Abstract
The dynamically changing environment forces companies to introduce changes in production processes and the need for employees to adapt quickly to new tasks. Therefore, it is expected to implement solutions to support employees. The system that will manage the work on a manufacturing line should work in real time to support the ongoing activities and, to be implemented in SMEs, must not be expensive. The authors identified important system components and expected functionalities. The methodology of the work is based on human-centered design. A concept of a cyber-physical system is proposed. The aim of the proposed edge computing-based system is to manage the work on the manufacturing line in which certain elements communicate with each other to achieve common goals. The paper presents what the system can consist of, how information and knowledge are managed in the system, and what can be the benefits for enterprises from its implementation.

Keywords
Cyber-physical system; Information communication; Knowledge management; Edge computing; E-kanban.

Introduction

For any manufacturing process (MP), it is important to plan a work and to monitor its realization to ensure that the work will be completed on time to deliver a product to a customer without any delay. Therefore, it is vital to monitor tasks' completion, information flow, material flow, and react on any problems which appear. This can be done manually, by a manufacturing line (ML) manager, or with the help of a computer system (CS). Especially, when a company manufactures different kinds of products, as well as when the operating time needed for different products varies, and when, additionally, the products are complex, it is difficult to monitor the MP manually a with high level of accuracy. Thus, companies implement computer systems such as Manufacturing Execution System (MES), Enterprise Resource Planning (ERP), or traceability systems using Radio-frequency Identification (RFID), which are based on information acquisition that support the monitoring and decision-making process (Zhao et al., 2020).

Monitoring systems can use Internet of Things (IoT) technologies including, already mentioned RFID (Lin & Chen, 2017), or other technologies such as Bluetooth (Kulshrestha et al., 2017), GPS (Global Positioning System) (Xu & Chen, 2016), or combinations of these technologies (Huang et al., 2017) to track material flow as well as information flow.

However, for SMEs such systems can be too expensive to cover all workstations to monitor them with high level of details. Moreover, the system could be quite complex if it had to react to any arising problem. Rather, MLs are monitored to see if they deliver ready products on time. If not, the causes of such a situation are identified and analyzed. In addition, edge computing systems are proposed more and more often (Kubiak et al., 2022; Carvalho et al., 2019). Such systems can cover and manage one ML.

Currently, apart from actual process monitoring, it is also very important to ensure a fast reaction to the

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changing market situation. New competitors and new customer requirements force companies to implement changes in products as well as in manufacturing systems (MSs). Therefore, MSs as well as the CSs supporting them have to be agile and adapt fast to changing environment (Jin-Hai et al., 2003). Thus, both MS and CS have to be built up from the bottom to be not only flexible but also agile.

Other problem, which exists in SMEs, is that many operations are still performed by human operators. In the MP where tasks are demanding, a human operator has to focus on the merits. Therefore, maximum operator support is necessary to ensure high work quality. Sometimes, an operator can be supported by a cobot (Kim et al., 2019), but for SMEs, it can still be too expensive. Thus, to minimize psychical load of operators, they can be supported by a system, which helps them in performing the manufacturing/assembly operations and in decision-making process. Currently proposed systems can be difficult to implement in SMEs, which the authors of this paper see as a practical problem that can be solved by proposing a simple system that supports the work of operators and does not generate high costs.

Therefore, in this article, the authors first present existing solutions and then propose an edge computing self-managing cyber-physical system (CPS) which can be implemented with relatively low costs and can be used in a ML to manage a MP. In the paper it was assumed that a human operator is a core element of the manufacturing system and will perform manufacturing tasks and participate in information transfer. The edge computing cyber-physical system (EC–CPS) is based on IT solutions that enable communication between MS elements.

The following section introduces the CPSs proposed in the literature for MP monitoring, as well as supporting tools and methods to help illustrate the range of possibilities and just how broad the topic is. Based on the performed literature review, the main problems connected with CPS implementation that can appear in SMEs to monitor MPs were identified and the main gaps are presented. Then, a research goal and a methodology applied for development of the structure of the system are described. The next section analyses an MS with all the components which should be monitored. After that, a concept of the EC–CPS is described together with rules of information flow. Then, the IT solutions that are proposed to be applied in the EC–CPS are presented. The paper ends with conclusions. The limitations of the work and further research are also described in the conclusion section.

Cyber-physical systems to monitor manufacturing processes

Cyber-physical systems (CPS) are computational entities that cooperate with each other in close connection with the surrounding physical world, providing and using, at the same time, access to available data, processing information, and possibly executing or suggesting decisions (Villalonga et al., 2018).

In companies approaching digital solutions, the kanbans can have a digital form (El Abbadi et al., 2018). e-Kanbans digitally transfer information between components of a manufacturing system (Menanno et al., 2019). However, in SMEs, especially when high levels of craftsmanship exist (Stadnicka et al., 2017), the implementation of e-Kanbans can be more complex.

