Methodology proposal for the design of cyber-physical systems based on product design and development approach

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Abstract – The cyber-physical system (CPS) is a pillar of Industry 4.0. Its impact on various sectors such as production, transport, health or energy has been increasing in recent years, as it allows the integration of computational capacities to physical contexts, unlocking more sophisticated capabilities in engineering systems. To keep up with this innovation stream, a methodology is needed that properly guides the entire process of creating, designing, building and implementing a CPS. Methodologies addressing the essential aspects of CPS design already exist. However, there is no methodology that properly concerns the particular reality of a company helping it to understand the nature of its business and its way of market interaction, in order to identify opportunities where the use of CPS resources could improve the company's performance. Thus, this dissertation proposes the first CPS design and development methodology approach based on generic product design and development (PDD) methods. The goal is to demonstrate that when a development team considers that the product in this case is the CPS itself and by following the various methods, steps and logics of PDD, the result can be a CPS more adjusted to the real needs of the organization. The proposal is divided into two main parts: a conceptual project at the macro level of the general system and an implementation project at the micro level of the subsystems. Examples are presented based on a case study application.

Keywords – Cyber-physical system, product design and development, business model, operational and production needs, design of cyber-physical systems, Industry 4.0.

I. INTRODUCTION

The cyber-physical system (CPS) is one of the foundations of the Smart Factory which is the heart of Industry 4.0 [1], [2]. Several articles concerning Industry 4.0 and CPS have been published in the last decade, indicating these are increasingly important topics in the academic and industrial worlds. In particular, CPS engineering has been increasingly addressed, as it allows the integration of computational capacities to physical contexts, unlocking more sophisticated capabilities in engineering systems. That is why CPS is introduced as a technological concept with wide impact [3] in sectors such as production, transportation, health and energy [4]–[6].

To keep up with this stream of innovation, a methodology is needed that properly guides the entire process of creating, designing, building and implementing a CPS. By definition, a CPS is a complex system which may include features and capabilities chosen from a wide list of alternatives, of varying degrees of maturity, different levels of technological complexity and which imply different levels of investment. When investing in such a system, a difficulty in understanding what is really necessary for the developer company arises. Furthermore, in the midst of so many opportunities for innovation, it is often not even known where to start, and mistakes are made in investing in technology that is not entirely necessary.

Thus, this document proposes the first CPS design and development methodology approach based on generic product design and development (PDD)methods. The goal is to demonstrate that when a development team considers that the product in this case is the CPS itself and by following the various methods, steps and logics of PDD, the result can be a CPS more adjusted to the real needs of the organization. In other words, the following criterion is proposed: it makes sense to invest in a CPS if it helps the organization to satisfy the requirements of its business model (BM).

The present document is structured as follows.

Section II reports a state of the art research with two objectives. Firstly, to understand what a CPS is (concept definition), how it is constituted (components) and how it works (features and requirements). For this, a research about the Industry 4.0 paradigm is relevant, in order to understand its principles and foundations, and how the CPS fits into it. Secondly, to investigate existing CPS design and development approaches in order to analyse the suitability of each proposed methodology, identify the literature gap and support the suitability of this proposal.

Section III presents an applicability analysis with the aim of demonstrating that most of the different generic methods, steps and logic of PDD are useful for CPS design and development (CPSDD) and indicating how this approach may help fill the referred gap.

Section IV proposes a new methodology for CPSDD which is divided into two main parts: 'conceptual design' at the general system level and 'from concept to implementation' at the subsystems and their components level. Alongside each step, output examples following a case study are given and conclusions are drawn.

Section V ends the article with several conclusions.

II. Industry 4.0 and CPS

II. A. Industry 4.0

Since the beginning of industrialization, technological leaps led to paradigm shifts called "industrial revolutions" [7]. Nowadays, the industrial world is being transformed by the fourth industrial revolution [8] which is the first to be addressed before it actually happens or is widely implemented [9]. This opens up a wide range of opportunities for any type of business that would be interested in participating in this new innovation stream.

Derived from this future expectation, the term "Industry 4.0" was established *ex ante* for a planned fourth industrial revolution [10]. Industry 4.0 refers not only to a technological leap as it is "*a collective term for technologies and concepts of value chain organization. Within the modular structured Smart Factories of Industry 4.0, CPS monitor physical processes, create a virtual copy of the physical world and make decentralized decisions. Over the Internet of Things (IoT), CPS communicate and cooperate with each other and humans in real time. Via IoT, both internal and cross-organizational services are offered and utilized by participants of the value chain"* [11]. This definition introduces and highlights the important role of the CPS, a topic that is more deeply analysed in the following paragraphs.

In order to systematize the Industry 4.0 knowledge and describe its elementary constituents, Hermann et al. [12] conducted an extensive study resulting in four design principles of Industry 4.0, summarized by Figure 1.

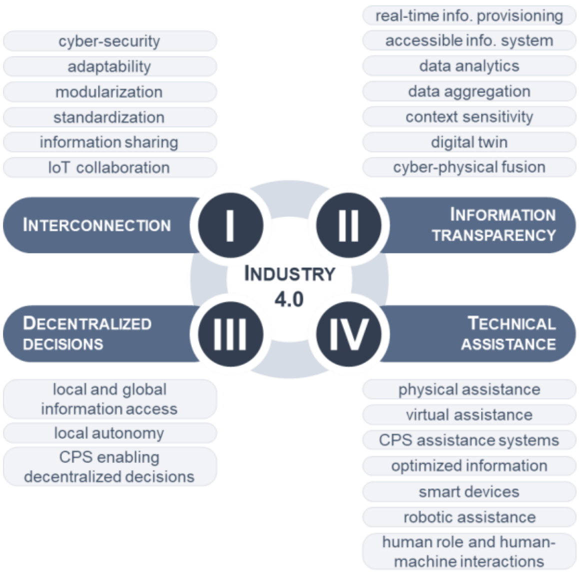

Figure 1 – Design principles of Industry 4.0. Adapted from [12].

