ISSN: 2230-9926

Available online at http://www.journalijdr.com

IJDR

International Journal of Development Research
Vol. 10, Issue, 12, pp. 42600-42609, December, 2020
https://doi.org/10.37118/ijdr.20563.12.2020

RESEARCH ARTICLE **OPEN ACCESS**

BENEFITS OF CYBER-PHYSICAL SYSTEMS FOR MAINTENANCE IN THE INDUSTRY 4.0

Gleison Matana[1], Alexandre Tadeu Simon[1] and Carlos Roberto Camello Lima[2]

[1]Production Engineering Graduate Pogram, Methodist University of Piracicaba, Sta Bárbara d'Oeste – SP, Brazil
[2]School of Engineering, Mackenzie Presbyterian University, Rua da Consolação, 930, São Paulo, SP, Brazil

ARTICLE INFO

Article History:
Received 27th September, 2020
Received in revised form
29th October, 2020
Accepted 07th November, 2020
Published online 30th December, 2020

Key Words:
Cyber-physical systems,
Maintenance,
E-maintenance,
Industry 4.0.

Corresponding author:
Carlos Roberto Camello Lima

ABSTRACT

The need to survive in a competitive market forces companies to serve their customers with higher agility at even lower prices. Industry 4.0 technologies enable faster responses and lower costs in various operational processes, including the maintenance area. Maintenance has a significant impact on companies' operational costs, and a program that contributes to the reduction of these costs is the Condition Based Maintenance (CBM). The advancement of Information and Communication Technologies (ICT) is leading CBM towards the so-called E-maintenance, defined as a communication network, with asset information management, which integrates and synchronizes the various maintenance and reliability applications. E-maintenance brings the promise of collecting and delivering asset information where and when it is needed. Its implementation depends on the development of specific skills that can emerge from research in the technological areas of Industry 4.0, such as the Internet of Things, Cyber-Physical Systems, Wireless Sensor Networks, among others. The Cyber-Physical Systems (CPS), a fundamental basis for the existence of Industry 4.0, meet the unique characteristics of E-maintenance with technologies of physical awareness, planned and foresighted acting, cooperation and negotiation, human-machine interaction, learning, evolution and basic infrastructure. The objective of this work is to identify the benefits of deploying CPS technologies to E-maintenance. For this, a systematic literature review was conducted, identifying the CPS properties and technologies, E-maintenance characteristics and requirements, and the benefits of their integration in an Industry 4.0 environment. The research presents that CPS technologies are already available for application and, also, satisfy the technological challenges for E-maintenance implementation. Thus, benefits of increasing equipment availability, improving product quality, increasing maintainer and operator safety, increasing productivity and reducing maintenance costs, as well as other advantages attributed to Industry 4.0, have been identified.

Citation: ***Gleison Matana, Alexandre Tadeu Simon and Carlos Roberto Camello Lima.*** "Benefits of Cyber-Physical Systems for maintenance in the Industry 4.0*", International Journal of Development Research*, 10, (12), 42600-42609.

INTRODUCTION

Global competition requires companies to meet customer needs by offering quality products and services with availability and reduced prices, thus gaining competitive advantages over competitors. Therefore, it is essential to carry out manufacturing operations with quality, speed, reliability, and flexibility, at reasonable costs [1]. Maintenance is an area of manufacturing operations which has a significant impact on the company competitiveness [2], operational costs [3], and can encompass 15% to 60% of manufacturing costs [4]. Its importance for industrial operations has grown [5], due to the need to improve equipment availability, product quality, safety for employees and operations efficiency, to gather lower costs [6]. However, to meet these needs, it is inevitable to increase equipment automation [7] and, consequently, the more automated, the more complex and sophisticated the equipment with higher maintenance costs [8].

A maintenance program that contributes to the operational cost reduction is Condition-Based Maintenance (CBM) [9] recommended, over the other maintenance programs, in systems and equipment of high technology [10-11]. CBM evolved, with the advancements of Information and Communication Technology (ICT) applied to equipment and systems, to the E-maintenance [12]. This concept is presented as a ubiquitous communication network that collects asset information to integrate various maintenance and reliability applications [13].To support its operation, information and communication technologies are required, as well as autonomous equipment control [12]. The ability to manage heterogeneous information and ubiquitous network communications with control of the physical processes by computing systems is the main characteristic of the Cyber-Physical Systems (CPS) [14]. CPS are defined as the integration of physical with computational processes, where computers and communication networks monitor (from physical to cybernetic) and control (from cybernetic to physical) these physical processes [15]. In the industrial application, the CPS are considered the enabling technology of Industry 4.0 [16-17] and the main pillar to obtain its benefits [18]. Industry 4.0, recognized as the fourth industrial revolution, has the potential to increase quality, agility, flexibility [19], and productivity, reducing operating costs for competitiveness gains [18]. With the implementation of Industry 4.0 concepts, a 25% increase in operational efficiency [20] and a 14% reduction in manufacturing costs [21] are expected, attaining around 40% lower industrial equipment maintenance costs [22]. Given the above, as systems that share the same technological base of communication and information (ICT), it is understood that the application of CPS to E-maintenance can present benefits, such as the enablingof companyinclusionin the Industry 4.0 and its following gains. This work aims to identify the benefits of CPS technologies applied to maintenance. For this, a systematic literature review is performed, identifying the properties and technologies of the CPS, as well as the characteristics and requirements of E-maintenance, allowing to present the advantages of its integration in the Industry 4.0 environment.

Overview of E-maintenance and CPS principles: This section presents a theoretical review of E-maintenance and Cyber-Physical Systems with the purpose of explaining its characteristics, challenges and application benefits.

E-maintenance: Maintenance is understood as the combination of actions to replace, repair, revise or modify identifiable components or groups of components of an industry, so it operates within a specified availability [23]. Maintenance can be classified into three types: corrective, preventive and predictive [4]. Corrective maintenance is understood as any repair action after the occurrence of a stoppage, intended to replace an item in conditions to perform a required function [24]. In preventive maintenance, the component replacement action is performed at predetermined intervals, or according to defined criteria, to reduce the probability of failure or functioning degradation of an equipment item [25]. Predictive maintenance guarantees a desired quality of service, based on the systematic application of analysis techniques, using centralized monitoring or sampling, to minimize preventive maintenance and reduce corrective maintenance [4].

A predictive maintenance program that monitors the equipment to define the moment of intervention, reducing preventive and corrective maintenance, is named Condition-Based Maintenance (CBM) [26]. CBM is defined as a maintenance program that recommends the maintenance action based on the information gathered through the monitoring of the equipment condition [9]. In the high technology industrial systems, CBM is recommended among other maintenance programs [27]. Many authors recognize that maintenance conception is in continuous evolution, due to the heterogeneity and complexity with which the equipment develops [28-29]. Thus, CBM evolved with the application of Information and Communication Technologies (ICT) in manufacturing systems and equipment, being presented as E-maintenance (Fig. 1).