Synchronising data and information from different activities in the factory is a difficult task to implement, particularly when the core of production is based on traditional manual work (e.g. manual assembly) rather than advanced automation systems. Efforts have been made in fields such as human safety (Bonci et al., 2021a) or more advanced applications of brain computer interfaces (Bonci et al., 2021b), but real-time monitoring of manufacturing processes that largely involve manual or semiautomated work is extremely difficult to achieve in practice. This is because the use of Industry 4.0 principles in such processes requires the development of new production monitoring and control solutions that involve the worker in the monitoring process without negatively affecting production times and the psychological state of workers.

In this section, a monitoring architecture is proposed that aims to facilitate the application of Industry 4.0 principles in the context of industry with low automation penetration.

It is described how a monitoring system can be designed to use standard tools already available on the market to detect delays, errors, or problems in manual production with the aim of increasing the quality of work without worsening the psychological status and cycle times of workers.

In order to pursue the above goals, first, a cyber-physical monitoring system (CPMS) has to be defined. It can be thought of as computer-based algorithms of a CPS that are dedicated to monitoring the activities in the cyber-physical world and then making interpretations of these activities available to the CPS. The activities of the cyber-physical world will clearly consist of either action in the physical world (e.g., of a human being) or actions in the cyber world (e.g., a set of data events). CPMS is, by its nature, closely integrated with working environment and constitutes the means that make it possible to apply the principles of Industry 4.0 in industries with a low degree of automation penetration. Such a tool must therefore first be conceptualized and then operationally declined on technological devices capable of allowing the interpretation and encoding of actions from the physical world to the cyber world and vice versa. The conceptualization phase of a monitoring system addressing manual assembly actions must first consider the principles of 1) interoperability, 2) virtualization of processes, and 3) decentralization of decisions typical of Industry 4.0 (Penas et al., 2017). These principles can be achieved through the set of choices suggested as follows. 1) Interoperability with any device is ensured (Burns et al., 2019) by realizing interconnectivity between different devices and allowing the acquisition and integration of large amounts of data. This means, by choosing communication protocols that are independent of the specific hardware, such as the OPC-UA standard (Pauker et al., 2016) or other similar ones, that it can in fact be implemented indifferently on a multiplatform java app residing on the operator's device or on the industrial PLC allowing data interchange based on tasks and not depending on hardware executing tasks. 2) Virtualization of processes in manual or semi-automatic work environments does not mean to address a digital twin model because such processes still need to be automated before virtualized. A lower-level virtualization is required because many companies still use paper-based monitoring systems or the processes are simple enough to be considered manageable without additional support. In both cases, they require persons to manage decisions. Therefore, to allow lower-level virtualization, according to (Tarallo et al., 2018), a virtualization of manual assembly actions is here proposed by considering the goal of a single manual assembly action as the virtual result of the manual process. The goal is considered achieved when the following conditions are satisfied: a) the end of operator action is regularly reported to the system, b) the operator acted on time, c) the action was a planned action, otherwise an assembly error occurs. This is achieved by equipping the operator with ICT solutions for product and manual work process traceability such as: RFID or similar product tracing technology for each part that constitutes an assembled subpart of interest for traceability, and an ICT terminal (touch display, HMI, etc.) for each assembly station that can record breaks, stops, rejects, completed assembly, and so on. 3) The decentralization policies must be a prerogative of the CPS with which the CPMS must necessarily interface. So, the actions that the CPMS can take in this respect are mainly to make available, in a decentralized manner for each assembly station, the information recorded by the system at the local level to ensure that the CPS can implement decentralized reasoning policies.

To better focus on the concept of CPMS, an example of manufacturing implementation is discussed here. Consider a CPMS for monitoring the following tasks: monitor the classical traceability of raw materials and finished products, record and share assembly data from different workstations including manual ones, record and share production KPIs. These tasks are difficult to integrate with standard automation approaches.

The CPMS will consist of three interconnected subsystems, a traceability unit, a set of operator terminal units, and a system for interfacing information with databases. The traceability unit allows virtualization of the process by recording the production flows, including the manual assembly phases and all subsequent phases up to the final stage.

An RFID tag (or barcode depending on the situation) related to the order will be applied to a part to be assembled that is involved in all stages. Not necessarily all parts of the product need to be tracked. Depending on the case, it is often sufficient to track only subparts of the product (the semi-assembled parts). In order to originate the finished product, various subparts can be made in either automatic or manual assembly stations. The assembly stations equipped with an RFID reader allow the assembly operator (in the case of a manual workstation) or the machine (in the case of an automatic workstation) to read the RFID tag at the beginning of the processing phase, which represents the entrance into the station processing phase. Reading the start of the machining phase of the next part will close the machining phase of the previous part.

