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Cyber Physical Systems implementation to develop a Smart Manufacturing

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Abstract: This paper aims to show how the Cyber Physical Systems (CPS) are able to transform the actual manufacturing process. For that purpose, a case of study has been developed as an example of how to implement a CPS in a machine tool, specifically a 5-axis vertical milling machine of the Haas brand. This CPS transforms the acquisition of real-time data into worthy information for the industry. CPS implementation consists of 5 levels, which are explained and exemplified in this study. As a result of the implementation, it is shown a real-time indicator which takes part of our research. Our study concludes that CPS implementation enhance and speed up the decision-making of the companies.

Keywords: Industry 4.0, Cyber physical systems, Internet of things, Smart manufacturing, Key performance indicators.

1. Introduction

Industry 4.0 terminology is known as the recent revolution of the industrial environment. This revolution pretends to transform the traditional manufacturing process into a smart manufacturing [1]. One of the more distinguished characteristics of smart factories is their ability to increase production flexibility using real-time reconfigurable machines [2]. Although Industry 4.0 is based on several technologies, Cyber-Physical Systems (CPS) are regarded as a core technology of Industry 4.0 [3]. CPS are the integration of physical and computation processes, which main functional components are their advanced connectivity, that allows real-time data acquisition and their intelligent data management [4].This paper aims to show how the CPS are able to transform the actual manufacturing process. For that purpose, a case study has been developed as an example of how to implement a CPS in a machine tool, specifically a 5-axis vertical milling machine of the Haas brand, in order to transform the acquisition of real-time data into worthy information for the industry. When it is talked about worthy information, it is not only referred to productive information, but also to sustainable and economic one. In that way, this Industry 4.0 research allows the decision-making attending to different terms, e.g., the combination of production and sustainability, which enlighten the potential that Industry 4.0 has in this kind of decision-making [5].

2. Cyber Physical Systems, a literature review

The term Cyber-Physical System appeared in 2006, coined by Helen Gill at the National Science Foundation (NSF) in the United States. The term cyberspace is attributed to William Gibson, when he

used it in his novel Neuromancer. However, the roots of this term are much older, coming from the root "cybernetics" coined by the American mathematician Norbert Wiener, who was very important in the Development of Control Systems Theory, who derived it from the Greek term kubern (kybernetes), which means rudder or pilot [6]. Wiener was a pioneer during the Second World War in developing technology capable of automatically aiming and firing anti-aircraft guns. Although he did not use digital computers for this purpose, the methods involved are similar to those employed in control systems today [7]. A CPS is defined as an integration between physical systems and communication, computer and control systems [8]. Physical processes are controlled by computers and integrated networks that monitor them, usually using feedback loops that make physical processes affect computing and vice versa. For this reason, the real challenge of CPS is to achieve the intersection between the physical and the cyber, not the union [9].

The fundamental components of these systems are [4]:

- Advanced connectivity that ensures real-time data acquisition from the physical part of the system and is able to feed back into the cyber part.
- Intelligent data management, analysis and computational capacity to build the cyberspace.

The German National Academy of Science and Engineering (ACATECH) defines the seven abilities of the CPS together with its seventeen respective technologies [10]. Among these abilities stand out the detection and evaluation of the physical environment with technologies such as sensor fusion [11], pattern recognition [12] or situation recognition [13]. The interaction between machine and humans [14-16] or the capability of learning from situations based on the experience of interactions in different contexts enhance knowledge development, thanks to machine learning [17].

2.1. CPS implementation process

In recent years, CPS implementation has been emerging. However, a variety of challenges need to be solved to ease the physical and cyber worlds integration [18].

The International Society of Automation proposed the ISA-95 architecture, which divided the system into levels 0-4. Being Level 0 the actual physical processes. Level 1 sensors and manipulates the physical processes. Level 2 oversees monitorization and control of physical processes. Level 3 defines the activities of the workflow to produce the desired end-products. Finally, Level 4 is business-related to activities needed to manage a manufacturing organization [19].

