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Cyber-Physical Production System Assessment Within the Manufacturing Industries in the Amazon

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Abstract:

Cyber-physical production systems (CPPS) represent a relevant aspect related to industry 4.0 and the advances promoted by the digitization and use of artificial intelligence in the production environment in the search for the development of smart factories. This study aims to assess the maturity level of cyber-physical production system (CPPS) within manufacturing industries in the Amazon. The research uses a quali-quantitative approach to analyze the problem by conducting exploratory case studies (in-depth case) and the research framework used aimed to evaluate and measure the CPPS within three manufacturing industries in the Amazon (n = 3) to measure their maturity. Findings reveal a positive relationship between the type of production system adopted by the company, the level of automation, and the maturity of the CPPS. The proposed methodology can assist other companies in the development of the technological strategy, supporting the digital transformation process in order to obtain competitive advantage. The study contributes by addressing the topic of cyber-physical production systems from the point of view of operations management and strategy.

Key words:

Industry 4.0, Cyber-physical production system, Operations management, Strategic process, Amazon.

1. Introduction

Industry 4.0 increases the digitization of manufacturing with the cyber-physical system (CPS), in which connected networks of humans and robots interact and work together with shared and analyzed information, supported by big data and cloud computing along value chains whole industrial plants (Yang, 2017). CPS bring more functionality, autonomy, multi-area integration, application in all sectors, such as industry, medical systems, service/user relationship, among others (Baheti & Gill, 2011) being characterized by robustness, security, and protection (Sha et al., 2008) and where self-organized manufacturing, context-/situation-aware control and symbiotic human-robot collaboration can play an important role in transforming current factories into factories of the future with greater stability and security (Wang et al, 2015).

The application of CPS in the production and manufacturing environment gave rise to the term Cyber-Physical Production Systems (CPPSs) which have great potential to make production systems intelligent, resilient and self-adaptive (Wu et al., 2019a). In CPPSs systems, the model generated for cyberspace forecasting incorporates data from sensor networks for each critical asset to reflect changes. They are online networks of social machines

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that interconnecting to information technology with mechanical and electronic components that communicate using RFID technology (Radio Frequency Identification), for example (Lee et al., 2017; Delloite, 2015).

Since 2011, models have emerged to assess Industry 4.0, such as the Acatech Maturity Model (Schuh et al., 2020), Impuls – VDMA (Lichtblau et al., 2015), Uni-Warnick (Agca et al., 2017) and PricewaterhouseCoopers – PWC (Geisbauer et al., 2016).

Recently studies have investigated CPPSs in the most different contexts, such as digital twin (Zhang et al., 2019; Zang et al., 2020; Liu et al., 2020; Ait-Alla et al., 2019), internet of things (Berlak et al., 2020; Stock et al., 2020), cloud computing (Mourtizis & Vlachou, 2016; Mourad et al., 2020; Borangiu et al., 2020), voice assistant (Afanasev et al., 2019) and shop floor (Romero-Silva & Hernández-López, 2020; Govender et al., 2019; Torres et al., 2019; Rocha et al., 2019).

There are researchs/reports that assess Industry 4.0 readiness, however the characteristics that make up cyber-physical production systems from the point of view of operations management remain unexplored.

Therefore, the following research questions were developed for investigations:

RQ1: Does the company implement practices associated with cyber-physical production systems?

RQ2: Does the research framework provide adequate assessment of CPPS practices?

RQ3: What is the level of implementation observed in the company concerning the literature?

In this context, this study aims to assess the maturity level of cyber-physical production systems (CPPS) within manufacturing industries in the Amazon. The second section deals with the literature background on the concepts and applications of CPPS existing over the last few years in the literature. Section three discusses the study's methodology and its research framework; section four deals with the presentation of the case study companies; section five presents the results and discussion carried out throughout the study. Finally, the last section presents the conclusion with the final position in the study.

2. Literature background

2.1. The concept of CPPSs

The implementation of Industry 4.0 in manufacturing environments occurs with the development and complete industrial implementation of cyber-physical production – CPS (Francalanza et al., 2017).

CPSs represent an emerging area of research that has attracted the attention of many researchers due to expectations that they will play an important role in the design and development of future engineering systems (Sanislav & Miclea, 2012), being introduced by Helen Gill of National Science Foundation in the United States in 2006 (Gill, 2008).

CPS can be considered an extremely important step in the development of future manufacturing (Monostori et al., 2016) to make manufacturing more competitive by integrating advanced computing and CPS to adapt and take advantage of the current big data environment (Lee et al., 2013).

Over the last few years the concept of CPS has expanded as a result of the advancement and complexity of instruments that are related to industry 4.0 improving for cyber-physical production system (CPPS).

CPPSs consist of autonomous and cooperative elements, as well as subsystems; these elements are connected and can communicate independent situations, at all levels of production, from the field device and process level to the factory and production planning levels (Francalanza et al., 2018), that is, denotes a mechatronic system (physical world) coupled with software and digital information entities (cyber part), both allowing the concept of the intelligent factory for the Industry 4.0 paradigm (Cruz Salazar et al., 2019).

CPPSs offer new possibilities for production planning and control (PPS) due to their characteristics of decentralized organization, real-time capacity, and intelligent data processing (Berger et al., 2019), integrating physical and computational resources due to sensors and power increasingly available processing tools. This allows the use of data, to create additional value, such as monitoring or optimization of conditions (Bunte et al., 2019) and involves multi-disciplinary engineering activities that depend on the exchange of effective and efficient knowledge for better collaboration between engineers from different disciplines (Meixner et al., 2019).

Lee et al. (2018) present a CPPS architectural framework, where the core elements (sub-system) are (1) big data analytics, (2) detection and coordination, and (3) KPI simulation. Among the components are big data storage, quality prediction model builder, model repository, real-time data listener, quality and productivity detector, coordinator, cyber model builder, simulation engine, and reference KPI builder.

In conclusion, the manufacturing processes at CPPS allow for more self-regulation and self-organization in semi-autonomous production teams, create greater complexity and dynamics in the work process, require more collaboration, communication, and problem-solving skills from operators, enable new forms of human-machine-human collaboration, and can significantly increase the productivity and quality of manufactured products (Mühlfelder, 2019).