Hence, the CPS is mentioned directly in the third and fourth principles. It is also referred indirectly through many other features present in all four principles, which the CPS can also include (if necessary) as will be shown further on this article.

In 2019, Yao et al. [1] pointed out 'smart manufacturing' as a central part of Industry 4.0. From the four key components of Industry 4.0 identified in their article which are IoT, Internet of Services (IoS), Smart Factory and CPS, the last one is classified as the most prominent. According to [13]–[15] the framework for smart manufacturing systems that includes these disciplines:

- Smart design
- Smart machine
- Smart product
- Smart monitoring
- Smart control
- Smart scheduling.

Along with the transformation of BM, Industry 4.0 will also influence the evolution of technologies [8]. There are many different types of technologies that can be introduced, allowing companies to evolve towards Industry 4.0. These types of technologies have many names and definitions and Bibby et al. [16] categorizes these technological concepts in different groups. By analysing several articles, Amaral [17] concluded that the group "IoT and CPS" refers to two different components of Industry 4.0 and should be divided into two different categories ("IoT" and "CPS"). Thus, the nine technological concepts are named in the following list:

- 3D Printing
- Cloud
- Manufacturing Execution Systems (MES)
- Big Data
- Sensors
- e-Value Chains
- Autonomous Robots
- IoT
- CPS.

The importance of CPS is once again highlighted as being one of the technological concepts.

II. B. Cyber-physical systems

The CPS designation can be traced back to 2006 when it was coined in the USA at an R&D conference [18]. However, the CPS was formally defined for the first time by Lee [19] in 2008. This definition proved to be remarkable as it was later cited by other authors such as [20]. In 2016, Monostori et. al. [21] proposed a definition after reviewing 1982 works. More recently in 2019, Burns et al. [22] proposed another one based on 31 previous definitions. These and other results [6], [19] were reviewed, and all definitions converge to these essential aspects:

A cyber-physical system:

- ✓ Operates on physical and engineering contexts
- ✓ Is formed by distributed heterogeneous systems
- ✓ Records physical data using sensors
- ✓ Stores, processes and evaluates data
- ✓ Uses globally available data
- ✓ Consists of subsystems connected to each other and in global networks
- ✓ Involves information, communication and control technologies (ICCT)
- ✓ Affects physical processes through actuators
- ✓ Has programmable features and structure
- ✓ Allows the intersection of the physical context with the cyber context
- ✓ Is based on time integration system of the physical context with event-oriented computing
- ✓ Is an orchestration of ICCT and physical engineering systems
- ✓ Requires reliability, security and protection.

This systematization may help understand why the CPS is a pillar of Industry 4.0, once every essential aspect is noticeably related to its four design principles.

CPS engineering enhances business in different sectors such as industrial production[4]–[6], which is the scope for now. According to Thiede et al. [23], in production systems the implementation of CPS technology elements leads to cyber-physical production systems (CPPS).However, throughout the present document the generic acronym 'CPS' is more accurately used, as it refers not only to production but also to other value chain operations.

Regarding the conceptualization of the CPS components and features, there are several different approaches where authors use the term "architecture" [14], [24]–[26]. To properly leverage the proposal of this document the researched literature identified among several articles a set of five that together conjecture a final CPS architecture. Each architecture is briefly presented before the final model is illustrated on Figure 2 and its key topics are listed afterwards.

La and Kim [24] proposed the 'service-based CPS architecture' which considers three tiers:

Context tier – includes sensors, actuators, physical devices and their end-users (target environment).

Service tier – consists of a computing environment with service, a repository and framework.

Control tier – receives monitored data in order to make decisions, with possible human control.

Hu et al. [27] studied the previous architecture and proposed a new approach with five tiers:

Perceive tier – includes the data source and the environment awareness, achieved by sensors.

Data Tier – consists of the computational and storage devices.

Service Tier – consists of decision-making, task analysis and task schedule, which interacts with each other.

Execution Tier – contains actuators that execute received commands from the system.

Security Assurance – consists of access security, data security and device security of the whole system.

Ahmadi et al. [14] considered the existence of three CPS components: Human Component (HC), Cyber Component (CC) and Physical Component (PC), considering also their interactions:

HC: includes learning techniques for workers; and the integration of human intelligence.

CC: includes the processing tools, data management and services, and failure and repair management.

PC: consists of the physical and hardware part, focusing on communication and M2M interaction.

HC-CC Interface: consists of the user interface.

CC-PC Interface: consists of data acquisition.

HC-PC Interface: focus on human machine interaction.

In 2015, Lee et. al. [25]clearly structured CPS guidelines for its implementation, proposing a 5-level structure named 5C architecture which provides a sequential flow for the CPS development. The 5C are: Connection, Conversion, Cyber, Cognition and Configuration. In 2017, Jiang [26] concluded that the 5C are suitable for mass production but not for mass customization because it does not concern all the value chain activities along the whole product life cycle. To solve this problem, the author added 3 facets: Coalition, Client and Content (3C). In Figure 2 the final 8C architecture schema is exposed, where the initial 5C triangular structure is complemented with the 3C at sides.

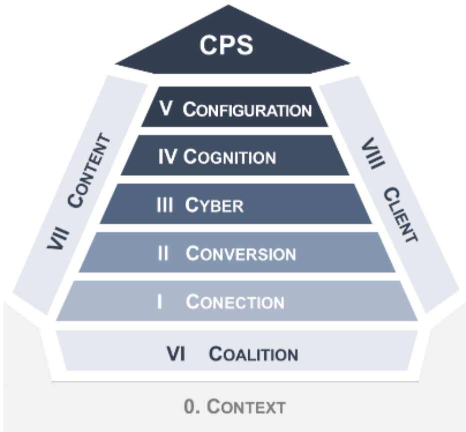

Figure 2 – 8C CPS. Adapted from [24]–[26].