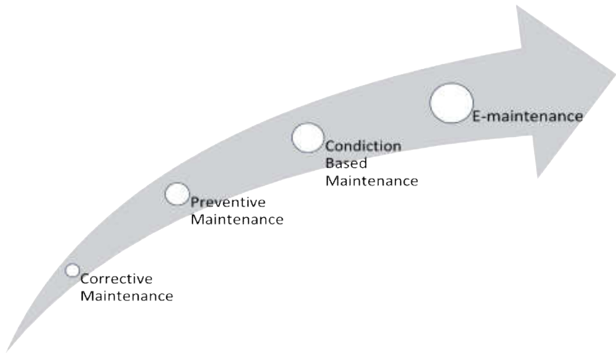

Fig.1.Maintenance evolution [12]

Han and Yang [8] predict that, with the evolution of communication systems, E-maintenance will gradually replace traditional types of maintenance with autonomous systems of predictive and proactive diagnosis. For Iung [30], E-maintenance is a revolution in maintenance processes rather than a simple evolution of its processes. Moore and Starr [13] present E-maintenance as a communication network with asset information management, that integrates and synchronizes the various maintenance and reliability applications to collect and deliver asset information where and when it is needed. For Muller et al. [31], E-maintenance is a maintenance strategy that includes the resources, services, and management necessary to enable proactive execution of the maintenance process, encompassing e-communication technologies and e-activities for monitoring, diagnosis, prognosis, among others. In a simpler and more comprehensive way, Iung et al. [32] understand E-maintenance as a maintenance philosophy that supports the transformation from "fail and fix" practices to a "predict and prevent" strategy. E-maintenance is embedded in the digital manufacturing (E-manufacturing), which, in turn, is incorporated into the E-business, as one of the main pillars that support its execution [33]. The relationshipbetween E-maintenance, E-manufacturing, and E-business is presented in Fig. 2.

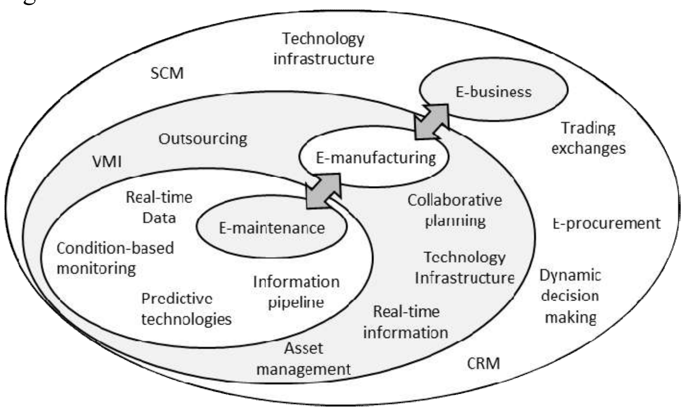

Fig. 2.Relationship of E-maintenance, E-manufacturing, and E-business [33]

The characteristics of E-maintenance are presented as [31]:

- **Remote maintenance:** competence to allow anoperator or administrator to connect remotely to the equipment for actions execution, such as installation, configuration, control, diagnosis, repair, monitoring, data collection, and data analysis;

- **Cooperative maintenance:** competence to structure the information in an existing network, connecting geographically dispersed sub-systems and agents to allow strong cooperation between human agents, areas of the company (production, maintenance, procurement, etc.) and different companies (suppliers, customers, third parties, etc.);
- **Immediate maintenance:** competence to real-time monitoring, coupled with programmable alerts that allow maintainersto quick response to any situation with an optimized intervention in the equipment;
- **Predictive maintenance:** competence to improve asset utilization using holistic approaches, combining predictive maintenance techniques (detection, diagnosis, and prognosis).

However, there are still technological challenges, to be researched and resolved, to deploy full implementation of E-maintenance [12]:

- Coverage: extension of monitoring systems to achieve all necessary elements and agents;
- Quantity of sub-systems: a large number of different sub-systems in which scalability is required;
- Information structure: a variety of information structures that interconnect in a decision-making system;
- Instruments and tools accuracy: obtaining valid and accurate information from the various elements in the equipment;
- Senders location: metering points may vary with equipment operating on different conditions;
- Environmental condition: measurements can be influenced by the environment different conditions in which the equipment operates;
- Method of analysis: choosing the best analysis method, among several possibilities, and identification of problems to aid decision making;
- Interpretation of results: degradation patterns recognition of the various physical quantities (temperature, pressure, vibration, voltage, humidity, etc.);

- Connection with company goals: prediction of operations results, considering the equipment's downtime for maintenance;
- Parameters understanding: constant increase of the knowledge about the monitored parameters, improving the interpretation of the acquired data;
- Continuous improvement: system must continuously improve to avoid failures, not only monitor the conditions of the equipment;
- Automation: improve response time to actions, reduce costs and errors of maintenance activities, monitor equipment conditions in real-time and increase the reliability of the decision-making process.

Thus, to deploy E-maintenance in the company's operations, it is necessary to develop technologies that meet the challenges presented. For this, the application of CPS in E-maintenance can meet these technology challenges. This application can additionally offer benefits for the company's competitiveness and enable its inclusion in Industry 4.0.

Cyber-physical systems: Cyber-Physical Systems (CPS) are the integration of physical processes with computational processes, where computers and communication networks monitor (physical to cybernetic) and control (from cybernetic to physical) the physical processes, where both physical and computational elements interact mutually [15]. In a holistic and summarized way, CPS are systems in which there is the union of the computational properties with the elements communication properties applied in the physical processes for shared monitoring and control with other systems. The elements that encompass the CPS are shown in Fig. 3.