The second subsystem is the operator terminal (touch-display or HMI), which performs the tasks of interoperability and virtualization. It will be a feature of manual stations. It will show the operator the job and the machining phase in progress (virtualization) and will be equipped with an OPC-UA interface and buttons to allow recording of stops, pauses, and rejects, and of fault signals from the field (PLC etc.) or from supervision or planning systems such as MES, ERP, etc. when suitable (interoperability). The last subsystem consists of software equipment capable of communicating information with databases.

To guarantee a reasonable level of decentralization and therefore reliability, each subsystem must be designed as autonomous while being aware of the surrounding systems. Thus, each subsystem will have internal state machines driven by internal and external events. Each autonomous component of the subsystem will change state as a result of external events and process information through internal processes that will eventually communicate with external systems.

The main gap, which was identified in the literature review, is that currently proposed CPSs are built with the use of expensive technologies, and they are typically too complex for factual adoption by SMEs.

Research goal and work methodology

The main research goal of this paper is to develop a concept of an edge cyber-physical self-managing system that has suitable features that enable its viable implementation in SMEs. The main contribution of this work is connected with the proposal of edge computing implementation that can be realized autonomously based only on information presented in a manufacturing order and connected documents.

The work is based on the human-centered design methodology that is built on understanding the users of the system, tasks to be performed, and environment in which the system will be applied (ISO 9241-210:2019). In the work, the following steps were applied:

- Step 1: Analysis of an MS. The analyzed MS is an example of a system which includes typical problems existing in MPs in which human operators are involved. The example was developed based on the authors' experience coming from collaboration with SMEs.
- Step 2: Analysis of the possible role of the system components in the information management process and in the decision-making process. The product and its components, the manufacturing operator, the transport operator, and other elements were taken into consideration.
- Step 3: Analysis of Information and Communication Technologies (ICT) and the possibilities of their application in the MS. ICT solutions were chosen and presented together with a justification of their possible application.
- Step 4: Designing of an edge computing cyber-physical system (EC–CPS) used for ML management. A concept of the system is proposed together with its components. Different constraints existing in the MS were considered and analyzed. Agility problems were also discussed.
- Step 6: Designing of a structure of a database intended to store data indispensable for edge computing. The structure of the database concerns information about the product and the MP. It is necessary that certain CPS elements have access to adequate information.

The implementation of the presented steps is described in the following section of the paper.

Analysis of a manufacturing system

The main purpose of the analysis of a manufacturing system was to identify ML components through a case study relating to a system that produces a complex product. Then, it was important to identify the main requirements for a system that can support the processes realized in the ML.

The manufacturing system analyzed in this paper concerns a manufacturing process that is performed manually by human operators. The manufacturing process contains neither automation nor robotic system. The whole work is performed manually based on operators' knowledge and experience. Such a manufacturing system is characterized by a high risk of human errors, since the process and quality of the product depend greatly on how the operators can focus on their work. The additional difficulty lies in the complexity and diversity of the product. One operator has to perform many operations in a sequence, which vary from one product to another.

In SMEs, often manufacturing processes are not carefully monitored. Lead time (LT) is assessed on the basis of operators experience and historical data. LT is the time in which a manufacturing process is completed to deliver a ready product to a customer on time (Rother & Shook, 2003). Sometimes it is difficult to assess whether a product can be finished on time or when there is a risk of delay. Even if LT was initially assessed correctly, when a process takes several or dozens of days and one operator performs a task for a few days and the process is not carefully monitored, a risk of delay might not be noticed. Implementation of an ICT solution can support the monitoring process. To design an adequate solution, an analysis of the MP is indispensable. Therefore, it is important to identify the MP structure first.

To monitor the MP, every single task does not have to be monitored. Sometimes, it is enough to summarize the time needed to perform a group of tasks. Figure 1 presents an example of an MS consisting of seven processes (P1–P7). Process 5 is divided into 4 subprocesses. Each subprocess is performed by different operators. Arrows represent material flow in the system. The presented example can help to understand the complexity of the EC–CPS relations and the functions it will perform.

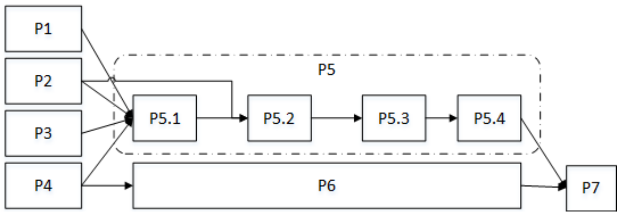

Fig. 1. An example of a manufacturing process structure

Based on a set of tasks that should be performed in the processes, a planned time to manufacture a product can be predicted. Then, a real execution time of processes can be monitored and compared with the planned time. In this way, the risk of delay can be easily identified.

In the presented example of MS it can be seen that:

- Process P5.1 has 4 internal suppliers (P1–P4). It is important to know that the P2 process delivers the main component of the product, which is a steel box into which other components are assembled until the product is ready. Therefore, the manufacturing process cannot continue until the P2 process delivers the metal box to the process P5.1. Tasks are realized in a sequence as soon as other processes (P1, P3, P4) provide other components.
- Processes P2 and P4, additionally, deliver components to processes P5.2 and P6, respectively.
- Processes P5.3 and P5.4 do not need any additional components to be performed.
- Process P7 is a process in which the final product is assembled using the outputs of P5 and P6.