After a thorough comparative analysis of all architectures and an identification of common aspects among them, the 8C CPS was chosen for the final architecture basis as it is the most holistic. Because the CPS is the core concept of Industry 4.0 [26], on this final model aspects of the design principles, technological concepts and smart manufacturing are also included. Thus, the resulting 8C key aspects are:

I. Connection – raw data collection, sensor modelling, transfer, acquisition, storage, centralization, connection, protocols, devices, wearables, interfaces, tele/electronic communications.

II. Conversion – data-to-info transformation, algorithms, deductions, self-consciousness machines

III. Cyber – massive data collection, database, network of machines and devices, information center, history records, automatic updates, cloud computing, virtual platforms, collaborative processing, similarity analysis, self-comparison/prevention, Big Data, IoT.

IV. Cognition – supervision, monitoring, intelligence, service framework, information structuring and organization, optimization, intelligence, smart monitoring, visual treatment, dashboards, smart scheduling tools, decision-making support, MES, predictive maintenance, smart scheduling, machine learning.

V. Configuration – control actions, application of decisions, smart control, centralization, self-configuration, self-adaptation, smart machine, 3D-Printing, Autonomous Robots.

VI. Coalition – integration of the value chain in manufacturing, support for stakeholder collaboration, intelligent reaction to changes, process programming, dynamic reconstruction of supply chains, e-Value Chains.

VII. Content –enabling access to detailed information for the entire VC (supply, logistics, production, marketing, etc.), production parameters, product traceability record, smart product, product life cycle management, demand forecasts, business planning, smart design.

VIII. Client – customers' role in design, production and after sales services, mass customization, stakeholder participation in processes, flexible specification modification, order tracking, product-centric manufacturing.

After identifying the components and features to be designed, one of the next steps will be to specify the requirements. According to 3 different articles [28]–[30], CPS requirements include credibility, availability, energy, stability, reliability, flexibility, maintenance, standardization, physical security, logical security and usability.

II. C. CPS DESIGN APPROACHES

Karsai and Sztipanovits [31] refer that a good design is more than functional, it should also anticipate faults and fail modes, and be able to manage them. According to the authors, the physical and computational components should be designed, modelled and analysed together. According to Jensen et al. [32], the CPS design techniques that are commonly used include the following steps: mathematical modeling of physical systems, formal computing models, heterogeneous system simulation, software synthesis, verification, validation, and testing. Lee and Seshia [33] proposed a simpler approach for the CPS development process, consisting of three phases: modelling, design and analysis. Modelling is the process that specifies the system function (*what* it does). The design phase begins with the selection of the components while putting them together (*how* it does). Analysis specifies *why* the system function was established. These three phases overlap and might be restructured in case of identified flaws in the initial prototype.

Besides these authors [32], [33], there are more proposed approaches regarding CPS development and design procedure. Some refer specially to design challenges and critical aspects, and their potential solutions. One example is the work by Prasad and Son [34] which presents the main issues concerning CPS development, considering complex interactions among communication, computing and physical components. Although they refer to CPS design, their work is focused on the modelling and analysis phases. Lee [19] does not present a procedure to CPS design, but recommends the rethinking of computing and networking in order to address the identified requirements for CPS.

Jensen et al. [32] proposed a model-based design (MBD) for CPS, consisting of ten steps:

1. State the problem: to describe the problem to be solved and to present design requirements.
2. Model physical processes: representation of the physical environment by mathematical models and its refinement.
3. Characterize the problem: isolation of fixed parameters and controllable variables in order to characterize physical processes.
4. Derive a control algorithm: algorithm development to suitably measure and control physical dynamics.
5. Select model of computation: selection of allowed instructions which interact and communicate with the computational components.
6. Specify hardware: selection of suitable hardware for the interaction with physical systems and implementation of control algorithms.
7. Simulate: computational simulation of the problem solution.
8. Construct: device development according to defined specifications.
9. Synthesize software: code synthetization to faithfully execute the model semantics.
10. Verify, validate and test: components testing, refining and requirements verification of previous models.

The practical implementation of MBD is to iteratively visit each step until the requirements are achieved.

The approach of this document is that the CPS must firstly be conceptually created, and only then modelled, designed and analysed. The ultimate goal of a design methodology must always be to build a CPS that helps the developer company to improve its business performance. So, the focus must be on how the CPS will help the production and the operations to be more accurate, efficient and without waste. When researching for CPS design approaches aligned with this idea, the only relevant paper found was one published by Zheng et al. [35], where they reviewed 11 methodologies and grouped them in three categories. One of them is the V-model based methodologies, that follow the concept of general flow for the product development process and begin with the identification of user requirements. This was the only article found during the research where there is an approximation to the product development methodology applied to the CPS. However, the authors state that these methodologies based on the V-model only offer a general development flow and the design phases should be detailed according to the particularities of the CPS.

In summary, some authors refer to the CPS design as the CPS architecture design procedure [26]. Others focus mainly on the architecture approach development, while there is not a defined CPS design procedure [27]. Although there are several CPS proposed components, there are few CPS design methods. Besides, none of them properly addressed the design of the CPS according to a focus view on the reason why the system is to be designed.

III. PRODUCT DESIGN AND DEVELOPMENT APPLIED TO THE CYBER-PHYSICAL SYSTEM

III. A. APPROACH

According to Eppinger and Ulrich [36], a product development process is the sequence of steps or activities that a company employs to conceive, design, prototype, test and commercialize a product. The proposed approach by the present article is to consider that the development "product" is the CPS. Analogously, a CPS development process is the sequence of steps or activities that a company employs to conceive, design, prototype, test and implement the CPS. So, 'commercialization' of a CPS means to implement it for production purposes, or to 'sell' its functionalities and capabilities to the developer company. 'Implementation' includes not only the implementation of the development process, which culminates in the acquisition and assembly of components and devices. It also consists of the operationalization, testing and integration, to ensure the correct functioning of the CPS. In short, any product is conceived, designed and marketed to the customer. For a CPS, the customer is the company that will benefit from the CPS, as it will help improve its business performance. Following this approach, the application potential of PDD to CPS is analysed throughout this section III.