2.2. CPPSs applications

Numerous authors have expressed interest in the applications of CPPSs in the most diverse contexts. Four categories of studies related to CPPS stand out. The first related to industrial application and manufacturing, highlighting the studies of implementation of CPPS in a real factory to predict the quality of metal casting and control of the operation from the design of a CPPS architecture framework (Lee et al., 2018), or even, implementation of the cyber-physical production system in intelligent manufacture estimating how companies want to implement disruptive technologies (Drennan-Stevenson, 2019), 5C architecture as a cyber-physical development guide for industrial application (Lee et al., 2017), Chawla et al. (2020) presented a generalized synergic framework between different production facilities and in different geographical locations to obtain an efficient and energy-saving CPPS for the production of different types of jobs in the context of industry 4.0, implementation of CPPS using low-cost devices in a simulated factory to control the industrial process and integrate shop floor communications using the AMQP - Advanced Message Queuing Protocol (Llamuca et al., 2019), Ferreira et al. (2020) contributed data on the applicability of CPS components in the current SMEs (small and medium enterprises) environment, with the intention of improving the performance of manufacturing processes (within the concept of CPPS), Lins & Oliveira (2020) presented the standardization of the retrofitting process to transform old equipment into a CPPS, and Pinzone et al. (2020) dealt with the implications of operative and sustainability functionalities on the health, learning and operational performance of human workers within the concept of CPPS.

The second category presents studies involving new CPPS application models, highlighting the studies of a new event-based approach (Berger et al., 2019), such as the 3S-oriented design concept for resilient and integrated cyber-physical systems based on three standards: stability, security, and systematicity (Hu et al., 2016), design patterns of multi-agent systems (MAS), indicating that agent-based patterns greatly benefit the design of CPPS (Cruz Salazar et al., 2018), a new event-based approach (Berger et al., 2019), Prist et al. (2019) who proposed an intermediate layer in the architecture that allows each device, production line and machine to be connected independently, despite the protocol adopted, Bunte et al. (2019) analyzed the existing reference architecture on their cognitive skills (related to CPPS), architectures that define the structure and interaction of components software development in CPPS (Mayrhofer et al., 2019), a software module for a monitoring system focused on the evolution of the ICPS - Industrial Cyber-Physical System (Iglesias Sagardui & Arellano, 2019), development of a computer-based model to simulate physical aspects of the material flow using a physical mechanism in CPPS (Glatt & Aurich, 2019), Eckhart et al. (2019) proposed a methodology called Security Development Lifecycle for Cyber-Physical Production System (SDL-CPPS) that aims to promote security designed for CPPS, Stock et al. (2019), approach to create a cyber-physical data access layer, based on in the self-description capability of CPPs components, Wu et al. (2019b) proposed a meta model to formalize the integrative link between CPPS and enterprise information systems (EIS), Patalas-Maliszewska & Schlueter (2019) explored the possibility of integrating the Knowledge Management System (KMS) and System Integrator (s) in Cyber-physical Production Systems (CPPS), and simulation of various degrees of autonomy in a CPPS using a hybrid lab approach (Gronau, 2019).

The third category involves digital twin studies and their application to smart shop-floor at scale via digital twin (DT), highlighting the opportunities to use DT for CPPS to support work scheduling during operation (Zhang et al., 2019), the concept of Intelligent Digital Twin that can be used to perform autonomous CPPS (Ashtari Talkhestani et al., 2019), cyber-physical system (CPS) and digital twin to build the interconnection and interoperability of a physical shop floor and correspondent cybershop floor (Ding et al., 2019), transforming traditional manufacturing into a CPPS through the e-CORE approach (Loucopoulos et al., 2019), and Park et al. (2020) proposed a digital twin based CPPS architectural framework that overcomes performance obstacles.

In conclusion, the fourth category involves support for the decision-making process. Highlights are the studies of Alves & Putnik (2019) presented research on the influence of the duration of decision making at CPPS on the performance of the manufacturing system, for different programming paradigms, an innovation system for effective planning of production and maintenance integrated into the CPPS complex using multi-criteria decision-making (Schreiber et al., 2019).

3. Methodology

A mixed method was adopted to analyze the problem. This approach enables a better understanding of the research problems that each of the approaches (quantitative and qualitative) would allow separately. The combined methods make it possible to expand the understanding of research problems (Miguel, 2012; Creswell, 2009), as occurred in this study.

The purpose of this research was to conduct exploratory case studies (McCutcheon & Meredith, 1993) in which the conclusions obtained from the analysis of the data will be based on empirical evidence. The choice of single cases is justified by the need for greater depth in the research framework (Voss et al., 2002).

The case study is a methodological procedure in which it examines a phenomenon as a whole, using multiple data collection methods to collect information from one or a few entities, such as people, groups, or organizations. It examines contemporary events where the behavior of the research subjects cannot be manipulated, having a generalized character to the theoretical prepositions. It can also be used to analyze longitudinal change processes. Thus, it aims to expand and generalize theories and not populations and universes (Benbasat et al., 1987; Eisenhardt, 1989; Yin, 1994).

The research framework used in the study aimed to evaluate and measure the cyber-physical production system (CPPS) within three manufacturing industries in the Amazon to identify the maturity level of these organizations.

The constructs were determined from PricewaterhouseCoopers (2014), European Parliament (2016), Thiede (2018), Thiede et al. (2016), Germany Trade & Invest (2014), Delloite (2015), Lee et al. (2017) and Lee et al. (2018).

This research framework considers 15 constructs, consisting of a form containing 42 questions to provide an adequate assessment of the evaluated productive system. The constructs considered are (1) Organization of the machines in a network; (2) Integration of machines and the production process; (3) Sensors and control elements; (4) Data exchange and control in real-time; (5) KPI simulation, (6) Dashboard, (7) Data treatment and storage, (8) System interoperability; (9) Level of autonomy; (10) Vertical integration; (11) Connection; (12) Conversion; (13) Cyber; (14) Process cognition and optimization; and (15) Configuration - artificial intelligence and machine learning. Table 1 presents the relation between constructs and source.

Table 1. Relation between constructs and source.

Constructs	Source
Organization of the machines in a network Integration of machines and the production process Sensors and control elements	Delloite (2015)
Data exchange and control in real-time	PWC (2014)
KPI simulation Dashborad	Lee et al. (2018)
Data treatment and storage	Thiede (2018) & Thiede et al. (2016)
System interoperability Level of autonomy	EP (2016)
Vertical integration	GTAI (2014)
Connection Conversion Cyber Process cognition and optimization Configuration - artificial intelligence and machine learning	Lee et al. (2017)

Source: Authors.

Each question received a score according to the evidence that was presented by the company and observed in loco on a Likert scale (1 to 5) to adequately measure the evaluated production system. The scores are: 1 - Practice not even thought out, rarely occurs, does not apply to the reality of the company; 2 - Some awareness, but disorderly and occasional responses, informal systems, Basic level of implementation of CPPS; 3 - Consciousness and appropriate formal systems - but could be further improved, Intermediate level of implementation of CPPS; 4 - Effective and highly developed systems, Advanced level of CPPS implementation, including provisions for improvement and development; 5 - Highly effective and developed systems, Highly advanced level of CPPS implementation, including self-configuration and organization of systems.