It may happen that an *LT* of the product manufacturing process is shorter or much longer than originally anticipated. This can cause problems such as higher inventory or delays in delivering the product to a customer.

It is worth emphasizing that the MS includes supermarkets and FIFO lanes, which are inventories with limited space (Rother & Shook, 2003). The number of components/units in inventories also influences the *LT*.

The general structure of a complex product is presented in Figure 2. The product consists of m units and p components. The dashed line symbolizes that units can consist of different numbers of components. At the same time, one type of component can be assembled in different units. The EC–CPS should have the possibility to monitor the material (components/units) flow even if each product will have a different structure. The EC–CPS will see the structure as presented in Figure 3.

From Figures 2 and 3 it is seen that the product can have the form of Ready Product (Complex product) or Not Ready Product. These classes along with the class Association represent a generic model of an undirected graph consisting of parts and relations between them. Such a graph can model the structure of a complex product shown in Figure 2. In the graph, a vertex is a part, and an edge is a relation between parts. One vertex of the graph has a special meaning: the final product what is modelled by the class Ready Product. This class is necessary because as Figure 2 shows the one node on the Level 1 is distinguished.

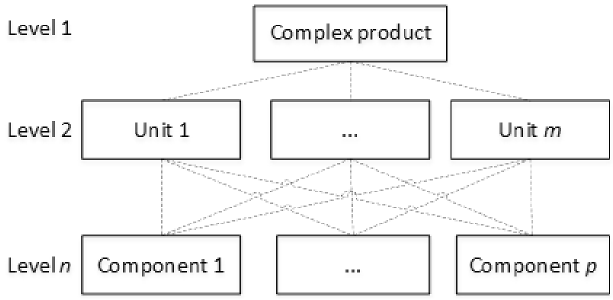

Fig. 2. A structure of a complex product

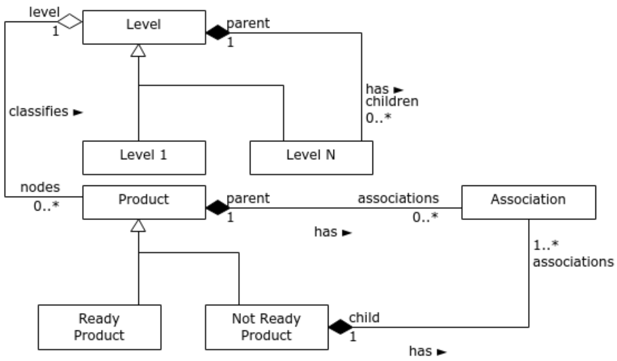

Fig. 3. Logical connections between complex product components and product levels

Figure 2 presents the parts that are classified as components, units, etc. The hierarchy of types in Figure 2 is following: component – unit – product. It is a hierarchical tree structure where the product is the root of the tree. The types names shown here are examples, and they should come from a domain of the problem. The classes Level, Level1, and Level n model the hierarchy of parts types. They correspond respectively to a tree node, the root node and a non-root node. The Level1 class is at the top of the hierarchy. It can have many subordinate nodes but it has no parent. Exactly one parent node is bound to every non-root node. Class Level n inherits properties of the class Level so it can have its own subordinate nodes and be their parent.

The structure of the product and the logical connections between complex product components and product levels are important from the EC–CPS design point of view. Even if a product will have just few components and units, the MP flow can be complex.

The analyzed MS consists of:

- Product and its units/components that flow through the ML. A product can wait for a next process in a supermarket or in a FIFO lane. The waiting time also influences *LT*.
- Supermarkets with units/components to be assembled. The MS can consist of many supermarkets that can be situated in different places. For supermarkets, it is important to know what is inside, what should be inside, and what next should be delivered to certain supermarkets.
- Kanbans applied to information flow. If the kanbans have a form of containers, they can also be used for physical transport.
- FIFO lanes with limited space for the products that have left the previous process and have to wait in queue for the next process.
- Human operators working on certain workstations (Figure 4) performing operations according to a technology. They also have to report the work done.
- Transport means. They are applied to ensure that materials/units/components are safely transported in the right quantity to the right place.