A thorough PDD is useful for five reasons: it provides quality assurance; enables better coordination of people and tasks; supports the planning of the development project; boosts project management; and drives quality improvement of the processes which may result in better manufactured products [36]. Analysis: Once implemented, the CPS will have a direct impact on the company's production and operations. Therefore, it only makes sense to develop such a system if the quality and requirements of its services are certified. For that, it is crucial to promote improvement actions in all developments. CPS is by definition a complex system formed by several distributed but related subsystems. Its development may require the participation of a vast multidisciplinary team that must be in constant collaboration and coordination. To succeed in such a complex project, management and planning support can also be indispensable. Thus, the five mentioned reasons are applicable to CPSDD and more related analysis are exposed in the following subsections.

III. B. PHASE APPLICABILITY

PDD [36] consists of six phases and each phase consists of several steps (Figure 3) [36]. Although the used term is 'step', the whole process is iterative, and most developments must be done simultaneously.

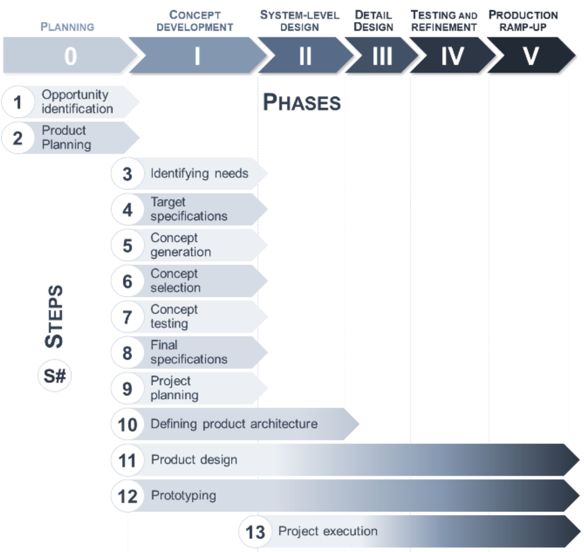

Figure 3 – PDD phases and steps. Adapted from [36].

Phase 0 precedes project approval and starts from the opportunity identification (S1) guided by the corporate strategy which includes assessments of recent technological developments and market analysis. The main outputs come from (S2) where the development process is planned [36]. Analysis: a CPS developer company has opportunities resulting from an established market interaction (BM) that must be understood and identified. For a better CPS approach that enhances that interaction, a process planning can be crucial to formulate a development strategy that must be tuned with the BM.

Phase I consists of generating, selecting and testing concepts (S5, 6 and 7) for products which satisfy customer's needs of the target market (S3). To provide targeted guidance, product specifications are preliminarily drafted in S4 and finally established in S8. Architectural, designing and prototyping concept development (S10, 11 and 12) are also started before phase I is concluded with post-conceptual project planning (S9) [36]. Analysis: enabling the transformation of the CPS development opportunities into an adequate CPS solution requires a thorough development of a macro CPS concept. Once the company's production and operational needs are identified, different CPS concepts can be more efficiently generated. All the steps (S3 to 12) are applicable as is concluded in subsection C.

Phase II is about defining and designing the product architecture (S10) which requires its decomposition in subsystems, blocks and interfaces. The preliminary design of the main components is also included [36]. Analysis: being a system of systems, the CPS system-level design includes similar steps of architecture development and preliminary design. Specific technological development tasks are firstly addressed at this post-conceptual stage.

Phase III consists of developing S11 in an advanced stage. Complete and detailed specification of the geometry, materials and tolerances of all exclusive parts of the product and the identification of all standard parts to be purchased must be accomplished. Materials selection, production cost, and robust performance are critical issues finalized in this phase [36]. Analysis: once the CPS has its architecture defined and the layout of the technological features is well established, the detail design of each CPS subsystem should begin. This phase includes working on the details about how the CPS will function in each production unit or line and how it will be implemented. The detailed list of CPS parts acquisition, whether internal or external, must be drawn up. All these choices should be included in a design procedure to attain a robust CPS performance.

Phase IV has the objective of testing whether the product will work as designed and confirming the customer's needs are met. It includes the construction and evaluation of several pre-production versions of the product and if necessary various types of prototypes (S12) are used [36]. Analysis: after the detailed CPS design is sufficiently elaborated, the next phase consists of testing the solutions and decisions through the simulation of virtual prototypes. If possible, the construction of real and partial physical or even local prototypes for critical operations can be very useful. Many development actions of S12 are applicable, as concluded in section C.

Phase V is when the company starts making the product using the intended production system. Products produced during the ramp-up of production are sometimes delivered to preferential customers and are carefully evaluated to identify remaining faults. The transition from production ramp-up to production in progress is generally gradual. Training the workforce is also a goal at this stage. Analysis: this phase is also applicable even though its name (and logic) changes to "ramp-up of implementation and use of CPS". After the testing and simulation of computational solutions and the hardware and software choices are confirmed, the full implementation and construction of the CPS begins. As the implementations are completed, every functioning of every CPS feature must be checked. Similarly, the first products manufactured with the help of CPS must be tested and evaluated for their quality.

Finally, training sessions should be held for employees who will use and interact with the CPS devices and features.

III. C. Step applicability

Each PDD step consists of several development tasks which produce important output. All of these are generally applicable to CPS, as can be concluded throughout the following analysis.

Step 1 consists of identifying opportunities. An opportunity is an idea for a new product. Starting from the definition of the general scope of innovation, several opportunities are generated and captured. Then, a screening is carried out, resulting in a shorter list of promising opportunities, which are then further refined and developed. Finally, only exceptional opportunities are selected [36]. Analysis: CPSDD should begin by identifying the opportunities (needs) of the fixed and pre-established company's BM, that can be better satisfied with CPS solutions. The aim is to develop a high-level analysis of the value that the organization intends to generate, what problems arise from its creation of value, both in terms of manufacturing and operational processes. Thus, several CPSDD opportunities should be stated, refined and the best ones sellected. Example of CPS opportunity statement: "to develop a customer service feature of monitoring the order production and delivery status". This step is useful to establish specific value chain scopes where needs must be identified (S3).