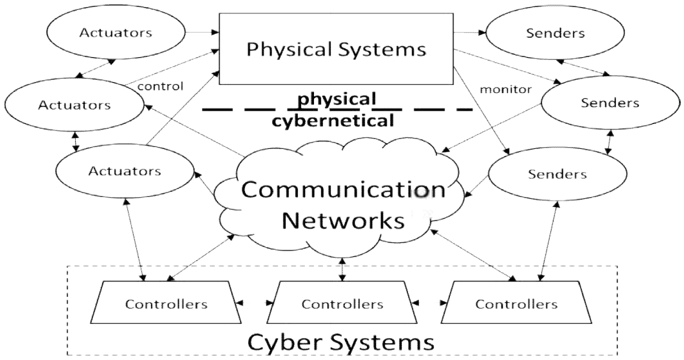

Fig. 3. Cyber-Physical Systems elements [34]

CPS are, then, the intersection of physical and cybernetic elements, and their communication interfaces. Physical elements refer to physical quantities that must be monitored or controlled. Cybernetic elements relate to computing devices that process information and communicate with each other. The communication interfaces are the data networks and the components that connect the physical processes with the cybernetic ones, allowing the monitoring and control (sensors and actuators)[35]; with proper protection against external attacks [36]. Many CPS development institutions have their research programs with their definitions of the CPS concept, properties, and technologies, such as the Advanced Manufacturing Partnership 2.0, in the USA, Industrie 4.0, in Germany, Factories of the Future, in the European Union, and Monozukuri, in Japan [37]. Germany stands out among the other knowledge-producing countries regarding CPS, seeking to unify research efforts among academics, government and technology companies, aiming to be the pioneer country in the full implementation of these systems [38]. The European Commission proposed the development of a plan to research CPS ensuring continent's competitiveness and founded in 2013 the CyPhERS project (Cyber-Physical European Roadmap and Strategy), within professionals from academy and industries [39]. This project carried out an extensive analysis of literature and determined as CPS characteristics the previously ones defined by the National Academy of Science and Engineering of Germany – ACATECH [40]. In this way, the German academy determines the CPS characteristics as [41]:

- Merging of the physical and virtual worlds: the ability to merge physical and virtual worlds by local and global physical assessment with control of components and systems in real-time;
- Systems of systems with dynamically adaptive system boundaries: the ability to dynamically integrate services and components, enabling the multifunctional devices

and systems, cooperating with other systems, subsystems or services;

- Context-adaptive systems with autonomous systems: the ability to adapt to changes in the environment and application requirements allowing full or semi-autonomous operation by detecting the relevant employment conditions;
- Cooperative systems with distributed and changing control: the ability to reliable behave through the coordinated interaction of multiple full or semi-autonomous agents, encompassing interactive control of machines, systems, services, and humans;
- Extensive human-systems cooperation: the ability to detect and interpret user's physical and emotional conditions, establishing human behavior as a condition of the system and/or establishing interactive human-machine actions.

The necessary abilities (I to VII) and the respective technologies employed (1 to 17) are also defined for the CPS [41]:

Physical awareness: The ability to detect and recognize objects and the physical environment

- Sensor fusion: merging of data from various sensors to obtain more accurate measurements or higher-order data
- Pattern recognition: use of algorithms and systems to recognize data patterns and compare to existing patterns
- Situation recognition using situation maps: detection of dynamic physical situations by data received from sensors combined with patterns recognition algorithms
- Fully or semi-autonomously planned and foresighted acting: extended recognition ability with cooperative adaptation to the environment assuring the function execution
- Multi-criteria situation assessment: analysis, interpretation, and evaluation of situations by various criteria in real-time
- Artificial intelligence approaches: intelligent automation of system behavior, making decisions, in response to the environment
- Cooperation and Negotiation: ability of sub-systems to cooperate to meet their objectives
- Multi-agent systems: cooperation, negotiation, and interaction of different systems agents to control the situation in a variable environment
- Human-machine interaction: ability to automatically support human actions and interactions, performing operations in their favor, influencing even human behavior
- Human-machine interface and interaction modalities: modalities, logics, and rules of interaction between human and machine
- Intention and plan recognition: detection of the user's intention by analyzing previous behavior or the effect of behavior on the environment
- User and human modeling, human awareness: diagnosis, simulation, prediction or support to human behavior in interactions with technological systems
- Learning:the ability to construct knowledge regard to particular situations of human behavior based on the experience of interactions in different contexts
- Machine learning and data mining: use of information technology and mathematics to extract knowledge from available data
- Evolution: self-organization and adaptation strategies: ability of the system to self-organize and adapt operating strategies
- Self-organization in manufacturing: production capacity and adaption of the processes for manufacturing of components and execution of services by the identification of the material received
- Self-organizing communication networks: flexibility of communication networks to ensure the absence of problems and reliable operations facing constant changes in the environment and in the operational requirements
- VII. Basic technologies:the ability to execute basic technologies necessary for CPS full-functioning
- Domain models, ontologies and domain-specific languages: constructive format of the system allowing cooperation between parties with a high degree of autonomy (system design, hardware or software architecture, operating system, programming languages, device simulation, tangible applications of CPS, among others)
- Sensor and actuator technology: competence of sensors to qualitatively and quantitatively measure the physical environment, and of actuators to converting electrical signals into physical parameters
- Communication infrastructure and platforms: the ubiquitous technology of communication network infrastructure and information control platforms (network design, hardware or software architecture, scheduling and queuing data, heterogeneous communication interface, analysis of energy consumption, network security and robustness to attacks, among others)
- Efficient parallel processors: making a smaller, more affordable and powerful unified electronics with optimized power consumption
- Stable distributed controllers: control systems hierarchically structured with geographically dispersed network components

CPS is the fundamental basis of Industry 4.0 [42,16]. Its conception is based on the application of CPS in production systems and industrial areas, such as production, logistics, maintenance, and other operational services [43].

Research Method: In the search, identification, and analysis of the academic documents on E-maintenance and CPS, the method of systematic literature review was adopted. This method allows the researcher to compile the data, refine hypotheses, estimate sample size, define the limit of knowledge given a problem and orientate future research [44]. The method of "systematic literature review" is understood as "the process of collecting, knowing, understanding, analyzing, synthesizing and evaluating a set of scientific articles, with the purpose of creating a theoretical-scientific foundation (state of the art) on a particular topic or subject" [45]. The systematic literature review model of Levy and Ellis (2006)[45] was selected as a technical procedure due to its reliability and scientific rigor. This technical procedure is based on three steps: input, processing, and output.

Table 1. Search results on CPS and E-maintenance

"cyber-physical system*" OR CPS OR "maintenance" AND
charact* OR defin* OR propert* OR concept* OR implement* OR technolog* OR design* OR challeng*

	Stage 1			Stage 2
	searched quantity	1º filter: no repeated	2º filter: articles, books and proceedings	relevant to research objetctive
CPS	1489	1045	904	40
E-maintenance	329	239	202	18