The delimitation of the universe of this research was three manufacturing industries located in the Amazon. A form was used to identify organizational characteristics, based on Guérin et al. (2011) and aspects related to CPPSs, based on PricewaterhouseCoopers (2014), European Parliament (2016), Thiede (2018), Thiede et al. (2016), Germany Trade & Invest (2014), Delloite (2015), Lee et al. (2017) and Lee et al. (2018).

As research techniques (Marconi & Lakatos, 2002) were used: (1) indirect documentation (documentary and bibliographic research); (2) intensive direct observation (In-loco observation and open structured interview); and (3) extensive direct observation (application of form).

The study took place in four moments: (1) open structured interview (Vergara, 2009) based on a script, based on Guérin et al. (2001), where fundamental information was identified to complement the forms applied in the company, later; (2) documentary research took place intending to collect preliminary data in written documents (reports, internal reports, and website) and structured observation (Vergara, 2009); there was (3) application of the form with those responsible for the organization (after observation and interviews); and concluding, (4) quantitative and qualitative data were analyzed and tabulated.

The quantitative data obtained from the script responses were tabulated in a summary table, grouped according to the content, and stratified according to the structure of the evaluation and measurement form of cyber-physical production systems. For qualitative data, discourse analysis (Bardin, 1977) was used based on the following steps: (1) pre-analysis (systematization and establishment of interpretation indicators), (2) data exploration (coding, classification, and categorization), and (3) treatment of results, inference, and interpretation. A summary of the methodological procedures used is presented in Table 2.

Table 2. Summary of the methodological procedures.

Stage	Method	Source	Comments
Approach to the problem	Mixed methods	Miguel (2012), Creswell (2009)	Interpretation of the opinion of the interviewees Use of productive quantitative data
Type of research	Exploratory case study (Single case)	McCutcheon & Meredith (1993), Voss et al. (2002)	Chemical company Thermal power plant Plastic injection molding company located in the Amazon
Procedure	Indirect documentation Intensive direct observation Extensive direct observation	Marconi & Lakatos (2002), Vergara (2009), Guérin et al. (2001)	Reports, internal reports, and website
Data gathering	Multiple case study In loco observation = 15 days Open structured interview = 20 hours of interview Form application = 05 days	Marconi & Lakatos (2002), Vergara (2009), Guérin et al. (2001)	Quality department Operations management department Industrial engineering department Observation in the productive and administrative area Interviews with company managers and employees Application form with company managers and employees
Analysis of data	Analysis of content	Bardin (1977)	Description, understanding, and explanation of research framework (evaluation and measurement of a cyber-physical production system (CPPS) from the following steps: (1) pre-analysis, (2) data exploration, and (3) treatment of results, inference, and interpretation.

Source: Authors.

4. Companies

4.1. Case 1. Chemical company

The first case represents a company in the chemical sector, being one of the best known and respected manufacturers of hygiene and cleaning products in the world, operating in the categories of hygiene and cleaning, personal care, insecticides, and more recently, domestic storage. Currently, the plant located at the Industrial Pole of Manaus (PIM) has approximately 320 employees.

4.2. Case 2. Thermal power plant

The second case represents a thermal power plant, operating since 2002. The company has an installed capacity of 9MW, with a continuous production process, and with a high level of automation. Currently, the plant located in Amazon has approximately 60 employees.

4.3. Case 3. Plastic injection molding company

The third case represents a plastic injection molding company, being an important national player in the segment of plastics for the electronics, home appliance, automobile, and electrical products industries. Currently, the plant located at the PIM has approximately 400 employees.

5. Results and discussion

RQ1: Does the company implement practices associated with cyber-physical production systems?

Case 1. Chemical company (Table 3).

Table 3. Case 1 – Chemical company.

Constructs	Evidences
Organization of the machines in a network	The company's machines are not organized in networks and also do not use RFID technology or other technology. The machines do not share information between them, such as stock levels, problems or failures, changes in orders, or levels of demand. Also, remote access to them is not possible.
Integration of machines and the production process	There are no sensors or control elements in the company that allow the machines/equipment to be connected to the manufacturing plant, fleets, work networks, and human beings.
Sensors and control elements	Over the years the company has developed a series of improvements in machines and equipment as a result of the adoption of lean thinking, which included the implementation of TPM. The machines have several productive control sensors or fail-safe devices (Poka-Yoke), however, they do not communicate with each other.
Data exchange and control in real-time	Information is collected by operators directly from each machine at each workstation through-out the production process. Then these data are inserted in spreadsheets and also in the ERP system (Enterprise Resource Planning). There is no real-time control of the production process, however, the data collected from each workstation, manually, is used to monitor pro-duction.
KPI simulation	Company has KPIs in its production process, however they are not simulation results.
Dashboard	The information generated by the production process is located in visible places on the plant
Data treatment and storage	There is no standardized communication proto-col between machines/equipment and data sys-tems. The information is not categorized and there is also no responsibility for analyzing the data generated by the systems.
System interoperability	There is no system interoperability, does not exist the connection and communication between human and smart devices available (real and virtual).
Level of autonomy	The level of automation adopted by the company is low considering industry 4.0. Just a production process has a high level of automation.
Vertical integration	Vertical integration (suppliers, company, and consumers) takes place from the network of machines/equipment using ERP.
Connection	There is no standardized communication protocol between machines/equipment and data systems. However, the company presents an initial stage of connection between activities, ERP and machines in its production process
Conversion	There is no big data storage and other methods for conversion meaningful information
Cyber	There is no application and generation of predictive/cyber models.
Process cognition and optimization	There is no application of decision-making and reasoning methods to recommend operations aimed at maintaining optimal production.
Configuration - artificial intelligence and machine learning	The system does not provide features that are self-configuring or involve machine learning and artificial intelligence.

(Table 3 continues in the next column)

(Table 3 continues from the previous column)

Source: Authors.

Case 2. Thermal power plant (Table 4).

Table 4. Case 2 – Thermal power plant.