Some authors proposed a CPS architecture distributed into 5 levels (5C architecture) (see figure 1). These levels constituted an easier methodology of design and implementation of a CPS step by step, from the data acquisition stage to the final analysis and creation of value [20]. These levels are described below in detail because this is the followed methodology for our CPS implementation.
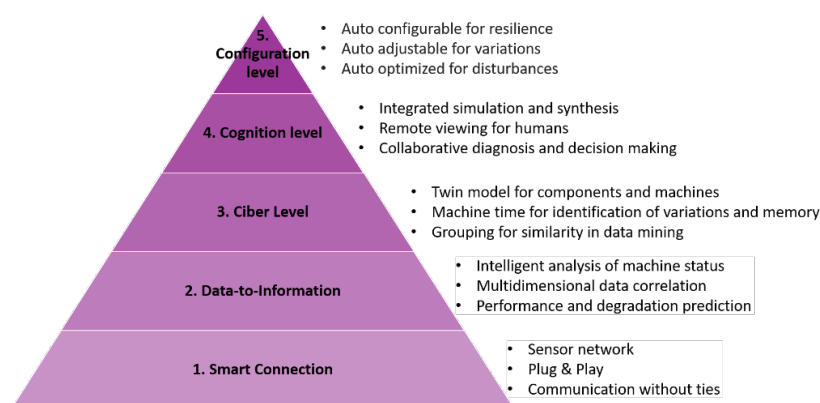
Figure 1. CPS architecture levels.

2.1.1. Smart connection. The first step is the accurate and reliable acquisition of data from the machines and their components. This data can be acquired via sensors or obtained from controllers or company systems such as ERP or MES systems.

Not only is the selection of the sensors crucial, but also the data transfer to a central server, where a specific protocol, such as MTConnect, is able to unify the data types and the way of acquisition [21].

2.1.2. Data-to-Information Conversion. At this second level, meaningful information is obtained from the data. There are numerous applications capable of predicting and checking the state of the systems, since in recent years the focus has been on developing algorithms for this purpose [21]. This level can provide "self-awareness" to cyber-physical systems [8].

2.1.3. Cyber. The cybernetic level acts as an information hub in the architecture of CPS. The information acquired by each machine is stored at this level, forming a network of machines. This allows additional information to be extracted by being able to compare the individual status of a machine with the rest of the fleet and analyse the performance and historical data of the machine. This comparison enables the predictive maintenance of the machines to be carried out [4].

All levels are important for the correct implementation of a CPS. However, the cyber level, which acts as a bridge between the data acquisition of lower levels and the higher levels of decision making, is indispensable. Therefore, a good performance of the data analysis functions implemented at this level is so essential [4].

2.1.4. Cognition. The implementation of this level provides a thorough knowledge of the monitored system. In order to correctly transfer the information to the users, the most relevant information must be adequately represented. This level makes possible remote and collaborative diagnostics and decision making. The priority of tasks for the maintenance process can be easily determined due to the availability of comparative information and individual machine status [21].

2.1.5. Configuration. The last level is the feedback between the cyber and physical space. It is responsible for the supervision of the machines, making them "self-configured" and "self-adjusted". This stage is said to act as a RCS (resilience control system) that allows corrective or preventive decisions to be applied that have been taken at the fourth level, cognition [4].

This 5C architecture is focused on vertical integration more than in the horizontal one. In view of this, this research [22] proposed a 8C architecture by adding 3C concepts (coalition, customer and content) into the existent 5C architecture. Coalition focuses on the value chain integration and production chain integration between different parties in terms of the production process. Customer focuses on the role that the customers play in the production process. Content focuses on extracting, storing, and inquiring all contents related to products, such as the design, the manufacturing parameter, the product traceability record, and the after-sales service record.

3. Materials and Methods

3.1. Case study: implementing our own CPS
For this study, the physical system consists of a machine tool (HAAS VF-3), which is a five-axis vertical milling machine (figure 2 (a)); three linear axes (X, Y, Z) and two rotatory axes (A and C) were added by incorporating a Trunnion 160 double-cradle table (figure 2 (b)).

(a)   (b)

Figure 2. (a) Haas VF-3. **(b)** Trunnion TR 160.

3.1.1. Smart connection. An accelerometer and a network analyser have been installed for the precise and reliable acquisition of machine tool data, in addition to using the machine's own global and system variables.

Global variables are always available variables that are retained in memory when the power is turned off, while system variables provide the ability to interact with control conditions.

With regard to the accelerometer (figure 3 (a)), this is an accelerometery sensor for monitoring and diagnosing vibrations in machines and installations. The accelerometer is complemented by a VSE100 diagnostic electronics system (figure 3 (b)) to acquire data.

(a)   (b)

Figure 3. (a) IFM VSA005 acelerometer. **(b)** VSE200 diagnostic electronics.

The other element to be placed is a Circutor CVM-MINI network analyser (figure 4). A network analyser is a programmable measurement instrument, capable of analysing the properties of electrical networks. This type of sensor can be installed in any type of installation, having an internal memory in which the measurement parameters are stored.