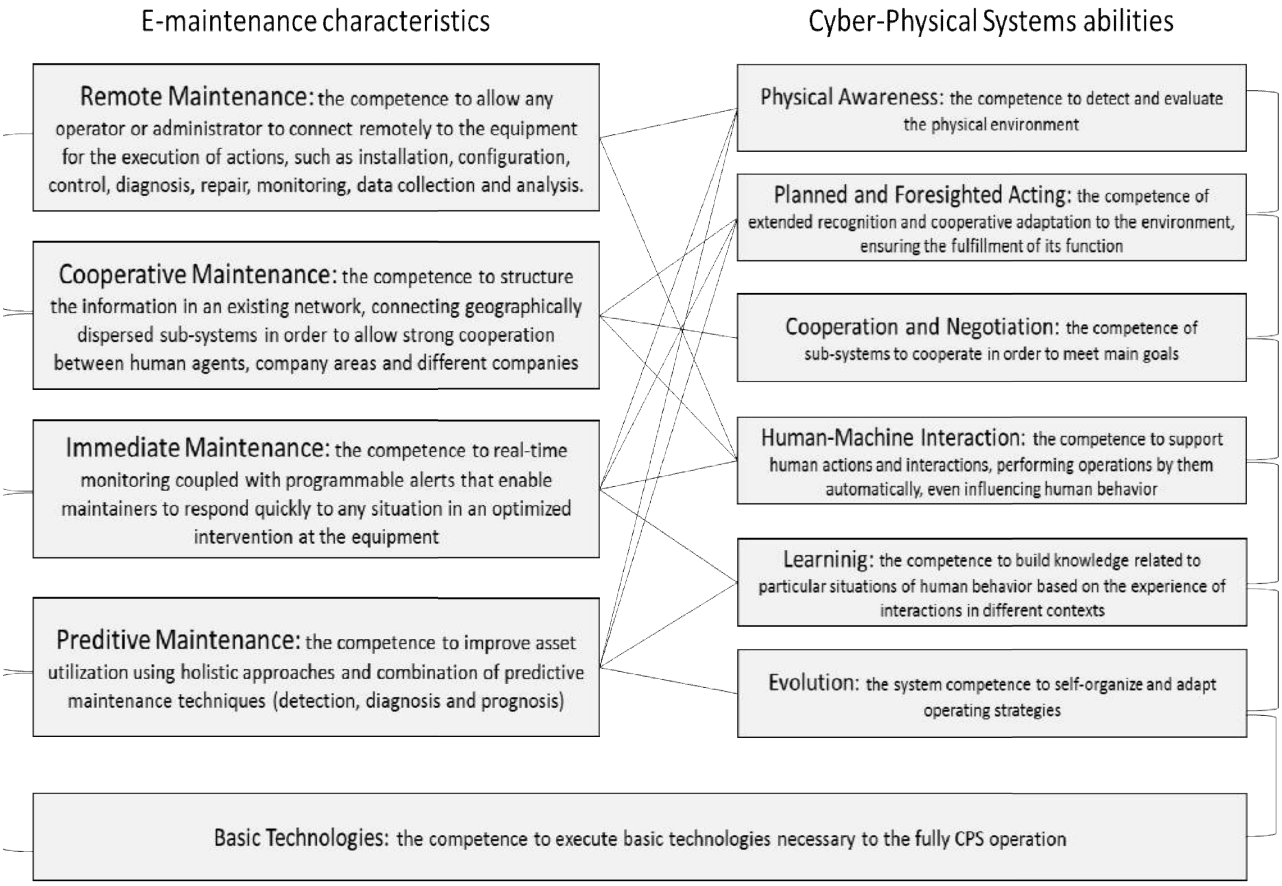

Fig. 4. Connections of CPS abilities with E-maintenance characteristics

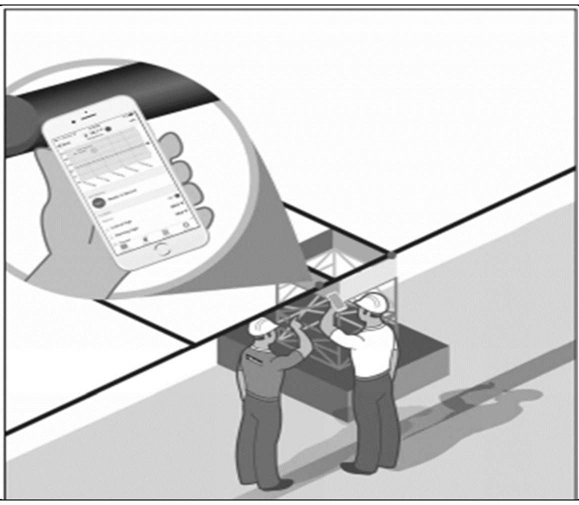

Fig. 5. Integrated sensor solution for simultaneous measurement and ubiquitous communication[46]

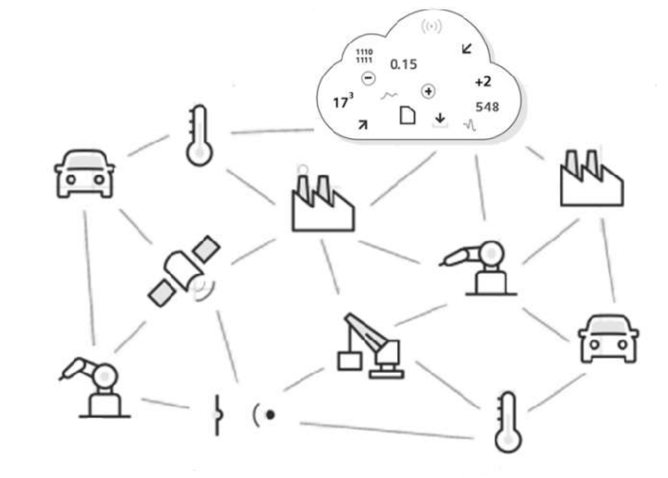

Fig. 6. Technological solution schematics for cooperation among manufacture and maintenance[47]