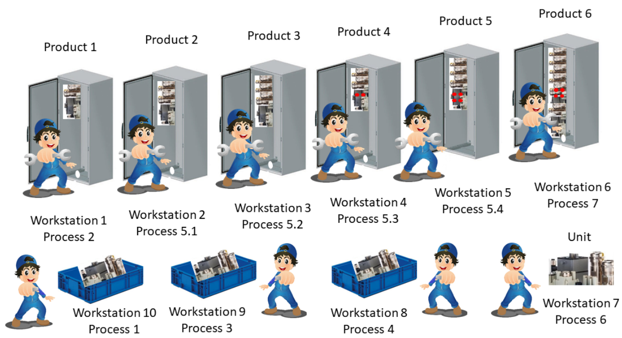

Fig. 4. Workstation in the ML

The ICT solution that could support the MP realization should have the following characteristics. The proposed ICT solutions:

- should not be too expensive for SMEs,
- should be intuitive to minimize cognitive effort of human operator,
- should be possible to be implemented for a complex product and a complex MS,
- should be flexible to cover changing number of component/unit types in supermarkets,
- should be agile to ensure fast implementation of a new product.

Currently available solutions that are based on digitalization and intelligent automation (Dotoli et al., 2019) were analyzed to check how they could possibly be used in the current research. The authors even reached the publication (Li et al., 2014) in which the presented system is devoted to complex products. However, since the analyzed problems concern aviation industry, the system includes many functions which are redundant in the analyzed SMEs MS. Therefore, an original solution is presented in this work.

Components of the proposed solution and communication flow

The main purpose of this section is to present the system components that will be able to communicate and to present the functions they will perform in the system.

For the most part, in SMEs of manufacturing areas, a key role in information flow is played by human operators. They accept production orders and report execution of work, as well as the different problems that appear. In CPSs, it is important to minimize the involvement of operators in information flow and to use ICT technologies to automatize it. Usually, most of the MS components such as products, supermarkets, kanbans, transport means, etc., have passive roles in information flow. The key is to transform their passive role into an active one. This can be achieved with the application of IoT technologies. This can elevate the monitoring process to the level of intelligent management of process operations. For example, electronic kanbans (E-kanbans) can be applied to transfer information about what is needed to be delivered or what is delivering, in an electronic form (MacKerron et al., 2014). Moreover, containers used for the transport of product components can contain some information. This information can be under a barcode or in RFID.

Products can also carry information. Intelligent products (smart products) can be defined as "*a manufactured item which is equipped with an ability to monitor, assess and reason about its current or future state and if necessary influence its destiny*" (McFarlane et al., 2002). Therefore, instead of having just a product which is treated alone, the product can carry information and play an active role in the monitoring and decision-making process of the manufacturing process. Therefore, the product can actively communicate with other components of the manufacturing system and play a role of an active holon (Derigent et al., 2020).

In addition, supermarkets, being the components of the manufacturing system, can be a part of a symbiotic edge computing cyber-physical system. How to transform passive supermarkets into active components will be presented later in this work.

Operators can be considered as smart components of the MS since they can use RMAS motes (Bonci et al., 2019), possibly with chatbot-enabled technology. With the use of the RMAS mote, an operator can communicate with the RMAS app (Figure 5).

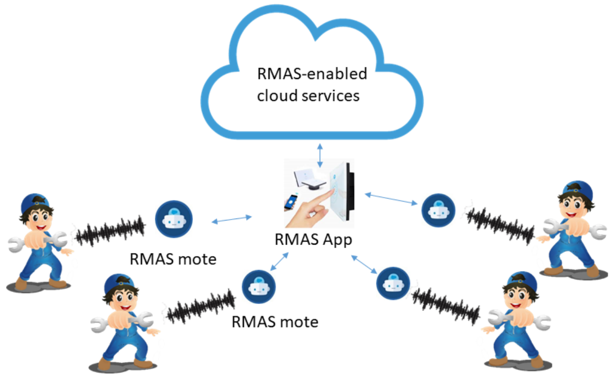

Fig. 5. A concept of communication between manufacturing operators and RMAS-enabled cloud service

In case of transport operators, they can also have access to a barcode or RFID reader since they transport containers with attached barcodes or RFIDs. Therefore, a transport operator can operate with the use of barcode reader and/or RFID reader, chatbot device, or RMAS mote (Figure 6).

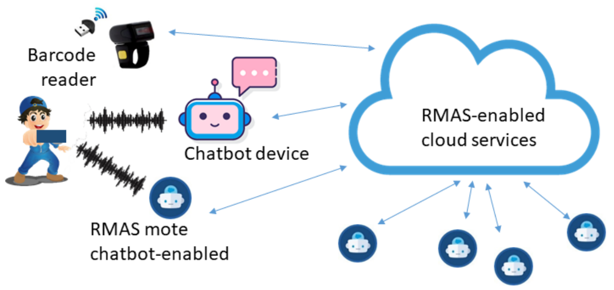

Fig. 6. A concept of communication between transport operators and RMAS-enabled cloud service

What is most important, the components of the distributed intelligent MS can be connected to each other. A relational multiagent system (**RMAS**) that uses a core database management systems (DBMS) (Bonci et al., 2019) can be developed. For example, in the work (Khadiri, 2022) a multi agent architecture was proposed for workshop scheduling. RMAS units (MS components) can appear in every layer of the ICT starting from cloud to embedded tiny devices (RMAS motes). They can be installed and dispersed across the ML objects (Figure 7). RMAS installed as a typical Web-based interface back-end can take the form of a RMAS app.