Constructs	Company has KPIs in its production process, however they are not simulation results.
Organization of the machines in a network	The machines are organized in a network using PLCs for production control.
Integration of machines and the production process	The process can be controlled remotely or automatically. Its main process variables to be controlled: pressure and temperature. Sensors are coupled to the equipment to provide system data to then be analyzed and stored, then they are shown on the screens of the computers supervised by the operators.
Sensors and control elements	The information comes from sensors that capture the process variables of the industrial plant.
Data exchange and control in real-time	The data is still transmitted informally, only with the help of intranet via radio, e-mail, and documentary. There is control of the entire production process in real-time
KPI simulation	Company has KPIs in its production process, however they are not simulation results.
Dashboard	Information generated by the production process is available in the plant's control room
Data treatment and storage	The company uses a supervisory system designed to capture and store information about the production process in a database.
System interoperability	There is system interoperability through the connection and communication between human and machines (real and virtual)
Level of autonomy	Approximately 85% of the production process is automated.
Vertical integration	There is no vertical integration with the raw material supplier
Connection	The company adopts well-defined communication protocols due to the characteristic of the production system. Communication between machines is observed at different stages of the production process.
Conversion	There is no big data storage and other methods for conversion meaningful information
Cyber	There is no application and generation of predictive/cyber models.
Process cognition and optimization	There is no application of decision-making and reasoning methods to recommend operations aimed at maintaining optimal production.
Configuration - artificial intelligence and machine learning	The system does not provide features that are self-configuring or involve machine learning and artificial intelligence.

(Table 4 continues in the next column)

(Table 4 continues from the previous column)

Source: Authors.

Case 3. Plastic injection molding company (Table 5).

Table 5. Case 3 – Plastic injection molding company.

Constructs	Evidences
Organization of the machines in a network	The machines are connected to a central network, where the production data of all assets are stored, however, they do not communicate with each other, sharing only the storage database.
Integration of machines and the production process	The company has a performance, production, and problem control based on remote sensing, which sends the collected data immediately to the production control telemetry system.
Sensors and control elements	there is no direct communication between the machines, the information generated by the productivity sensors and controllers present in the assets are diagrammed and sent to a control platform
Data exchange and control in real-time	There is the collection of information directly from machines and workstations. This information is available on a panel in the production area. There is real-time control of a significant part of the production process.
KPI simulation	Company has KPIs in its production process, however they are not simulation results.
Dashboard	The information generated by the production process is visible on a dashboard in the production area and in the ERP system.
Data treatment and storage	The company has a communication of its data which is transmitted digitally. There is a great dependence on a direct communication between the PCP, engineering, logistics, and production teams, which can make it many times the exchange of information that is crucial for decision-making on the process is inefficient.

(Table 5 continues in the next page)

(Table 5 continues from the previous page)

Constructs	Evidences
System interoperability	There is system interoperability through the connection and communication between human and machines (real and virtual). Especially in production process.
Level of autonomy	The level of automation adopted by the company is low considering industry 4.0. Just a production process has a high level of automation.
Vertical integration	Vertical integration (suppliers, company, and consumers) takes place from the network of machines/ equipment using ERP.
Connection	It is observed the adoption of communication protocols in the production process, through ERP. However, there is a greater need for connection between the production process and other areas of the company.
Conversion	There is no big data storage and other methods for conversion meaningful information
Cyber	There is no application and generation of predictive/cyber models.
Process cognition and optimization	There is no application of decision-making and reasoning methods to recommend operations aimed at maintaining optimal production.
Configuration - artificial intelligence and machine learning	The system does not provide features that are self-configuring or involve machine learning and artificial intelligence.

Source: Authors.

RQ2: Does the research framework provide adequate assessment of CPPS practices?

The instrument deals with 15 constructs that correspond to the main aspects that involve the concept of cyber-physical production systems. The instrument allows a comprehensive analysis of a company, seeking to identify the current stage of adaptation to the precepts related to cyber-physical production systems (PricewaterhouseCoopers, 2014; European Parliament, 2016; Thiede, 2018; Thiede et al., 2016; Germany Trade & Invest, 2014; Delloite, 2015; Lee et al., 2017; Lee et al., 2018), in addition to identifying what level the company is about the 5C architecture presented in Lee et al. (2017).

Also, the complementary research techniques used in the in-depth case provided a diversity of sources of information and provided the scientific reliability necessary for this case study. The realization of an open structured interview, structured observation, content analysis, and document research enabled an in-depth case that contributes to the literature by deepening the observations in the real context about the application of concepts involving cyber-physical production systems in a company.

In conclusion, the research framework made it possible to assess the maturity level of cyber-physical production systems within three manufacturing industries in the Amazon, making it an original contribution to operations management. When associated with other research techniques (open structured interview, structured observation, content analysis, and documentary research) it provided a more comprehensive and deeper understanding of the phenomenon within the companies studied, as pointed out in Voss et al. (2002), Miguel (2012), Creswell (2009) and McCutcheon & Meredith (1993). The internal validity of the case study is confirmed by the systematic comparison of the literature concerning the research framework, whereas the reliability of the study is justified by the preparation of the database that was organized, integrated, and synthesized of the information obtained from different sources of evidence, resulting from the various research techniques employed (Villarreal, 2017; Villarreal & Calvo, 2015; Villarreal & Landetta, 2010).

RQ3: What is the level of implementation observed in the company concerning the literature?

Case 1. Chemical company

Considering the information collected about the cyber-physical production system theme at the chemical company, the radar graph was created (Figure 1) presenting the measurement to the adoption of practices related to the theme. The constructs with the best performance were (1) integration of machines and the production process (2.0), (2) data exchange and real-time control (2.0), and (3) organization and networked machines in line with Delloite (2015) and PricewaterhouseCoopers (2014). The connection level averaged 1.5 and the conversion level averaged 1.25. Cyber, cognition, and configuration scored 1.0. Finally, the company's overall average was 1.29. The chemical company has a level of implementation of the concepts of cyber-physical production systems in an initial stage to the connection level (Lee et al., 2017) due to the process of integration of the machines and the use of control sensors still to be found in a stage that there is no single communication between these elements in the production environment, in addition to the lack of a single communication protocol. The standardization of the communication equipment of the manufacture is still lacking.

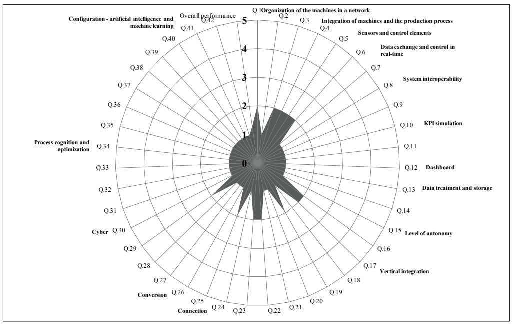

Figure 1. Performance – Chemical company. Source: Authors.