Table 2. Benefits of CPS applied to E-maintenance

E-maintenance Characteristics	CPS Abilities and	Technologies	Benefits
Remote Maintenance	Physical Awareness	Sensor fusion	higher degree of measurement and environmental monitoring
		Pattern recognition	system self-configuration to suit to the remote communication manner
		Situation recognition	request for environment intervention by exceeding the equipment technical characteristics
	Human-Mahcine Interaction	Human-machine interface	friendly system allows easily and quickly maintainer access
		Intention and plan recognition	measurements, history, catalogs and alarms information presentation in any smartdevice
		Human modeling	access only to maintainer with appropriate skills to the required intervention
Cooperative Maintenance	Planned and Foresighted Acting	Multi-criteria situation assessment	improvement of equipment design with feedback of fault information to the manufacturer
		Artificial intelligence approach	risks self-locking prior to the maintainer intervention
	Cooperation and Negotiation	Multi-agent systems	fault investigation shared with other companies that have the same equipment
	Human-Mahcine Interaction	Human-machine interface	flexibility and efficiency in maintenance service with friendly interface
		Intention and plan recognition	integration with equipment manufacturer to fault analysis and solutions
		Human modeling	guidance to production operators for the execution of cyclical maintenance processes
Immediate Maintenance	Physical Awareness	Sensor fusion	accuracy in the detection of failures by the availability of simultaneous measurements
		Pattern recognition	recommendation of faulty components based on system history and behavior
		Situation recognition	prioritization of attendance by integrating production and environmental variables
	Planned and Foresighted Acting	Multi-criteria situation assessment	intervention direct to failure by the previous evaluation of sub-systems functioning
		Artificial intelligence approach	self-segregation of the failed sub-system allowing direct maintenance
	Human-Mahcine Interaction	Human-machine interface	presentation of possible faulty components by probability of occurrence
		Intention and plan recognition	recognition of damaged parts with automatic request to the warehouse
		Human modeling	system recommends the most efficient maintenance process for the maintainer
	Learning	Machine learning and data mining	auto-adaptation of new components assuming historical data of the previous component
Preditive Maintenance	Physical Awareness	Sensor fusion	best prediction of fault behavior by integrating concurrent measurements
		Pattern recognition	monitoring of alerts evolution to support a scheduled maintenance
		Situation recognition	higher degree of behavior prediction by the environmental influences consideration
	Planned and Foresighted Acting	Multi-criteria situation assessment	production system autonomously schedule the maintenance based on equipment condition
		Artificial intelligence approach	self-regulation of sub-systems to grant production without damaging the equipment
	Learning	Machine learning and data mining	systems self-regulation based on the equipment historical behavior
	Evolution	Self-organization in manufacturing	flexibility to adjust the maintenance periods according to the production schedule
		Self-organizing communication networks	continuous equipment monitoring even in case of communication systems failure
Basic Technologies		Domin models, ontologies and languages	wide range of maintenance conditions independent of the means and equipment
		Sensor and actuator technology	shorter response time to needs with increased accuracy of information
		Communication infrastructure and platforms	ubiquity of equipment and maintenance communication systems
		Efficient parallel processors	flexibility and efficiency in parallel information analysis by relevant systems
		Stable distributed controllers	integration of maintenance intelligence for companies that have similar equipment

E-maintenance technological challenges		Cyber-Physical Systems Technologies
Coverage	------	Domain models, ontologies and languages
Quantity of sub-systems	------	Domain models, ontologies and languages
Information structure	------	Communication infrastructure and platforms
Instruments and tools accuracy	------	Sensor and actuator technology
Senders location	------	Sensor fusion
Environmental condition	------	Situation recognition
Analysis method	------	Multi-criteria situation awareness
Interpretation of results	------	Pattern recognition
Connection with company goals	------	Self-organization in manufacturing
Parameters understand	------	Machine learning and data mining
Continuous improvement	------	Machine learning and data mining
Automation	------	Multi-agent systems Human-machine interface Artifitial intelligence approaches

Fig. 9. Attendance of E-maintenance technological challenges by CPS technologies application

The input stage is delineated by the definition of the research problem, the establishment of clear and feasible objectives, selection of primary sources of research, determination of search terms, delimitation of inclusion criteria, and the establishment of exclusion and qualification criteria. The processing step reinforces the need to run cycles through six phases, increasing knowledge about the subject and repeating them as often as necessary until the objectives are met. Within the processing stage, the phases of knowing the literature, understanding the literature, performing the review, analyzing results, synthesizing results and evaluating the results are presented. The output stage is characterized by the registration and archiving of information researched, presentation of results and publication of the theoretical model.

Input stage: For the sources of the primary documents, Scopus and Web of Science were considered as bases of research. The keyword phrase searched for has been established as ("cyber-physical system" OR CPS OR maintenance) AND (charact* OR defin* OR propert* OR concept* OR implement* OR technolog* OR design* OR challeng*), to grant all variances of semantics and applications. These words were applied in the title, keywords and summary fields of selected search bases. With this search, 1818 related documents were obtained, 1489 on CPS and 329 on E-maintenance (Table 1).

The inclusion criteria established for the filter of the selected documents were the selection of articles, proceedings, and books of all years of publication. As exclusion criteria, the editorials, serials, and repeated documents were removed. Executing the inclusion and exclusion criteria on the 1818 documents related to the CPS and E-maintenance, 1106 documents were selected, being 904 on CPS and 202 on E-maintenance.

Processingstage: The six phases of the processing stage were applied to the documents found in the input stage, cyclically, to select the documents relevant to the investigation, as defined in the objective of this research. Thus, 40 documents on CPS and 18 on E-maintenance (Table 1) were achieved. So, with the reading of the 58 documents selected, the properties and technologies of the CPS were sought, and the characteristics and requirements of E-maintenance were established.

Output stage: Based on the systematic literature review, it was identified that the documents of Geisberger and Broy[41], with the properties and technologies of CPS, and Muller, Marques and Iung[31], with the characteristics of E-maintenance, are highlighted by the relevance and quantity of citations.

With the information from the processing stage, the overview of E-maintenance and CPS (section 2) and the integration between the CPS and E-maintenance were developed, presenting the results (in section 4) for the academic society with rigor and reliability.

RESULTS AND DISCUSSION

The integration of CPS abilities and technologies with the characteristics of E-maintenance make benefits possible for companies, such as the advantages of operating in the Industry 4.0. With the analysis of the selected documents, the CPS can be applied to the E-maintenance by the relationship of its competences. Fig. 4 presents the supporting relationship of CPS abilities to the required E-maintenance characteristics.

In Fig. 4, it is possible to observe that the Remote Maintenance characteristic, with the function of allowing the operators a remote connection with the machine systems to analyze, monitor, configure, control, diagnose and repair, is enabled by the CPS abilities of Physical Awareness and Human-Machine Interaction. Physical awareness has great benefits for remote maintenance, with its sensor fusion technologies, pattern recognition and situation recognition. The sensor fusion technology ensures a higher precision degree in the device systems measurements and in the environmental monitoring, due to the increased interaction among measured quantities. Pattern recognition is a technology that allows the equipment self-configuring to any required communication means, recognizing the requested communication pattern and adapting to data transmissions and receipt. Situation recognition technology can analyze the environment the equipment operates and request interventions from a predictive based condition analysis.

Human-machine interface technology creates a user-friendly and intuitive environment for the maintainer to easily and quickly access machine information by executing their activities in a shorter time. On the other hand, the intention and plan recognition technology can promptly provide the maintainer with access to the measurements and history of the faulty system, components catalog and parts lifetime of that system, before any maintenance is required by the maintainer. Human modeling is a technology that allows the maintainer to access the equipment systems in which he has the abilities to execute his activities, still supporting this maintainer with relevant information about those systems as long as the maintenance is carried out. Fig. 5 presents an integrated sensor from Parker [], which enables the recognition of situations from the measurement of several physical quantities simultaneously, merging and integrating the data for holistic analysis.E-maintenance's Cooperative Maintenance characteristic is supported by the CPS abilities of Planned and Foresighted Acting, Cooperation and Negotiation, and Human-Machine Interaction, enabling equipment systems to structure information for cooperation between their agents and industry areas (Fig. 4). The multi-criteria situation assessment technology can improve the equipment design with the feedback of relevant information about the devices operation (and their failures in the operating environment in which they are allocated) the manufacturer, who should use data in the improvement of a new version of this machine. The artificial intelligence approach is a technology that can automatically analyze equipment failure and lock-out systems that expose the maintainer to risk, allowing rapid device intervention.