Figure 4. CVM-MINI network analyser

The CSV-MINI measures, calculates and displays the main electrical parameters of balanced or unbalanced three-phase industrial networks. This sensor allows the display of all the electrical parameters, by means of a backlit LCD display, showing three instantaneous electrical parameters, maximum or minimum at each screen jump, or transmitting them by MODBUS communication.

These elements are connected to an industrial PC, in this case the C6015 from Beckhoff, which is responsible for collecting the data and storing it in the cloud.

3.1.2. Data-to-information Conversion. At this second level, the most relevant information is obtained from the data. Numerous applications can be used for this purpose. In our case, a cloud-based multi-device monitoring system automatically records and analyses the data captured by the machine. Thus, customers can query key operating data and obtain relevant operational indicators to optimise machine utilisation. The system consists of three subsystems:

- Data capture hardware (data logger): this system automatically records the machine's main signals.
- Web platform: the web application is hosted on a server administered and hosted by Oracle.
- Advanced tools for the analysis, maintenance and display of indicators of the machine's operating states, operating time, spindle use, etc.

First of all, the "Activity" menu collects the information related to the production of the machine in the previously selected period. And within "Activity" can be found "Timeline", which shows the main events related to the machine's operating status, as well as the activity during the selected period.

Within the "Timeline" there are the following parameters (figure 5):

- Operating mode: Current operating mode.
- Spindle: shows when and how long the spindle has been running.
- Tool number: Indicates the type of tool used during the period of time.
- Activity: Indicates the type of activity performed by the machine (machining, tool change, machine at rest, etc.)
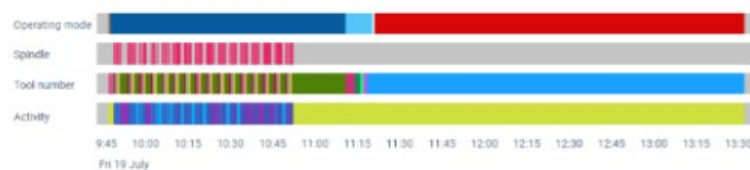
Figure 5. Timeline.

3.1.3. Cyber. This step has not yet been carried out, as there is only one machine tool, but it is a future step in continuing CPS research.

3.1.4. Cognition. At this level, the aim is to present the information in a way that is easy for all users to understand. This level is where most of our research is focused, as it is based on obtaining KPIs (Key Performance Indicators) to provide a simple and global vision of the state of the machine at the production, economic, environmental and maintenance levels.

Our software is developed by Python, a programming language that allows the development of software quickly and easily [23]. Some of the KPIs developed are shown in the following case study and finally they can be seen on a dashboard in a website.

3.1.5. Configuration. The last level is responsible for monitoring the machines. This is also an area of our research, as the information provided at level 4 not only is it intended to make decision-making easier but also to establish a multi-criteria decision-making tool.

3.2. Example case of KPIs implementation
Once the machine tool was integrated into the physical and computational system, the most appropriated for calculation of each KPI in real time are analysed, checked, and selected. . It has been developed software capable of transforming the data obtained by the CPS into indicators and other information relevant to the user using Python.

In this example, it is shown the implementation of OEE (Overall Equipment Effectiveness) and ECL(Energy Consumption Losses), whose development and deeper implementation can be seen in [24]. Our CPS is able to capture variables, such as machine time, energy consumption, number of pieces produced (number of parts), what tool is being used (tool number) and when it is changed (tool change), and the spindle rotation (rpm of the spindle). However, other parameters must be given as hypotheses. In this case, the number of reworks, rejects, and the maintenance time and breakdowns are hypothesized, and the difference between stoppage and minor stoppage was established as five minutes. Once the data are acquired, the combination of energy or time data with other variables allows us to know the time and energy associated with every big loss and, therefore, to calculate the OEE (time variables) and the ECL (energy variables) (see figure 6).
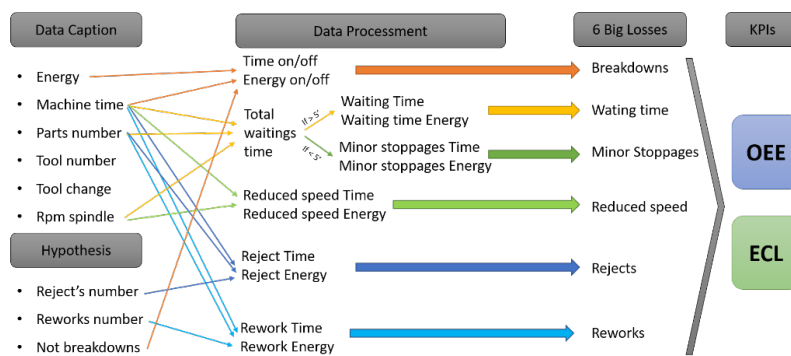

Figure 6. Flow chart of the Key Performance Indicator (KPI) calculation [24].