Case 2. Thermal power plant

Figure 2 shows the radar graph generated from the information collected in the thermal power plant about the cyber-physical production system. The best performing constructs were (1) organization of the networked machines with an average of 3.0, followed by (2) sensors and control elements (3.0), (3) integration of the machines and the production process (2.0), and (4) data exchange and control in real-time (2.0) in line with Delloite (2015) and PricewaterhouseCoopers (2014). The connection level averaged 2.5 and the conversion level averaged 1.25. Cyber, cognition, and configuration scored 1.0. Finally, the company's overall average was 1.52. The thermal power plant has a level of implementation of the concepts of cyber-physical production systems in an intermediate stage at the connection level, being possible to observe characteristics of the conversion level (Lee et al., 2017). The very nature of the company's activity reinforces the results because it

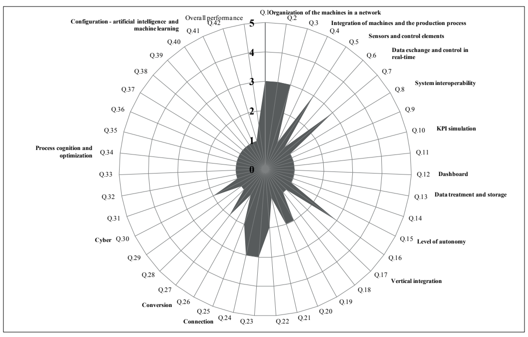

Figure 2. Performance – Thermal power plant. Source: Authors.

is an organization that has a continuous production system, with little variability in the volume of production and no variability in terms of the diversity of final products. A certain standardization of manufacturing communication equipment is evident and raw data from the production process are converted into "meaningful" information.

Case 3. Plastic injection molding company

Figure 3 shows the radar graph generated from the information collected in the plastic injection molding company regarding the cyber-physical production system. The best performing constructs were (1) organization of the machines in a network (3.0), followed by (2) sensors and control elements (3.0), (3) integration of the machines and the production process (2.5), and (4) data exchange and real-time control (2.0) Delloite (2015) and PricewaterhouseCoopers (2014). The connection level averaged 2.0 and the conversion level averaged 1.75. Cyber, cognition, and configuration scored 1.0. In conclusion, the company's overall average was 1.6. The plastic injection molding company has a level of implementation of the concepts of cyber-physical production systems in a similar stage to that observed in the thermal power plant (connection level, being possible to observe characteristics of the conversion level). The very nature of the company's activity reinforces the results because the production process has a moderate-high level of automation. It was possible to observe a certain standardization of the manufacturing communication equipment with a higher level of conversion and visualization of product data becoming "meaningful" information.

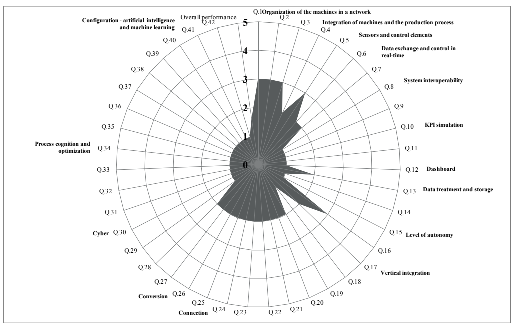

Figure 3. Performance – Plastic injection molding company. Source: Authors.

In summary, the plastic injection molding company obtained superior performance in the evaluation, followed by the thermal power plant and chemical company indicating that the cyber-physical production system has better performance when considering the type of production system adopted by the company and the level of automation in line with the cyber-physical production system (CPPS) architecture framework presented in Lee et al. (2018). Companies evaluated even at an early stage of implementing concepts of cyber-physical production systems already have an advantage in the competitive environment (Lee et al., 2013) about the competition and moving towards the concept of intelligent factories (Cruz Salazar et al., 2019; Drennan-Stevenson, 2019) in the Amazon context, with data processing becoming intelligent, monitoring, optimization, and multidisciplinary engineering activities according to Berger et al. (2019), Bunte et al. (2019) and Meixner et al. (2019).

This study differs from the works presented in this research regarding the application of CPPS (Hu et al., 2016; Lee et al., 2017; Lee et al., 2018; Drennan-Stevenson, 2019; Cruz Salazar et al., 2018; Ashtari Talkhestani et al., 2019; among others presented), as its focus is on the evaluation of cyber-physical production systems from the point of view of operations management, while most of the works on the subject work from the point of view of the science of computing. However, the approach to work with a focus on the shop floor stands out, especially Romero-Silva & Hernández-López (2020), Govender et al. (2019), Torres et al. (2019), and Rocha et al. (2019).

6. Conclusion

This study aimed to assess the maturity level of cyber-physical production systems within manufacturing industries in the Amazon. The research framework enabled a comprehensive assessment of companies by using different research techniques, making an original contribution to operations management, identifying opportunities for improvement, and assessing maturity in this context. The contributions of this research are relevant for academics and professionals.

The theoretical contribution is in expanding the theme by conducting research focusing on operations management's point of view on the subject. we seek to initiate a discussion of cyber-physical production systems from the perspective of planning, management, and evaluation characteristic of business management and expanding the body of knowledge related to the topic. All variables on the CPPS evaluation and measurement form have been previously examined in the literature. The study contributes to the development of research in the Amazon context and its application in other realities.

Among the managerial implications, the research contributed to the reflection on the part of the companies that participated in the study as to the current stage in which they are about the theme. The results can be used to optimize initiatives for productive and managerial excellence. The adopted form can assist other companies in the evaluation of their cyber-physical production systems and can be applied to evaluate an industrial sector as a whole. The proposed methodology can assist other companies in the development of the technological strategy, supporting the digital transformation process in order to obtain competitive advantage. Our findings reveal a positive relationship between the type of production system adopted by the company, the level of automation, and the maturity of the CPPS.

The limitations of the research are associated with limited sample size, although the study was carried out in the form of an in-depth case, which enabled a greater level of deepening of the reality of the companies, and the impossibility of carrying out a longitudinal analysis. For future research, it is recommended to conduct similar research in a specific industrial sector, in addition to expanding the number of cases reported per study.

References

Afanasev, M.Y., Fedosov, Y.V., Andreev, Y.S., Krylova, A.A., Shorokhov, S.A., Zimenko, K.V., & Kolesnikov, M.V. (2019). A concept for integration of voice assistant and modular cyber-physical production system. *In 2019 IEEE International Conference on Industrial Informatics (INDIN)* pp. 27–32. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/INDIN41052.2019.8972015

Ait-Alla, A., Kreutz, M., Rippel, D., Lütjen, M., & Freitag, M. (2019). Simulation-based Analysis of the Interaction of a Physical and a Digital Twin in a Cyber-Physical Production System. *IFAC-PapersOnLine*, *52*(13), 1331–1336. https://doi.org/10.1016/j.ifacol.2019.11.383

Agca, O., Gibson, J., Godsell, J., Ignatius, J., Wyn Davies, C., & Xu, O. (2017). An Industry 4 Readiness Assessment Tool. International Institute for Product and Service Innovation, 1–19.