Step 2 is product planning. The subprojects that result from each opportunity (or set of opportunities) are evaluated and prioritized, according to the organization's competitive strategy. The mission of the project statement is the main output and a crucial development guide. It includes: brief description of the product, benefit proposal, key business goals, target markets, restrictions, assumptions, and stakeholders. A good S2 performance ensures that selected projects have adequate resources for successful completion [36]. Analysis: a project planning could be useful in order to succed in CPSDD. The S1 opportunities and the development actions and resources of the 8C model that must be addressed and developed according to the BM are analysed. For instance, a company might conclude that level I (Connection) is the only level to be reached. Even within this level may it not be necessary to develop all resources. Thus, a better prioritization of potential development strands is enabled. The proposed mission statement tool is applicable to CPSDD as follows: a brief description of the CPS and each of its parts; a general and particular benefit proposal for each part; the "target markets" in this case are the target value chain environments; stakeholders are participants in the target contexts, who have needs (S3) and will ultimately be users of the CPS.

Step 3 is all about identifying 'needs': a term that labels any attribute of a potential product that is desired by potential clients.The collection of raw data from customers is the first task, followed by needs interpretation, which are then organized in a hierarchy of primary, secondary (even tertiary) needs. Finally, the relative importance of needs is established. Thus, S2 has the following objectives: to ensure that the product is focused on the customer's needs; elaborate a facts report to justify the product specifications; and ensure that no critical needs are missed or neglected [36]. Analysis: for the DDCPS conceptual design, "need" refers to the potential CPS-attributes that are needed by the organization's BM. For example, a company may need to "have the ability to quickly adapt the production process, when it comes to the unexpected demands of a customer order". In other words, the business has this "need". So, the aim is to identify the needs of all participants referred on S2. PDD tasks must be applied: needs (critical or normal) must be dissected, mapped and organized.

Step 4 consists of establishing target specifications that explain what the product should do through precise and measurable details, sealing an unequivocal agreement on what the team will try to achieve to satisfy the customer's needs. The S4 task line includes preparing the list of metrics, collecting competitive benchmarking information and setting ideal and marginally acceptable target values [36]. Analysis: despite the S3 results, more development guidelines are necessary. S4 has applicability potential for the conceptual design of CPS although the metrics are adapted to dimensions of needs satisfaction, or even levels of satisfaction. For example, the metric "Level of treatment and optimization of information" may have different levels of satisfaction, among which "ideal" that could correspond to "effective compatibility between applications, systems and data types". Benchmarking reports can be useful to help defining qualitative 'intervals' of satisfaction. After S5 to 7 the previously established metrics and satisfaction levels should be revised, to confirm if the targets have been reached, or if any 'exit' from the intervals is justified.

Step 5 is all about concept generation.A product concept is an approximate description of the technology, operating principles and shape of the product. It is a concise description of how the product will meet the customer's needs, considering the range of target specifications established in the previous step. An excellent generation of concepts assures that the entire range of alternatives has been explored and greatly reduces the odds of finding a superior concept at the end of the process. S5 consists of four steps: clarifying the problem, searching externally, searching internally (brainstorming) and exploring systematically. The main output includes: problem decomposition (where function and user actions diagrams are usually drawn); interview and research reports; documents registering brainstorming of viable and unviable ideas, concept classification trees including records of comparisons between concepts and *pruning* of the unrational concept branches [36]. Analysis: most of this taskline and output is analagously applicable to CPS. Once the company's needs are fully identified and decomposed at the start of S5, approximate but detailed descriptions of operating principles, forms and possible technologies for each subsystem or block of CPS should be sought of. It is important to ensure that all CPS solutions have been considered, because that is the only way to reach the most interesting ones, enabling cost minimization and maximizing performance in meeting needs (important topic of S11).The goal is to obtain some systematic solutions of the functions that the CPS must perform. The logic of the user's actions is also developed and finally defined.

Step 6 consists of the iterative process of evaluating, comparing, improving and selecting concepts. It starts with the preparation of the comparative selection matrix:several selection criteria are placed on one axis and the various concepts on the other. A reference concept is chosen to serve as a basis for assessing the remaining concepts. Afterwards, each concept is evaluated and scored. After the evaluations, the final classification of each one is calculated. These first steps result in a reduction in the number of concepts, but the *pruned* concepts must be reorganized and improved, through combinations with other concepts, so that, when included in the next iteration, no crucial solution fragments are lost. Finally, one or more concepts positioned at the top of the classification are selected, which have been refined with fragments of the remaining concepts [36]. Analysis: after S5,several different documents that describe alternative conceptual paths to satisfy the needs of the existing productive and operating system, should be in hand. For example, solution A could bet on a more robust MES, which requires greater investment. Solution B could bet on a simpler MES but with less features. Different alternatives must be evaluated and compared with the reference MES solution: the one that responds best to all criteria, although it may not be the cheapest and most appropriate solution. Thus, the referred tasks are highly applicable.

Step 7 is about concept testing, which consists of soliciting comments, opinions and feedback on a description of a product concept. It is closely related to prototyping (S12), because both invariably involve some kind of representation of the product concept, usually a prototype [36]. Analysis: having selected CPS alternatives with great potential to address a certain set of BM needs, it is useful to ask for feedback from future CPS users. Additionally, an investment-benefit analysis can be developed for the various alternative solutions.

Step 8 consists of defining final specifications. It includes developing technical and cost models of the product, initial specifications refining (trade-offs where necessary) and flowing down the specifications as appropriate [36]. Analysis: the satisfaction levels that were defined in S4 must be worked on, now that a final CPS concept is available. Details about CPS features and resources must be defined in S8. Many cost-versus-features trade-offs should be made to reach an optimized CPS solution.