However, multi-agent systems technology can investigate failures, or potential failures, in similar equipment to obtain a broader history and, therefore, a more accurate analysis, since the equipment of the companies and the manufacturers are connected in a global network with the provision of real-time maintenance information. The human-machine interface assures the cooperative maintenance, its friendly interface characteristic, allowing fast and easy maintenance service and efficient communication with other areas of the company. Intention and plan recognition is an important technology that enables cooperation with the equipment manufacturer, providing real-time equipment data, for joint analysis of the failure, potential failure or increased availability and reliability of the equipment. The human modeling technology can guide the equipment operators in the execution of preventive maintenance, in an assisted way, to ensure its effectiveness. Fig. 6 illustrates a Siemens [] technology solution that integrates multi-criteria situation assessment, artificial intelligence, and multi-agent systems technologies in the information interconnection between maintenance and equipment manufacturers to improve, in a cooperative environment, the device performance and to avoid system failures. The Immediate Maintenance characteristic can allow the equipment monitoring in real time to be assertive and fast, at the right time, optimizing the equipment downtime and minimizing the costs of its execution. To that end, the CPS abilities of Physical Awareness, Planned and Foresighted Acting, Human-machine Interaction, and Learning support its realization (Fig. 4). Sensor fusion technology can increase the accuracy of investigation and fault detection by the availability of simultaneous and holistic measurements of operation, machine performance, and work environment. Pattern recognition is a technology that allows the determination of faulty components based on the history and behavior of the equipment operating in a specific application.

Situation recognition technology, however, assists the maintenance team in the prioritization of attendance to faulty equipment, or potential failure, by analyzing production and operational environment variables in an integrated manner. The multi-criteria evaluation technology gives the equipment the ability to holistically analyze the fault and drive the correction services, in the shortest time, and in the most assertive way. The artificial intelligence is a technology that can, from the understanding of the devices and faulty system, automatically segregate the other equipment systems, allowing direct and fast maintenance in the failure cause. The human-machine interface technology can, during the maintenance of the equipment, present the possible faulty components by the probability of occurrence and even the catalogs of these parts, in an intuitive and maintainer-friendly form. Intention and plan recognition technology allows the equipment to request the damaged parts directly from the warehouse, prior to the maintainer intervention, ensuring the availability of the components at the time of maintenance, and thus, a shorter than usual downtime time. Human modeling is a technology that can assist the maintainer by recommending the fastest and most efficient process sequence to execute equipment maintenance based on process time studies. The machine learning and data extraction technology allow the equipment maintenance system to automatically adapt to the newly replaced components, adjusting these characteristics to the equipment by the history of the faulty component. Fig. 7 illustrates a Balluff [] solution for the maintenance of injection equipment, which uses forecasting and action planning, human-machine interaction, physical recognition and learning, to monitor machine elements and injection molds, with the aim of support condition-based maintenance.

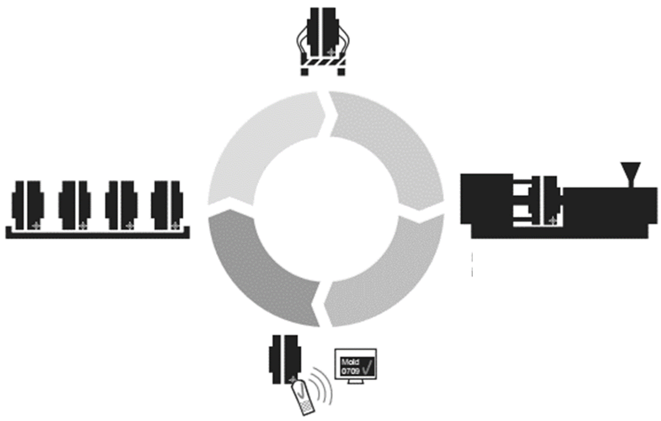

Fig. 7. Immediate maintenance solution based on equipment condition monitoring []

E-maintenance's Predictive Maintenance characteristic increases equipment availability and reliability by performing holistic predictions of behavioral prediction, through the detection and diagnosis of potential failures. The CPS abilities of Physical Awareness, Planned and Foresighted Acting, Learning and Evolution support this maintenance characteristic (Fig. 4). Sensor fusion technology ensures better prediction of potential failure behavior with a holistic analysis of concurrent measurements. Pattern recognition is a technology of potential failure autonomous evolution analysis, directing maintenance to scheduled equipment or the need for an immediate stoppage to avoid damaging other machine systems. Situation recognition technology allows prediction of equipment behavior, potential failure, integration of characteristics and influence of environment and application. The multi-criteria situation awareness technology can analyze the equipment conditions, and its history of failures, and schedule the maintenance of the device with potential failure, also analyzing the needs of the production. The technology of artificial intelligence allows the automatic production adjustment to levels appropriate to the potential failure equipment characteristics so that this does not affect the operation with its shutdown until the best moment for maintenance. Machine learning and data extraction technology can automatically regulate machine systems based on the history of system behavior to increase component life without interfering in productivity. The self-organization in manufacturing technology allows the autonomous adjustment of the appropriate equipment maintenance periods without affecting the production program. The self-organizing communication network technology ensures continuous monitoring of the equipment, even with information and communication system failure. Fig. 8 shows the Weidmüller [] predictive maintenance support solution, which intelligently monitors the equipment operation and, by analyzing sensor measurement data and fault history, schedules maintenance based on actual condition, integrating the maintenance and production areas vertically into the necessary interventions without compromising productivity.