Alves, C., & Putnik, G.D. (2019). Cyber-Physical Production System (CPPS) decision making duration time impact on manufacturing system performance. *FME Transactions*, *47*(4), 675–682. https://doi.org/10.5937/fmet1904675A

Ansari, F., Hold, P., & Khobreh, M. (2020). A knowledge-based approach for representing jobholder profile toward optimal human–machine collaboration in cyber physical production systems. *CIRP Journal of Manufacturing Science and Technology*, *28*, 87–106. https://doi.org/10.1016/j.cirpj.2019.11.005

Ashtari Talkhestani, B., Jung, T., Lindemann, B., Sahlab, N., Jazdi, N., Schloegl, W., & Weyrich, M. (2019). An architecture of an Intelligent Digital Twin in a Cyber-Physical Production System. *At-Automatisierungstechnik*, *67*(9), 762–782. https://doi.org/10.1515/auto-2019-0039

Baheti, R., & Gill, H. (2011). Cyber-physical systems. *The Impact of Control Technology*, p. 161-166.

Bardin, L. (1977). *L'Analyse de contenu*. Presses Universitaires de France.

Benbasat, I., Goldstein, D.K., & Mead, M. (1987). The case research strategy in studies of information systems. MIS Quarterly: Management Information Systems, *11*(3), 369–386. https://doi.org/10.4135/9781849209687.n5

Berger, C., Zipfel, A., Braunreuther, S., & Reinhart, G. (2019). Approach for an event-driven production control for cyber-physical production systems. *In Procedia CIRP, 79,* 349–354. Elsevier B.V. https://doi.org/10.1016/j.procir.2019.02.085

Berlak, J., Berg, J., Stangl, M., & Baumgart, L. (2020). Real-Time IoT-Based Production Planning and Control of Industrial Robots in an Automated Cyber-Physical Production System Under Dynamic Conditions: Lessons Learned from a Make-to-Order Usage Case. *In Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *12014 LNCS*, pp. 485–492. Springer. https://doi.org/10.1007/978-3-030-45096-0_59

Borangiu, T., Morariu, O., Răileanu, S., Trentesaux, D., Leitão, P., & Barata, J. (2020). Digital transformation of manufacturing. Industry of the future with cyber-physical production systems. *Romanian Journal of Information Science and Technology*, *23*(1), 3–37.

Brauner, P., & Ziefle, M. (2019). Why consider the human-in-the-loop in automated cyber-physical production systems? Two cases from cross-company cooperation. *In 2019 IEEE International Conference on Industrial Informatics (INDIN),* 2019-July, pp. 861–866. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/INDIN41052.2019.8972142

Brauner, P., Philipsen, R., Valdez, A.C., & Ziefle, M. (2019). Human interaction under risk in cyber-physical production systems. *In Advances in Intelligent Systems and Computing, 822,* 421–430. Springer Verlag. https://doi.org/10.1007/978-3-319-96077-7_45

Bunte, A., Fischbach, A., Strohschein, J., Bartz-Beielstein, T., Faeskorn-Woyke, H., & Niggemann, O. (2019). Evaluation of Cognitive Architectures for Cyber-Physical Production Systems. *In 2019 IEEE International Conference on Emerging Technologies and Factory Automation, ETFA*, 2019-September, pp. 729–736. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/ETFA.2019.8869038

Chawla, V.K., Angra, S., Suri, S., & Kalra, R.S. (2020). A synergic framework for cyber-physical production systems in the context of industry 4.0 and beyond. *International Journal of Data and Network Science*, *4*(2), 237–244. https://doi.org/10.5267/j.ijdns.2019.12.002

Creswell, J.W. (2009). *Research design: qualitative, quantitative, and mixed methods approaches*. 3. ed. California, USA: Sage.

Cruz Salazar, L.A., Ryashentseva, D., Lüder, A., & Vogel-Heuser, B. (2019). Cyber-physical production systems architecture based on multi-agent's design pattern—comparison of selected approaches mapping four agent patterns. *International Journal of Advanced Manufacturing Technology*, *105*(9), 4005–4034. https://doi.org/10.1007/s00170-019-03800-4

Delloite. (2015). *Industry 4.0: challenges and solutions for the digital transformation and use of exponential technologies*. Suíça: Delloite.

Ding, K., Chan, F.T. S., Zhang, X., Zhou, G., & Zhang, F. (2019). Defining a Digital Twin-based Cyber-Physical Production System for autonomous manufacturing in smart shop floors. *International Journal of Production Research*, *57*(20), 6315–6334. https://doi.org/10.1080/00207543.2019.1566661

Drennan-Stevenson, K. (2019). Real-world implementation of cyber-physical production systems in smart manufacturing: Cognitive automation, industrial processes assisted by data analytics, and sustainable value creation networks. *Journal of Self-Governance and Management Economics*, *7*(3), 14–20. https://doi.org/10.22381/JSME7320192

Eckhart, M., Ekelhart, A., Lüder, A., Biffl, S., & Weippl, E. (2019). Security Development Lifecycle for Cyber-Physical Production Systems. *In 2019 IECON Proceedings (Industrial Electronics Conference)*, 2019-October, pp. 3004–3011. IEEE Computer Society. https://doi.org/10.1109/IECON.2019.8927590

Eisenhardt, K.M. (1989). Building Theories from Case Study Research. *Academy of Management Review, 14*(4), 532-550. https://doi.org/10.5465/amr.1989.4308385

European Parliament. (2016). *Industry 4.0*. Bruxelas: EP.

Ferreira, J., Lopes, F., Doumeingts, G., Sousa, J., Mendonça, J.P., Agostinho, C., & Jardim-Goncalves, R. (2020). Empowering SMEs with Cyber-Physical Production Systems: From Modelling a Polishing Process of Cutlery Production to CPPS Experimentation. *In Studies in Computational Intelligence*, *864*, 139–177. Springer. https://doi.org/10.1007/978-3-030-38704-4_7

Francalanza, E., Borg, J., & Constantinescu, C. (2017). A knowledge-based tool for designing cyber physical production systems. *Computers in Industry*, *84*, 39–58. https://doi.org/10.1016/j.compind.2016.08.001

Francalanza, E., Mercieca, M., & Fenech, A. (2018). Modular System Design Approach for Cyber Physical Production Systems. *In Procedia CIRP, 72*, 486–491. Elsevier B.V. https://doi.org/10.1016/j.procir.2018.03.090

Geisbauer, R., Vedso, J., & Schrauf, S. (2016). Industry 4.0: Building the digital enterprise. 2016 Global Industry 4.0 Survey, 1–36. Retrieved from www.pwc.com/industry40.