As result of this implementation and according to level 4 (cognition), the results are shown in an easy way through graphs. The system allows the display of several types of visual information through different graphics, such as a Pareto diagram, which can inform us at a glance about the most important information (see figure 8 (a)). Furthermore, according to level 5 (configuration) the comparison between our KPIs enhance the multi-criteria decision making (see figure 7 (b)). This figure 7 (b) shows that the best case of OEE (case 2) does not fit with the lower energy consumption losses (case 1), so attending multicriteria decision (production and sustainability) it must be chosen between the most sustainable or the most productive case.
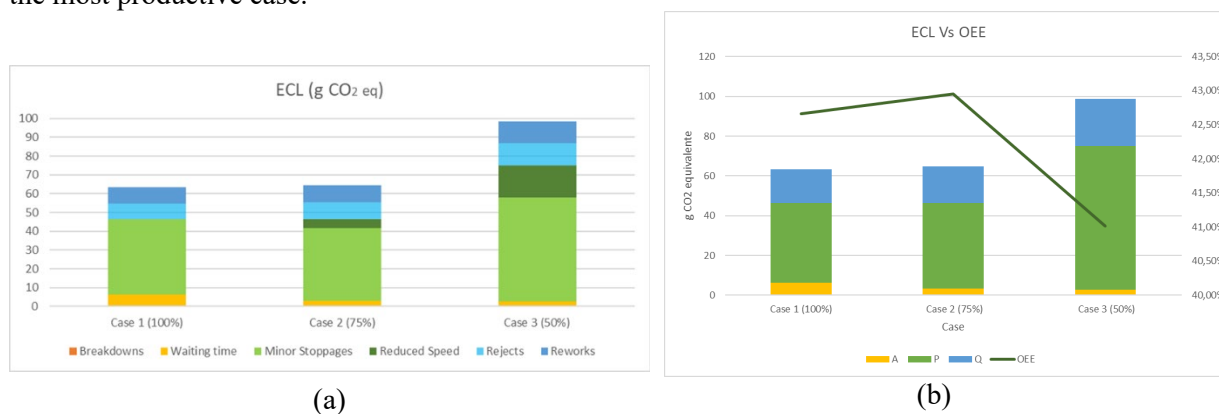

Figure 7. (a) ECL stacked bar chart. **(b)** Comparison between OEE and ECL.

Not only are existing KPIs implemented in this research, but new KPIs are also developed and implemented. As can be seen in [24, 25], new KPIs related with 6 big losses, energy consumption and costs has been developed and implemented in this dashboard, as well as a cost model has also been developed, and the CO_2 footprint is also calculated.

3.3. Final implementation

Once the KPIs are developed and implemented, a web application is configured to see all the indicators on a dashboard (see figure 8). This dashboard enhances the decision-making since companies can see and compare all the developed KPIs at a glance.

Figure 8. Dashboard.

4. Conclusions

The objective of this study is to highlight the benefits of industry 4.0, particularly the capabilities of implementing a CPS in an industrial process, and to show how it must be implemented. It enhances companies' decision-making, due to its capability of acquiring real time information and turning it into KPIs and graphical information. Moreover, the CPS correct implementation is crucial for further development and it consists of 5 levels which should be clearly understood before the beginning of the implementation. Our research transfers to the companies the capability of working with real time data and KPIs, what streamlines their decision-making and improves their performance. As the developed KPIs belongs to different categories, principally, economy, production and environment, the dashboard which is shown to the companies allows to pay attention to different categories at the same time to actuate to different improvement categories. For example, it can be seen if the improvement in OEE leads to an improvement in production costs or to a higher energy consumption. This research has some limitations that should be addressed in future research. This study has been carried out with a single machine, but it is being implemented a CPS in another machine tool, thus, level 3 of implementation could be implemented in future machine and enlarge our research with a study of the communication machine to machine. Moreover, our research would be extended to maintenance KPIs, in which the vibration sensor would play an important role. To conclude, this study enlightens the important role of Industry 4.0 in Supply Chain (SC) developing and implementing new KPIs by using monitorization. Furthermore, it is crucial to acquire real time information which can be used in decision-making.