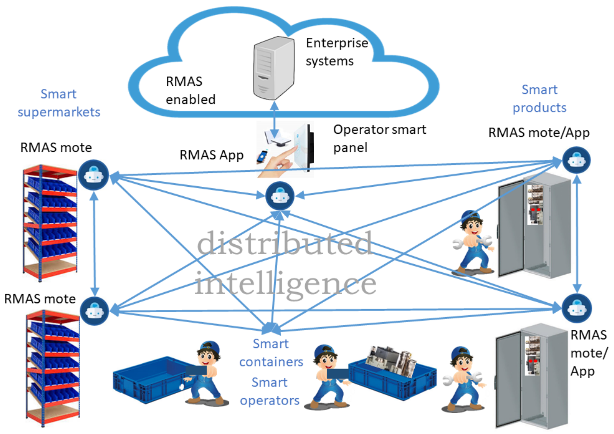

Fig. 7. A concept of an edge self-managing cyber-physical system

On the basis of the performed analysis, it was decided that the following system components will be embedded with the presented ICT solutions:

- Smart Product will have an embedded RMAS mote/app with intelligence. The RMAS mote/app contains product holon information. Another solution could be RFID but this does not have intelligence. Therefore, RMAS mote/app was chosen.
- E-Supermarket will have an embedded RMAS mote. This solution not only enables communication, but also gives the possibility for negotiations with other MS components. Another solution could be barcode or RFID but they have no context information.
- Manufacturing Operators will have an access to the smart panel for communication with the system. The smart panel gives the possibility of complex interaction. Operators could also interact with the system by voice, what results with immediate and complete information and querying, but it requires a quite environment and voice recognition system.
- Containers (E-Kanbans) will carry information with the use of barcodes. They will be Returnable Transit Items, – RTIs moving between a workstation and a supermarket (Neal et al., 2019). Although a barcode contains static and low information, it is enough to code the information regarding what the containers hold or should hold. Other solutions could be RFID, but in the presented case it is not necessary to increase the costs, since the RFID will not give any additional advantage. Moreover,

RMAS mote is also redundant, since the smart container should only carry rote information and actually will not be so smart. If it would be valuable to follow the containers routes, the solution would be useful, but it is not needed in the presented MS.
- Transport will be performed by a human operator who will have access to a barcode reader and can have a chatbot device to have access to work instructions. Despite the drawbacks such as vulnerability to errors, sometimes sloppy, the human transport operator is flexible and has the ability to cognition of the context. Instead of a human operator, an Automated Guided Vehicle (AGV) or even Autonomous Mobile Robots (AMR) (Unger et al., 2018) could be applied: But they are expensive and redundant in the kind of MS presented in this work. Another solution could be a conveyor belt but this solution is the least agile.

The edge computing system will manage the work of the ML without redundant continuous communication with the enterprise central system. The proposed EC–CPS will have embedded intelligence, which allows the ML to self-plan and self-organize the MP and material flow. The embedded intelligence will allow to make decisions in a distributed way. Interactions between the system components are made at every level, and they have a form of domain-dependent queries (Bonci et al., 2019). The manufacturing line management process is presented in the next section.

ML management process

This section shows how the proposed solution will facilitate the work of operators, as opposed to the current practice in MSP.

In company practice, usually a manufacturing operator registers a performed work entering into a paper form or into a computer system an adequate information. Paper forms for recording data and/or a computer panel are available for operators on their workstations or in a dedicated place. The operators also receive production/transport order from a computer system, or it is delivered to them in a paper form. The operators have also access to procedures/instructions, which they need to follow, in paper or electronic form. The manufacturing process is monitored on the basis of the registered data. Someone has to be assigned to carry out the monitoring process and identify any delays and obstacles. Such systems rely on people and require their attention. At the same time, they are prone to human errors. Therefore, supporting people with an intelligent system might prevent mistakes and facilitate the monitoring process. The proposed EC–CPS will be used not only for process monitoring but also for the ML management. The main assumptions for the system are as follows:

- An operator will automatically receive a new order when only she or he will report her or his readiness to accept the next task.
- An operator will have an access just to the procedures, instructions and/or other documentations needed to perform a certain work. Therefore, there is no chance that the operator will use the wrong documentation and, moreover, will not lose time searching for documentation.
- Information concerning material flow or work done will be immediately available in the system when only an operator confirms that a work or transport was done.