Gill, H. (2008). *From vision to reality: cyber-physical systems*. Present. HCSS Natl. Work. New Res. Dir. High Confd. Transp. CPS Automotive, Aviat. Rail.

Glatt, M., & Aurich, J.C. (2019). Physical modeling of material flows in cyber-physical production systems. *In Procedia Manufacturing, 28,* 10–17. Elsevier B.V. https://doi.org/10.1016/j.promfg.2018.12.003

Gronau, N. (2019). Determining the appropriate degree of autonomy in cyber-physical production systems. *CIRP Journal of Manufacturing Science and Technology*, *26*, 70–80. https://doi.org/10.1016/j.cirpj.2019.05.001

Germany Trade & Invest. (2014). *Industrie 4.0*. Germany, GTAI, 2014.

Guérin, F., Laville, A., Daniellou, F., Duraffourg, J., Kerguelen, A. (2001). *Compreender o trabalho para transformá-lo: a prática da ergonomia*. São Paulo: Blücher: Fundação Vanzolini.

Govender, E., Telukdarie, A., & Sishi, M.N. (2019). Approach for Implementing Industry 4.0 Framework in the Steel Industry. *In 2019 IEEE International Conference on Industrial Engineering and Engineering Management*, pp. 1314–1318. IEEE Computer Society. https://doi.org/10.1109/IEEM44572.2019.8978492

Hu, F., Lu, Y., Vasilakos, A.V., Hao, Q., Ma, R., Patil, Y., … Xiong, N.N. (2016). Robust Cyber-Physical Systems: Concept, models, and implementation. *Future Generation Computer Systems*, *56*, 449–475. https://doi.org/10.1016/j.future.2015.06.006

Iglesias, A., Sagardui, G., & Arellano, C. (2019). Industrial cyber-physical system evolution detection and alert generation. *Applied Sciences (Switzerland)*, *9*(8). https://doi.org/10.3390/app9081586

Lee, J., Lapira, E., Bagheri, B., & Kao, H. an. (2013). Recent advances and trends in predictive manufacturing systems in big data environment. *Manufacturing Letters, 1*(1), 38–41. https://doi.org/10.1016/j.mfglet.2013.09.005

Lee, J., Jin, C., & Bagheri, B. (2017). Cyber physical systems for predictive production systems. *Production Engineering*, *11*(2), 155–165. https://doi.org/10.1007/s11740-017-0729-4

Lee, J.H., Do Noh, S., Kim, H.J., & Kang, Y.S. (2018). Implementation of cyber-physical production systems for quality prediction and operation control in metal casting. *Sensors (Switzerland)*, *18*(5). https://doi.org/10.3390/s18051428

Lichtblau, K., Stich, V., Bertenrath, R., Blum, M., Bleider, M., … Schroter, M. (2015). *Industrie 4.0 Readiness*. Impuls-Stiftung, 0–76.

Liu, C., Jiang, P., & Jiang, W. (2020). Web-based digital twin modeling and remote control of cyber-physical production systems. *Robotics and Computer-Integrated Manufacturing*, *64*. https://doi.org/10.1016/j.rcim.2020.101956

Lins, T., & Oliveira, R.A. R. (2020). Cyber-physical production systems retrofitting in context of industry 4.0. *Computers and Industrial Engineering*, *139*. https://doi.org/10.1016/j.cie.2019.106193

Llamuca, E.S., Garcia, C.A., Naranjo, J.E., & Garcia, M.V. (2019). Cyber-physical production systems for industrial shop-floor integration based on AMQP. *In Proceedings - 2019 International Conference on Information Systems and Software Technologies, ICI2ST 2019*, pp. 48–54. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/ICI2ST.2019.00014

Loucopoulos, P., Kavakli, E., & Chechina, N. (2019). Requirements Engineering for Cyber Physical Production Systems. *In Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 11483 LNCS*, pp. 276–291. Springer Verlag. https://doi.org/10.1007/978-3-030-21290-2_18

Marconi, M.A., & Lakatos, E.M. (2002). *Técnicas de pesquisa: planejamento e execução de pesquisas, amostragens e técnicas de pesquisa, elaboração, analise e interpretação de dados.* 5. ed. São Paulo: Atlas.

Mayrhofer, M., Mayr-Dorn, C., Zoitl, A., Guiza, O., Weichhart, G., & Egyed, A. (2019). Assessing adaptability of software architectures for cyber physical production systems. *In Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 11681 LNCS*, pp. 143–158. Springer Verlag. https://doi.org/10.1007/978-3-030-29983-5_10

McCutcheon, D.M., & Meredith, J.R. (1993). Conducting case study research in operations management. *Journal of Operations Management*, *11*(3), 239–256. https://doi.org/10.1016/0272-6963(93)90002-7

Miguel, P.A.C. (Org.). (2012). *Metodologia de pesquisa em engenharia de produção e gestão de operações*. 2. ed. Rio de Janeiro: Elsevier: ABEPRO.

Meixner, K., Rabiser, R., & Biffl, S. (2019). Towards modeling variability of products, processes and resources in cyber-physical production systems engineering. *In ACM International Conference Proceeding Series (Vol. B). Association for Computing Machinery*. https://doi.org/10.1145/3307630.3342411

Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., … Ueda, K. (2016). Cyber-physical systems in manufacturing. *CIRP Annals, 65*(2), 621–641. https://doi.org/10.1016/j.cirp.2016.06.005

Mourad, M.H., Nassehi, A., Schaefer, D., & Newman, S.T. (2020). Assessment of interoperability in cloud manufacturing. *Robotics and Computer-Integrated Manufacturing*, *61*. https://doi.org/10.1016/j.rcim.2019.101832

Mourtzis, D., & Vlachou, E. (2016). Cloud-based cyber-physical systems and quality of services. *TQM Journal, 28*(5), 704–733. https://doi.org/10.1108/TQM-10-2015-0133

Mühlfelder, M. (2019). Analysis and design of a cyber-physical production system (CPPS) in sensor manufacturing. A case study. *In Advances in Intelligent Systems and Computing, 822*, pp. 391–400. Springer Verlag. https://doi.org/10.1007/978-3-319-96077-7_41

Park, K.T., Lee, J., Kim, H.J., & Noh, S.D. (2020). Digital twin-based cyber physical production system architectural framework for personalized production. *International Journal of Advanced Manufacturing Technology*, *106*(5–6), 1787–1810. https://doi.org/10.1007/s00170-019-04653-7

Patalas-Maliszewska, J., & Schlueter, N. (2019). Model of a knowledge management for system integrator(s) of cyber-physical production systems (CPPS). *In Lecture Notes in Mechanical Engineering* (pp. 92–103). Pleiades Publishing. https://doi.org/10.1007/978-3-030-18715-6_8

Prist, M., Monteriu, A., Freddi, A., Pallotta, E., Cicconi, P., Giuggioloni, F., … Longhi, S. (2019). Cyber-Physical Manufacturing Systems for Industry 4.0: Architectural Approach and Pilot Case. *In 2019 IEEE International Workshop on Metrology for Industry 4.0 and IoT, MetroInd 4.0 and IoT 2019 - Proceedings* (pp. 219–224). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/METROI4.2019.8792880

Pinzone, M., Albè, F., Orlandelli, D., Barletta, I., Berlin, C., Johansson, B., & Taisch, M. (2020). A framework for operative and social sustainability functionalities in Human-Centric Cyber-Physical Production Systems. *Computers and Industrial Engineering*, *139*. https://doi.org/10.1016/j.cie.2018.03.028

PricewaterhouseCoopers. (2014). *Industry 4.0: opportunities and challenges of the industrial internet*. Germany: PWC.