Step 9, its goal is to develop a project plan which consists of a roadmap for the downstream development effort. It is first configured in Phase I although it is a dynamic output that evolves throughout the whole process. S9 includes several steps that use the tools to optimize the critical tasks path such as the Design Structure Matrix, PERT charts and *Gantt* maps [36]. Analysis: to build a successful CPS, the aforementioned tools must be used in CPSDD. A design task can be either a conceptual development task, or an actual construction or implementation of the CPS.

Step 10 consists of defining the product architecture following four steps: creating a schematic of the product; clustering the elements of the schematic; creating a rough geometric layout; identifying the fundamental and incidental interactions. Thinking of a product both in physical and functional terms is how it starts. The functional elements are the operations and individual transformations that contribute to the overall performance of the product. They are usually described schematically before being implemented in specific technologies, components or physical working principles. The physical elements of a product are the parts, components and assemblies that implement the product's functions. The physical elements of a product are usually organized into several major physical building blocks. Thus, the definition of the product architecture is the allocation of functional elements to physical blocks. The goal is to define the basic blocks in terms of what they do and describe their interfaces to the rest of the product. If this goal is successfully reached, the detailed design and testing of these components can be assigned to multiple teams, individuals and/or suppliers, so that the development of different parts of the product can be carried out simultaneously. It is important to define well the level of modularity to facilitate: changes in products; a more varied range of product models; the standardization of components; the optimization of product performance; and manufacturing capacity enhancement. The output of S10 includes product diagrams which describe the understanding of the constituent elements of the product, and rough geometric layouts created in two or three dimensions, using drawings, computer models, or physical models [36]. Analysis: S10 includes one of the most useful sets of methods for CPSDD. A CPS can also be dissected in functional and physical terms. Functional elements must be studied and outlined before thinking about specific hardware or software technologies. A CPS subsystem is made up of several component blocks and the three types of components (CC, PC, HC) must be considered. Thus, the definition of the CPS architecture is likewise the attribution of the functional features of a product to its physical building blocks. For example, to reach the first level C, "Connection", one of the development actions is "to acquire accurate data from the machines and their components", which requires the creation of a block of sensors which are allocated to a block of physical components for the raw data collection. This collection will be directed to another information system block that will process data transformation. And so on, not forgetting to focus on the interaction interfaces (HC-CC, CC-PC and HC-PC). The creation of these blocks allows the modularity of the CPS, which can be useful. These decisions may have implications for how the product can be changed and updated, in order to be aware of the needs and business progress, which are handled at the productive level and therefore in the CPS. Standardization facilitation is also convenient, so that an actuator can be used in multiple blocks (for instance). In conclusion, by following the S10 steps, the CPSDD would be clearly enhanced with helpful output.

Step 11 is all about product design which consists of four disciplines. 'Design for manufacturing' and 'robust design' include the most relevant methods for CPSDD. 'Industrial design' (ergonomic and aesthetic improvements) and 'design for environment' (reduction of environmental impact) are important but less prioritary [36].

Design for manufacturing (DFM) main goal is to reduce manufacturing costs while improving (or, at least, not inappropriately compromising) product quality, as well as development time and cost. The tasks are: estimating the manufacturing costs; reducing the components, assembly and supporting production costs; considering the impact of DFM decisions on other factors. DFM is an integrative method taking place throughout the development process and requiring inputs from across the development team. DFM decisions can affect product development lead time, product development cost, and product quality. Trade-offs will frequently be necessary between manufacturing cost and these equally important broader issues [36]. Analysis: for CPSDD this step would be called 'design for manufacturing and implementation', aiming to reduce CPS components acquisition costs, as well as construction and assembly costs. This goal is pursued while improving the CPS quality. Thus, the logic slightly changes although the tasks and its output are generally applicable. In fact, estimating manufacturing and implementation cost can be quite useful to guide and prioritize efforts to reduce the cost of CPS components and devices acquisition. Thus, the proposed information systems (list of components, estimates, models, etc.) would be useful.

Robust design includes a set of engineering design methods used to create robust products and processes. The tasks are: identifying control factors, noise factors, and performance metrics (S4, 8); formulating an objective function; developing the experimental plan; running the experiment; conducting the analysis; selecting and confirming factor setpoints. Among important output the parameter diagram stands out as it may help to understand the logic and systematize the information [36]. Analysis: a robust CPS works properly even in the presence of noise effects. If the guarantee of quality and reliability (among other requirements) of the final product is one of the main guidelines of the BM, CPS design must be robust, so that its production output is also robust. Thus, the noise factors of the machines, components and devices through which the CPS acts must be studied. For instance, a CPS tool automation without precision would be harmful instead of beneficial. After examining a factory cell with several machines and inputs of raw material or parts, several control and noise factors are identified in each of the machines and pieces to enter. Several human factors must also enter the equation. The objective function method may allow to optimize the CPS design. The test plans and subsequent analysis are also useful to concretize a robust CPS design.

Step 12 is all about prototyping. Prototypes can be usefully classified along two dimensions: (1) the degree to which they are physical as opposed to analytical and (2) the degree to which they are comprehensive as opposed to focused, and can be used for learning, communication, integration, and milestones. Physical prototypes are usually best for communication, and comprehensive prototypes are best for integration and milestones. The method is: defining the purpose of the prototype; establishing its level of approximation; outlining an experimental plan; and finally creating a schedule for procurement, construction, and testing [36]. Analysis: prototype construction and testing can be very useful for CPSDD. All across the spectrum of the two dimensions referred, CPS prototypes of its blocks of features could be built. Initially, virtual prototypes of physical identities or even physical processes can be developed. Simulations and digital twin logics of some blocks or subsystems of the process could be made. Thus, it would enhance the studying of software solutions with virtual simulations of the dynamics involved. As physical prototypes are developed and built, the computational features used in the digital twin should be used. Many of these physical prototypes, or at least some of their components or devices, may be used in the final CPS. Building a CPS can be costly, so the more it is virtually tested the better. CPS prototyping would facilitate an understanding of which devices and components properly function in the target environment and then examining the best alternatives. Prototypes are also important to make sure that a certain level (8C) has been reached, or a specific level of reliability has been achieved, or to even check that a capability actually works (CPSDD milestones).