When only a manufacturing operator receives a new order, the system starts counting the time to complete the order. Preliminarily, a manufacturing process LT was decided, as well as a deadline for the work completion. This information is very important in the context of the ML management. The manufacturing operator will have access to the information about the order through a computer panel. While a transport operator will use a chatbot system to download a transport order and a barcode reader to upload information to the system about performed transport operations. The EC–CPS will collect data in a distributed way, transfer information between the system components, calculate LT and assess the risk of exceeding the assumed LT, and make communication with a central system when it will be indispensable. It is useful if there is a risk of extending the LT beyond the assumed LT (1) or if there is a necessity to communicate the need for an external (to the ML) supplier to supplement a supermarket (2) (Figure 8). The central system will send to EC–CPS the orders with additional information,

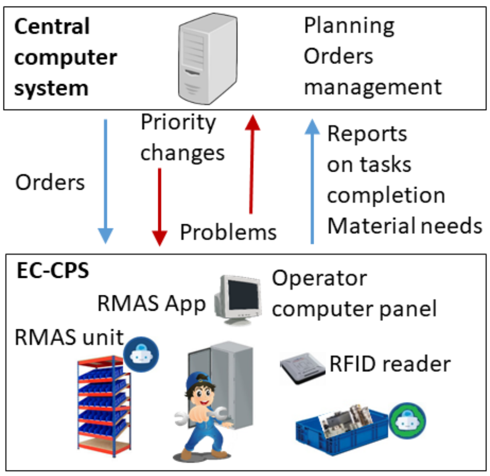

Fig. 8. Communication with a central computer system

such as preliminary deadline, planned *LT*, and information concerning applicable process documentation and information concerning priority changes. Problems concerning the implementation of new products or modification of already manufactured products will not exist from the EC–CPS point of view, since the agents will have access to currently used documentation whatever it was. Therefore, it can be said that the system will be agile.

Data in the EC–CPS are collected in a distributed way, which means that different system components (agents) possess and analyze different data that are important for the components. The agents also communicate information needed by other components to make decisions. This way, the ML is self-managing and self-optimized by using holonic approach (Derigent et al., 2020). Time is the optimization criterion, since keeping deadline and not exceeding *LT* are of utmost importance. Of course, ensuring the quality of work is out of question. Decision rules implemented in EC–CPS concern task sequence, and material/component/unit delivery priority.

The EC–CPS intelligence is also distributed among the agents, therefore, it is a multi-agent system which, as a whole, manages the ML. For the purpose of automatic decision-making process, the agents will autonomously make negotiations with other agents when it will be necessary. The embedded intelligence will support the decision-making process.

The EC–CPS intelligence will use data coming from the central system and information about constraints and problems existing in the ML to manage the work of the ML, to ensure orders completing on time. Decisions will be undertaken automatically, without human interaction, in most cases. However, when an exceptional problem will appear, an operator will be informed about the situation and then the central system if the decision is not taken by an operator in an expected time. The problems which appeared and the solutions which will be implemented will be registered in EC–CPS and they will be used in the learning process to maximize the number of automatically undertaken decisions. The system will also learn about the decisions that were not effective. This way, local problems will be solved locally in the ML. However, the knowledge database can also be available for other MLs, since the central system will have access to all data concerning the problems, the solutions and their effectiveness. Therefore, if a similar problem will appear in another ML an adequate information will be delivered to support decision-making process and to prevent mistakes, for example, undertaking ineffective actions. It can be said that the system will create a lesson-learned data base.

The main contribution of this work concerns presentation of the means and logic of communication between EC–CPS and the central computer system, as well as communication between EC–CPS agents (relational multi-agent system) for the purpose of self-managing and self-optimization of a ML. Moreover, a database structure is created for the presented solution, in the form of a symbiotic cyber-physical system dedicated for SMEs.

Structure of databases

This section presents the structure of the designed EC–CPS databases, that will be used to collect data. Each agent must have access to the information which allows to take decisions. The most important is the structure of the product and the process. A product structure was already presented in a previous section. Figure 9 presents a class diagram for a process structure.

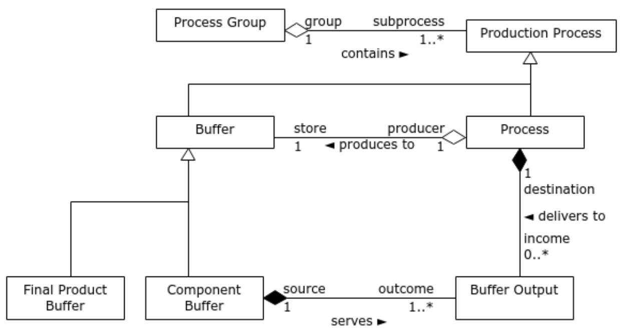

Fig. 9. A class diagram for process structure

Two types of nodes are visible in the structure: process and buffers. The authors of this work assume that every process produces into a Buffer. A buffer holds a Ready Product (Final Product Buffer) or Not Ready Product (Component Buffer). A Component Buffer serves its content to many processes via Buffer Outputs. Agents must have access to data concerning certain process steps (e.g. process time, predecessors, successors) and buffers (e.g. content, quantity). In the system there are three kinds of buffers: material buffer (supplemented by an external supplier and used by internal customer), component buffer (supplemented by an internal supplier and used by internal customer), and final product buffer (which is supplemented by an internal supplier and used by external customer). Of course, suppliers and customers are external for the ML, not necessarily for the company. Figure 10 shows the summary of the above considerations.