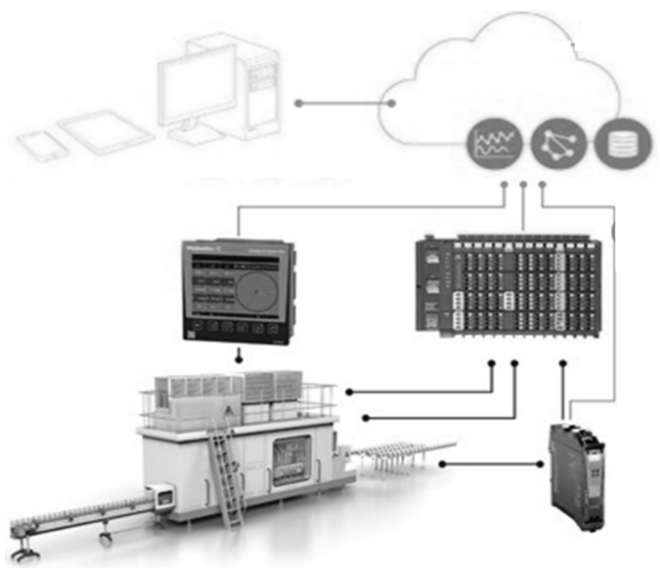

Fig. 8. Predictive maintenance solution integrated with production plan []

Basic Technologies characteristics, with Domain Models, Sensors and Actuators, Communication Networks, Parallel Processors and Distributed Controllers technologies, support the operation of the entire E-maintenance and CPS system, ensuring the levels of intelligent automation and ubiquitous communication that its operation demands (Figure 4). Domain models, with their systems languages and architectures, are technologies that allow a wide range of maintenance conditions, independent of communication forms and monitored equipment. Sensor and actuator technology, in addition to concurrent communication and operation, can minimize response time to production needs while increasing the accuracy of information and analysis. Infrastructure technology and communication platforms enable ubiquitous communication among equipment, production, and maintenance, providing information in real-time. Efficient parallel processor technology ensures maintenance flexibility and efficiency by reducing information processing time, which is analyzed in parallel by the relevant systems. In turn, the stable distributed controller technology allows the integration of intelligence from manufacturers and maintenance sectors of several companies that have similar equipment. Thus, from the analysis of the application of each CPS abilities in the E-maintenance characteristics, it is possible to verify its benefits, consolidated in Table 2. It is also possible to identify that CPS technologies can meet the technological challenges of E-maintenance presented by Guillén et al. []. Based on the analysis of the individual and grouped CPS technologies, it is conceivable to establish a correspondence with the proposed E-maintenance technological challenges. This correspondence is illustrated in Fig. 9. Also, it can be observed that many of the CPS technologies are already available for the E-maintenance concepts deployment in the enterprise. These technologies not only allow the E-maintenance characteristics execution but can enable the company's maintenance to operate in the Industry 4.0 concept, obtaining the expected advantages and benefits.

Conclusion

Maintenance has been increasing in importance to companies, especially with the implementation of Industry 4.0, where autonomous equipment seeks to provide high-quality customized products to customers at even lower prices. To meet this need, maintenance should increase the availability of equipment, improve devices to produce higher quality, increase operator safety, improve machine productivity and reduce operating costs. Condition Based Maintenance (CBM) is a maintenance program recognized for its contribution to reducing operating costs. Its evolution, with the advancement of Information and Communication Technologies (ICT), is called E-maintenance and has remote, cooperative, immediate and predictive maintenance characteristics. Many authors note that the implementation of E-maintenance depends on many technological challenges, still under development. Cyber-Physical Systems are known as the integration of physical processes with the computational and communication networks for the control and monitoring of the physical elements. Due to CPS are the foundation of Industry 4.0, many research institutions develop their technologies. Their abilities are defined as physical awareness, planned and foresighted acting, cooperation and negotiation, human-machine interaction, learning, evolution, and basic technologies. CPS can support E-maintenance, also offering benefits, by the ground that CPS abilities afford to the implementation of E-maintenance characteristics. This research has identified the benefits of applying CPS technologies in E-maintenance. Through the systematic literature review, it was identified that the physical awareness ability allows E-maintenance to perform an autonomous CBM investigation on the equipment.Prediction and planning of the actions and the cooperation and negotiation of the appropriate periods are CPS skills that support E-maintenance in the organization of scheduled maintenance shutdowns with minimal interference in production. The human-machine interaction ability collaborates with the maintainers in the process of problems identification and analysis, as well as assists production operators in the cyclic maintenance. The learning and evolution CPS abilities support E-maintenance with the automatic adjustment of equipment systems, ensuring their operation in the required capacity for a shorter downtime for maintenance. Also, the ability of basic technologies can support E-maintenance with the necessary infrastructure for its execution. Thus, the identified benefits of CPS deployment in E-maintenance satisfy its characteristics of remote, cooperative, immediate and predictive maintenance. Among the main benefits of CPS-Maintenance integration are increasing the availability of machines, improvement of the equipment for higher production quality, increased safety for operators and maintenance, improved machine productivity and reduced maintenance costs. These benefits bear Industry 4.0 operating advantages. Also, it was possible to observe that CPS technologies, already available for acquisition, are able to satisfy the technological challenges for E-maintenance operation, so enabling the implementation of Industry 4.0.

REFERENCES

[1] Slack, N. The manufacturing advantage: achieving competitive manufacturing operations; Mercury Books: London, 1991.

[2] Carnero, M. Multicriteria model for maintenance benchmarking. Journal of Manufacturing Systems2014,33 (1), 303-321.

[3] Gao, Q.; Ge, Y. Maintenance interval decision models for a system with failure interaction. Journal of Manufacturing Systems2015,36 (1), 109-114.

[4] Mobley, R. An Introduction to Predictive Maintenance; Elsevier: New York, 2002.

[5] Kamsu-Foguem, B.; Wandji, Y.; Tchuenté-Foguem, G.; Tchoffa, D. Experienced knowledge for the description of maintenance packages. Journal of Manufacturing Systems2015,37 (1), 448-455.

[6] Al-Najjar, B.; Alsyouf, I. Selecting the most efficient maintenance approach using fuzzy multiple criteria decision making. International Journal of Production Economics, 2003, 85-100.

[7] Liu, C.; Cao, S.; Tse, W.; Xu, X. Augmented reality-assisted intelligent window for cyber-physical machine tools. Journal of Manufacturing Systems2017,44 (1), 280-286.

[8] Han, T.; Yang, B.-S. Development of an e-maintenance system integrating advanced techniques. Computers in Industry, 2006, 569-580.

[9] Jardine, A.; Lin, D.; Banjevic, D. A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mechanical Systems and Signal Processing, 2006, 1483-1510.

[10] Campos, J. Development in the application of ICT in condition monitoring and maintenance. Computers in Industry, 2009, 1-20.

[11] Alrabghi, A.; Tiwari, A.; Savill, M. Simulation-based optimisation of maintenance systems: industrial case studies. Journal of Manufacturing Systems2017,44 (1), 191-206.

[12] Guillén, A.; Crespo, A.; Gómez, J.; Sanz, M. A framework for effective management of condition based maintenance programs in the context of industrial development of E-Maintenance strategies. Computers in Industry, 2016, 170-185.