Step 13 includes several project execution methods. Harmonized executions of well-planned projects (S9) depend on management actions along three vectors: use of task coordination mechanisms; supervision and evaluation of the project status; and correction of unwanted deviations from the project plan [36]. Analysis: these vectors are clearly applicable to CPSDD project execution so that the five reasons mentioned in section A are corroborated.

III. D. Conclusive analysis

Clearly, the vast majority of steps, logic and methods have a high level of applicability. Now, it is natural to make the following statement: being the CPS a technological concept [16], [17] and the core of the latest innovation revolution in manufacturing [26], following PDD instructions considering the CPS as the product under development could be extremely useful to increase performance of an established BM (BM enhancement is out of this article scope, although CPS integration may require new BM). It is also remarkable how this can be an approach that fills the gap identified in Literature: the lack of a methodology that focuses on designing a CPS that fits and helps the company to improve its performance.

Thus, on section IV a new methodology is proposed to further elaborate this approach.

IV. Methodology proposal

The proposed methodology for CPSDD consists of two main parts: 'conceptual design of CPS', and 'from concept to implementation projects'. Based on previous work by Machado [37], a case study of a wood processing company was prepared in order to present output examples for some of the proposed steps of the methodology. For instance, the value chain of Company A's main business is exposed in Figure 4.

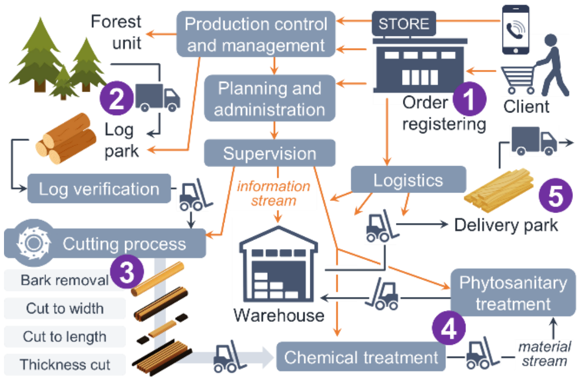

Figure 4 – Value-chain for Company A's business.

Company A was diagnosed with some *pain-points* and improvement opportunities such as inefficient logistics, communication problems, low machine availability, lead-time higher than takt-time and many others [37]. Thus, the goal is also to understand how CPSDD could help to mitigate some of these difficulties.

The proposed methodology is presented in Figure 5. On top, part one is presented throughout several steps adapted from PDD (**'S#.'** acronyms). Figure 5 includes also simple examples of what could be the company's output of some steps. The conceptual architecture of the selected concept A is qualitatively illustrated in Figure 6. Below in Figure 5, part two stands for the implementation of the result of part one, which may consist of several projects depending on the complexity of the CPS concept selected (quantity of features to implement). Part two consists of an integration of MBD [32] and PDD. The 10 steps enunciated before are now referred as 'activities' (**A#**).