Rocha, A. Di., Tripa, J., Alemao, D., Peres, R.S., & Barata, J. (2019). Agent-based plug and produce cyber-physical production system - Test case. *In 2019 IEEE International Conference on Industrial Informatics (INDIN),* 2019-July, pp. 1545–1551. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/INDIN41052.2019.8972169

Romero-Silva, R., & Hernández-López, G. (2020). Shop-floor scheduling as a competitive advantage: A study on the relevance of cyber-physical systems in different manufacturing contexts. *International Journal of Production Economics*, *224*. https://doi.org/10.1016/j.ijpe.2019.107555

Sanislav, T., & Miclea, L. (2012). Cyber-Physical Systems - Concept, Challenges and Research Areas. *CEAI*, *14*(02), 28-33.

Sha, L., Gopalakrishnan, S., Liu, X., & Wang, Q. (2008). Cyber-physical systems: A new frontier. *In Proceedings - 2008 IEEE International Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing*, pp. 1–9. https://doi.org/10.1109/SUTC.2008.85

Schreiber, M., Vernickel, K., Richter, C., & Reinhart, G. (2019). Integrated production and maintenance planning in cyber-physical production systems. *In Procedia CIRP, 79,* 534–539. Elsevier B.V. https://doi.org/10.1016/j.procir.2019.02.095

Schuh, G., Anderl, R., Dumitrescu, R., Krüger, A., & Hompel, M. (2020). *Industrie 4.0 maturity index. Managing the digital transformation of companies–Update 2020*. acatech STUDY.

Stock, D., Schel, D., & Bauernhansl, T. (2019). Cyber-Physical Production System Self-Description-Based Data Access Layer. *In 2019 IEEE International Conference on Emerging Technologies and Factory Automation, ETFA,* 2019-September, pp. 168–175. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/ETFA.2019.8869486

Stock, D., Schel, D., & Bauernhansl, T. (2020). Middleware-based cyber-physical production system modeling for operators. *In Procedia Manufacturing, 42*, 111–118. Elsevier B.V. https://doi.org/10.1016/j.promfg.2020.02.031

Thiede, S. (2018). Environmental Sustainability of Cyber Physical Production Systems. *In Procedia CIRP, 69,* 644–649. Elsevier B.V. https://doi.org/10.1016/j.procir.2017.11.124

Thiede, S., Juraschek, M., & Herrmann, C. (2016). Implementing Cyber-physical Production Systems in Learning Factories. *In Procedia CIRP, 54,* 7–12. Elsevier B.V. https://doi.org/10.1016/j.procir.2016.04.098

Torres, P., Dionísio, R., Malhão, S., Neto, L., Ferreira, R., Gouveia, H., & Castro, H. (2019). Cyber-Physical Production Systems supported by Intelligent Devices (SmartBoxes) for Industrial Processes Digitalization. *In 5th International Forum on Research and Technologies for Society and Industry: Innovation to Shape the Future, RTSI 2019 - Proceedings*, pp. 73–78. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/RTSI.2019.8895553

Vergara, S.C. (2009). *Métodos de coleta de dados no campo*. São Paulo: Atlas.

Villarreal, O. (2017). Is it desirable, necessary and possible to perform research using case studies? *Cuadernos de Gestion*, *17*(1), 147-172. https://doi.org/10.5295/cdg.140516ov

Villarreal, O., & Landeta, J. (2010). Case study as a scientific research methodology in business economics and strategic management. An application to internationalisation. *Investig. Eur. Direccion Econ. Empres*., *16*(3), 31-52. https://doi.org/10.1016/S1135-2523(12)60033-1

Villarreal, O., & Calvo, N. (2015). From the triple helix model to the global open innovation model: a case study based on international cooperation for innovation in Dominican Republic. *Journal of Engineering and Technology Management*, *35*(1), 71-92. https://doi.org/10.1016/j.jengtecman.2014.10.002

Voss, C., Tsikriktsis, N., & Frohlich, M. (2002). Case research in operations management. *International Journal of Operations and Production Management*, *22*(2), 195–219. https://doi.org/10.1108/01443570210414329

Yang, Lu. (2017). Industry 4.0: A survey on Technologies, application and open research. *Journal of Industrial Information Integration*, *6*, 1-10. https://doi.org/10.1016/j.jii.2017.04.005

Wang, L., Törngren, M., & Onori, M. (2015). Current status and advancement of cyber-physical systems in manufacturing. *Journal of Manufacturing Systems*, *37*, 517–527. https://doi.org/10.1016/j.jmsy.2015.04.008

Wu, X., Goepp, V., & Siadat, A. (2019a). Cyber Physical Production Systems: A Review of Design and Implementation Approaches. *In 2019 IEEE International Conference on Industrial Engineering and Engineering Management,* pp. 1588–1592. IEEE Computer Society. https://doi.org/10.1109/IEEM44572.2019.8978654

Wu, X., Goepp, V., & Siadat, A. (2019b). The integrative link between cyber physical production systems and enterprise information systems. *In Proceedings of 2019 International Conference on Computers and Industrial Engineering, CIE,* 2019-October. Computers and Industrial Engineering.

Yin, R.K.(1994). *Case Study Research, Design and Methods,* 2nd ed. Newbury Park, Sage Publications.

Zhang, H., Zhang, G., & Yan, Q. (2019). Digital twin-driven cyber-physical production system towards smart shop-floor. *Journal of Ambient Intelligence and Humanized Computing*, *10*(11), 4439–4453. https://doi.org/10.1007/s12652-018-1125-4

Zhang, H., Yan, Q., & Wen, Z. (2020). Information modeling for cyber-physical production system based on digital twin and AutomationML. *International Journal of Advanced Manufacturing Technology*, *107*(3–4), 1927–1945. https://doi.org/10.1007/s00170-020-05056-9