References

[1]   Cohen Y, Faccio M, Pilati F and Yao X 2019 Design and management of digital manufacturing and assembly systems in the Industry 4.0 era *Int. J. Adv. Manuf. Technol.* **105 (**9) pp 3565–3577

[2]   Koren Y and Shpitalni M 2010 Design of reconfigurable manufacturing systems *J. Manuf. Syst.* **29** (4) pp 130–141

[3]   Dalenogare L S, Benitez G B, Ayala N F, and Frank A G 2018 The expected contribution of

        Industry 4.0 technologies for industrial performance *Int. J. Prod. Econ.* **204** pp 383–394

[4]   Lee J, Bagheri B, and Kao H A 2015 A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems *Manuf. Lett.* **3** pp 18–23

[5]   Kamble S S, Gunasekaran A and Gawankar S 2018 A Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives *Process Saf. Environ. Prot.* **117** pp 408–425

[6]   Wiener N 1948 *Cybernetics or Control and Communication in the Animal and the Machine*. (MIT Press)

[7]   Lee E A 2015 The past, present and future of cyber-physical systems: A focus on models *Sensors* **15** (3) pp 4837–4869

[8]   Bagheri B, Yang S, Kao H A , and Lee J 2015 Cyber-physical systems architecture for self-aware machines in industry 4.0 environment *IFAC-PapersOnLine* **28** (3) pp 1622–1627

[9]   Lee E 2010 Categories and Subject Descriptors *Proc. 47th Des. Autom. Conf. (DAC) ACM* pp 737–742

[10] Matana G, Simon A, Filho M G, and Helleno A 2020 Method to assess the adherence of internal logistics equipment to the concept of CPS for industry 4.0 *Int. J. Prod. Econ.* **228** p 107845

[11] Hall D L and Llinas J 1997 An introduction to multisensor data fusion *Proc. IEEE* **85** (1) pp 6–23

[12] Devedžić V and Radović D 1999 A Framework for building intelligent manufacturing systems *IEEE Trans. Syst. Man Cybern. Part C Appl. Rev.* **29** (3) pp 422–439

[13] Endesley M and Jones D 2003 *Designing for Situation Awareness: An Approach to User-Centered Design* (New York: Taylor & Francis).

[14] Eason K D 1991 Ergonomic perspectives on advances in human-computer interaction *Ergonomics* **34** (6) pp 721–741

[15] Kanno T, Nakata K and Furuta K 2003 A method for team intention inference *Int. J. Hum. Comput. Stud.* **58** (4) pp 393–413

[16] Parasuraman R, Sheridan T B and Wickens C D 2000 A Model for Types and Levels of Human Interaction with Automation *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans* **30** (3) pp 286-297

[17] Somvanshi M, Chavan P, Tambade S and Shinde S V 2016 A review of machine learning techniques using decision tree and support vector machine *Proc. - 2nd International Conference on Computing, Communication, Control and Automation ICCUBEA*

[18] Wan J, Chen M, Xia F, Li D and Zhou K 2013 From machine-to-machine communications towards cyber-physical systems *Comput. Sci. Inf. Syst.* **10** (3) pp 1105–1128

[19] Gifford C and Daff D 2017 *ISA-95 International Society of Automation* (https://www.isa.org/intech-home/2017/november-december/features/isa-95-to-support-smart-manufacturing-iiot) accessed 19 Novembre 2020

[20] Kim J and Lee J Y 2021 Server-Edge dualized closed-loop data analytics system for cyber-physical system application *Robot. Comput. Integr. Manuf.* **67** p. 102040

[21] Lee J, Bagheri B and Kao H A 2015 A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems *Manuf. Lett.* **3** pp 18–23

[22] Jiang J R 2018 An improved cyber-physical systems architecture for Industry 4.0 smart factories *Adv. Mech. Eng.* **10** (6) p 2018

[23] Wagner M, Llort G, Mercadal E, Giménez J and Labarta J 2017 Performance Analysis of Parallel Python Applications *Procedia Computer Science* **108** pp 2171–2179

[24] Morella P, Lambán M P, Royo J, Sánchez J C and Corrales L del C 2020 Development of a New Green Indicator and Its Implementation in a Cyber–Physical System for a Green Supply Chain *Sustainability* **12** (20) p 8629

[25] Morella P, Lambán M P, Royo J, Sánchez J C and Latapia J 2020 Development of a new kpi for the economic quantification of six big losses and its implementation in a cyber physical system *Appl. Sci.* **10** (24) pp 1–17