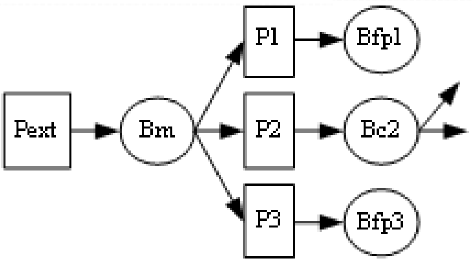

Fig. 10. Processes and buffers

Tables 1–3 show fragments of relational databases that store data about products (Fig. 3) according to the diagram shown in Figure 9.

As an example, let us consider the process P5.2 presented in Figure 1 which has two inputs, one output, and belongs to a process group P5. As Table 3 shows, there is a process group P5 that contains B5.1, B5.2 and P5.2. All the processes and buffers are kept in the relational table *Production Process*.

The data specific to the process P5.2 (see Fig. 1) is stored in the relational table *Process* (see Table 3). The essential information here is the output buffer B5.2 of the process P5.2. Table 2 presents the buffer B5.2 (hidden under ID = 407) which is a Component Buffer that holds a Not Ready Product with ID = 202. Table 1 presents Unit 1 (ID = 202) that is a part of the Complex product with ID = 201.

Table 1
A fragment of products relational database

Product			Ready product	Not ready product	
ID	Name	Type ID	ID	ID	Ready product ID
201	Complex product	101	201	202	201
202	Unit 1	102		203	201
203	Unit 2	102		204	201
204	Component 1	103		205	201
205	Component 2	103		206	201
206	Component 3	103		207	201
207	Component 4	103			

Table 2
A fragment of buffers relational database

Buffer	Buffer output (*arrows* $B \rightarrow P$)			Final prod. B		Component buffer	
ID	ID	Comp buffer ID	Process ID	ID	Ready prod ID	ID	Not ready prod. ID
402	603	402	416 B2 → P5.2	410	201	402	205
406	607	406	416 B5.1 → P5.2			406	202
407						407	202

Table 3
A fragment of relational database of MP structure

Production process			Process group		Process	
ID	Name	Proc Grp. ID	ID	Name	ID	Buffer. ID (*arrows* $P \rightarrow B$)
402	B2		501	P5	416	407 P5.2 → B5.2
406	B5.1	501				
407	B5.2	501				
416	P5.2	501				

In Table 2 there is additional information on buffers B2 and B5.1. They both are component buffers holding not ready products: Component 2 and Unit 1, respectively. From the relational table *Buffer Output*, it can be seen that both component buffers ID = 402 and ID = 406 are connected to the process ID = 416. This means that buffers B2 and B5.1 are input buffers for the process P5.2.

Conclusions

This paper focuses on the main problems of SMEs that relate to the planning of work and the monitoring of its execution to ensure timely delivery to the customer of products that meet the requirements. In such a class of problems, it is important to monitor the implementation of tasks, information flow, material flow, and respond immediately to emerging problems. Therefore, in this work an edge computing system is proposed. The presented EC–CPS can be implemented in a SME since the solution is simple and it is based on an inexpensive ICT component.

Moreover, because it is currently also very important to ensure a fast response to the changing market situation, the system is designed to consist of easily configurable modules, is flexible and agile.

In SMEs, many operations are still performed by human operators who need support. Implementing the presented system will relieve operators of performing actions that are not directly related to the manufacturing process.

The chosen means of communication between EC–CPS agents can work automatically based on the presented logic, and can perform communication inside the EC–CPS and outside, with central computer system. The presented relational multiagent system will allow for self-managing and self-optimization of the ML. Certainly, detailed management and optimization rules as well as the full set of relational databases and intelligence have to be still developed.

Moreover, the proposed solution will prevent unnecessary communication with a central computer system, and ongoing data analysis will allow to identify problems and respond to them immediately. Nevertheless, the vital information concerning problems that cannot be solved in the EC–CPS will be communicated to the central computer system. It is about problems that cannot be solved internally or cannot be solved in a certain time, which can have negative consequences and significantly influence the delivery of products to the customer.

The work has some limitations, as follow: (1) does not take into consideration robots and automatic workstations and (2) does not take into consideration CNC machines which could be a reason of additional problems, e.g. concerning internal communication if there are used different communication protocols in different equipment (e.g. old equipment). The work also does not consider the condition of tools used in the manufacturing process, their durability and accessibility, as well as does not contain a tool condition monitoring system. In the future works this issue will be discussed.

Moreover, in future work the authors will focus on more detailed EC–CPS management and optimization rules as well as on intelligence, which will be applied in learning and decision-making process.

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