[13] Moore, W.; Starr, A. An intelligent maintenance system for continuous cost-based maintenance prioritisation of

maintenance activities. Computers in Industry, 2006, 595-606.
[14] Lee, E.; Seshia, S. Introduction do Embedded Systems - A Cyber-Physical Systems Approach, 2nd ed.; LeeSeshia.org: Berkeley, 2015.
[15] Lee, E. CPS Foundations. Design Automation Conference, 2010, 737-742.
[16] Kagermann, H. Chancen von Industrie 4.0 nutzen. In Industrie 4.0 in Produktion, Automatisierung und Logistik; Springer Vieweg: Stuttgart, 2014; pp 603-614.
[17] Adamson, G.; Wang, L.; Moore, P. Feature-based control and information framework for adaptive and distributed manufacturing in cyber-physical systems. Journal of Manufacturing Systems2017,43 (1), 305-315.
[18] Schuh, G.; Anderl, R.; Gausemeier, J.; Hompel, M.; Wahlster, W. Industrie 4.0 Maturity Index - Managing the Digital Transformation of Companies; acatech: Munich, 2017.
[19] Kagermann, H.; Wahlster, W.; Helbig, J. Recommendations for implementing the strategic initiative Industrie 4.0; Acatech: Frankfurt, 2013.
[20] BCG. Industry 4.0 - The future of productivity and growth in manufacturing industries; The Boston Consulting Group: Boston, 2015.
[21] PwC. Industry 4.0 - Opportunities and challenges of the industrial internet; Pricewaterhouse Coopers: New York, 2014.
[22] McKinsey. Industry 4.0 at McKinsey's model factories; McKinsey & Company, Inc.: New York, 2016.
[23] Kelly, A.; Harris, M. Management of Industrial Maintenance; Butterworth-Heinemann Ltd: Oxford, 1978.
[24] Smith, D. Reliability, maintainability, and risk: practical methods for engineers; Elsevier: Oxford, 2011.
[25] Palmer, R. Maintenance planning and scheduling handbook; McGraw-Hill Professional Publishing: New York, 2005.
[26] Niu, G.; Yang, B.-S.; Pecht, M. Development of an optimized condition-based maintenance system by data fusion and reliability-centered maintenance. Reliability Engineering & System Safety, 2010, 786-796.
[27] Moubray, J. Reliability-centered maintenance; Industrial Press Inc: New York, 1997.
[28] Ruiz-Arenas, S.; Horváth, I.; Mejía-Gutiérrez, R.; Opiyo, E. Towards the maintenance principles of cyber-physical systems. Strojniški vestnik - Journal of Mechanical Engineering2014,60 (1), 815-831.
[29] Ruschel, E.; Santos, E.; Loures, E. Industrial maintenance decision-making: a systematic literature review. Journal of Manufacturing Systems2017,45 (1), 180-194.
[30] Iung, B. Research and development on E-maintenance: survey of some recent advantages and directions. International Conference on Maintenance and Facility Management, Sorrento, 2006.
[31] Muller, A.; Marquez, A.; Iung, B. On the concept of e-maintenance: Review and current research. Reliability Engineering and System Safety, 2008, 1165-1187.
[32] Iung, B.; Levrat, E.; Marquez, A.; Erbe, H. Conceptual framework for e-maintenance: illustration by e-maintenance technologies and platforms. Annual Reviews in Control2009,33 (1), 220-229.
[33] Koç, M.; Ni, J.; Lee, J.; Bandyopadhyay, P. Introduction of e-manufacturing. North American Manufacturing Research Conference, Hamilton, 2003.
[34] Cárdenas, A.; Amin, S.; Sastry, S. Secure Control: Towards Survivable Cyber-Physical Systems. International Conference on Distributed Computing Systems Workshop, 2008, 495-500.
[35] Lee, E. The past, present and future of cyber-physical systems: A focus on models. Sensors, 2015, 4837-4869.
[36] DeSmit, Z.; Elhabashy, A.; Wells, L.; Camelio, J. An approach to cyber-physical vulnerability assessment for intelligent manufacturing systems. Journal of Manufacturing Systems2017,43 (1), 339-351.
[37] Wang, L.; Törgren, M.; Onori, M. Current status and advancement of cyber-physical system in manufacturing. Journal of Manufacturing Systems, 2015, 1-11.
[38] Geisberger, E.; Cengarle, M.; Keil, P.; Niehaus, J.; Thiel, C.; Thönnissen-Fries, H.-J. Cyber-Physical Systems: driving force for innovation in mobility, health, energy and production; Acatech: Berlin, 2011.
[39] CyPhERS. Cyber-Physical European Roadmap and Strategy. Available at http://www.cyphers.eu (accessed December 27 2015).
[40] acatech. ACATECH. Available at http://www.acatech.de(accessed September 27 2017).
[41] Geisberger, E.; Broy, M. Living in a networked world - Integrated research agenda Cyber-Physical Systems; Herbert Utz Verlag: München, 2014.
[42] Anderl, R.; Strang, D.; Picard, A.; Christ, A. Integriertes Bauteildatenmodell für Industrie 4.0 - Informationsträger für Cyber Physische Systeme. ZWF Zeitschrift für Wirtschaftlinchen Fabrikbetrieb, 2014, 64-69.
[43] Lee, J.; Bagheri, B.; Kao, H.-A. A cyber-physical systems architecture for industry 4.0-based manufacturing systems. Research Letters2014,3 (1), 18-23.
[44] Cooper, H. Synthesizing research: A guide for literature reviews, 3rd ed.; SAGE Publications: London, 1998.
[45] Levy, Y.; Ellis, T. A Systems Approach to Conduct an Effective Lieterature Review in Support of Information Systems Research. Informing Science Journal, 2006, 181-212.
[46] Parker. SensorNode and ScoutSoftware. Available atwww.parker.com (accessed October 28 2017).
[47] Siemens. Siemens AG. Available atwww.siemens.com (accessed October 28 2017).
[48] Balluff. Balluff Mold-ID. Available atwww.balluff.com (accessed October 28 2017).
[49] Weidmüller. Weidmüller - Maintenance and Cloud Service. Available atwww.weidmuller.com (accessed October 28 2017).
[50] Gunes, V.; Peter, S.; Givargis, T.; Vahid, F. A Survey on Concepts, Applications, and Challenges in Cyber-Physical Systems. Transactions on Internet and Information Systems, 2014, 4242-4268.
[51] Macchi, M.; Marquez, A.; Holgado, M.; Fumagalli, L.; Martinez, L. Value-driven engineering of E-maintenance platforms. Journal of Manufacturing Technology Management, 2014, 568-598.
[52] Waeyenberg, J.; Pintelon, L.; Gelders, L. JIT and Maintenance. In Maintenance, Modeling and Optimization; Springer: New York, 2000; pp 439-470.

****