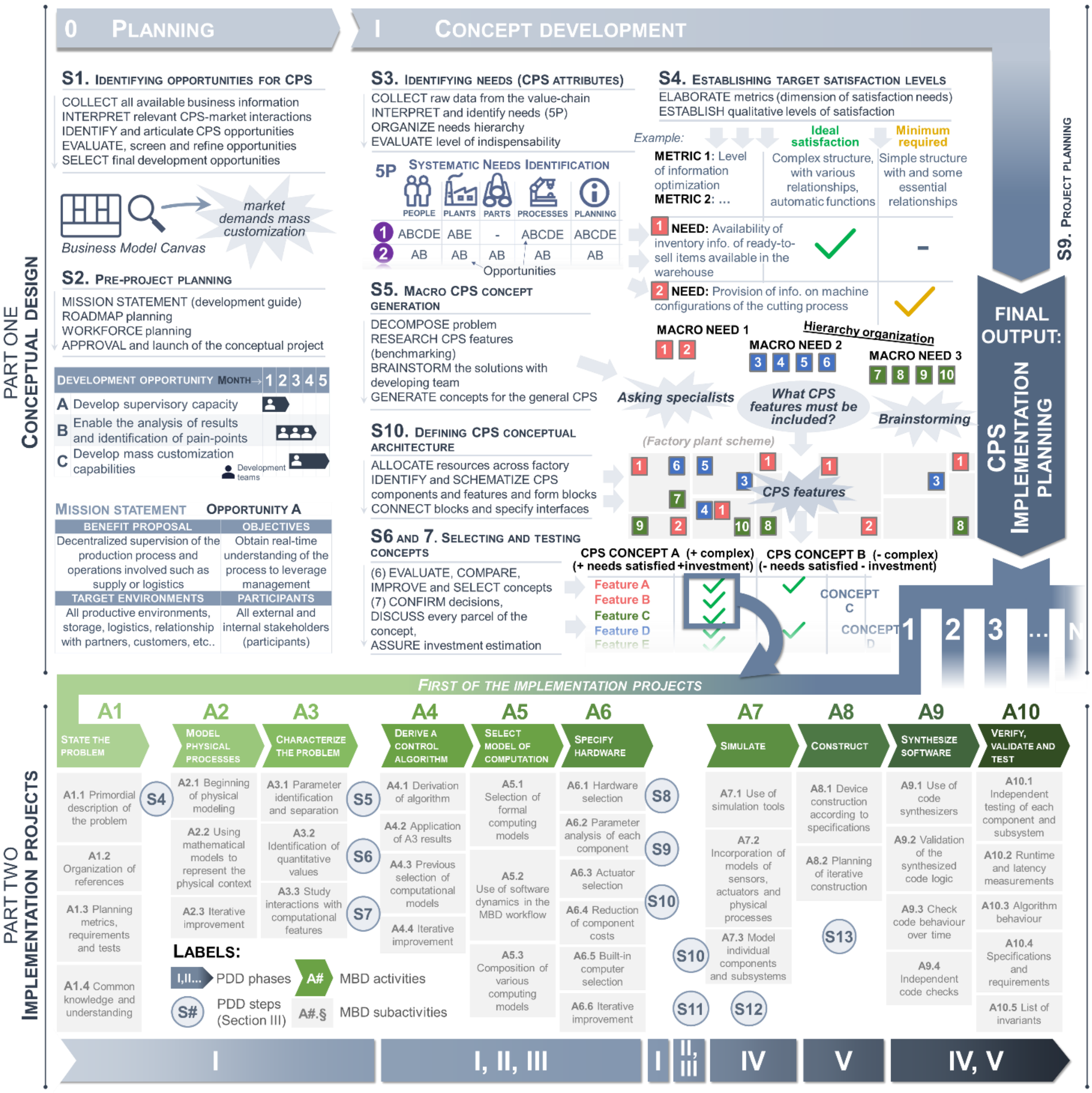

Figure 5 – Schema for the proposing methodology

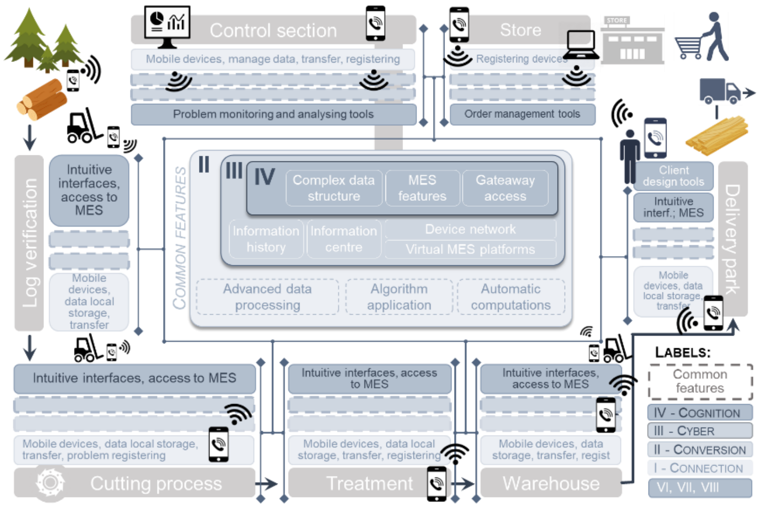

Figure 6 – Conceptual architecture for Concept A.

After analysing different methodologies, MBD stands out for including most of the topics of the remaining approaches and for being the most complete of them. That is why it is the chosen one for introducing CPS-PDD integration. Thus, throughout part two (Figure 5) it is explained how the complementarity between methodologies can help a better implementation of the selected CPS concept.

V. Conclusion

Clearly, despite involving some complexity, the use of a systematic product development strategy applied to the CPS enables the detailed identification of the essential features, resulting in a more adjusted CPS.

This new approach allows maximizing the benefits of the role of a CPS in improving business performance. Achieving this goal does not necessarily imply to develop a complex CPS with features of high 8C levels such as autonomous robots or machine learning.

Thus, to maximize the benefits that a CPS can leverage, a project of CPSDD consisting of a conceptual design that results in several sequential implementation projects can be useful.

[1] X. Yao, J. Zhou, Y. Lin, Y. Li, H. Yu, and Y. Liu, “Smart manufacturing based on cyber-physical systems and beyond,” *J. Intell. Manuf.*, vol. 30, no. 8, pp. 2805–2817, 2019.

[2] N. Jazdi, “Cyber physical systems in the context of Industry 4.0,” *Proc. 2014 IEEE Int. Conf. Autom. Qual. Testing, Robot. AQTR 2014*, pp. 2–4, 2014.

[3] Y. B. Reddy, “Cloud-based cyber physical systems: Design challenges and security needs,” *Proc. - 2014 10th Int. Conf. Mob. Ad-Hoc Sens. Networks, MSN 2014*, no. October 2015, pp. 315–322, 2014.

[4] Networking and Information Technology Research and Development, “CPS Vision Statement,” 2015.

[5] T. Sanislav and L. Miclea, “Cyber-physical systems - Concept, challenges and research areas,” *Control Eng. Appl. Informatics*, vol. 14, no. 2, pp. 28–33, 2012.

[6] R. Rajkumar, I. Lee, L. Sha, and J. Stankovic, “Cyber-physical systems: The next computing revolution,” *Proc. - Des. Autom. Conf.*, pp. 731–736, 2010.

[7] V. Alcácer and V. Cruz-Machado, “Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems,” *Eng. Sci. Technol. an Int. J.*, vol. 22, no. 3, pp. 899–919, 2019.

[8] Bitkom, VDMA, and ZVEI, *Implementation Strategy Industrie 4.0*, no. January. 2015.

[9] R. Lichtblau, Karl; Stich, Volker; Bertenrath, “Industrie 4.0 Readiness,” 2015.

[10] H. Lasi, P. Fettke, H. G. Kemper, T. Feld, and M. Hoffmann, “Industry 4.0,” *Bus. Inf. Syst. Eng.*, vol. 6, no. 4, pp. 239–242, 2014.

[11] M. Hermann, T. Pentek, B. Otto, and T. * Pentek, “Design Principles for Industrie 4.0 Scenarios: A Literature Review,” *49th Hawaii Int. Conf. Syst. Sci.*, no. January 2015, p. 16, 2015.

[12] M. Hermann, T. Pentek, and B. Otto, “Design principles for industrie 4.0 scenarios,” *Proc. Annu. Hawaii Int. Conf. Syst. Sci.*, vol. 2016-March, pp. 3928–3937, 2016.

[13] P. Zheng *et al.*, “Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives,” *Front. Mech. Eng.*, vol. 13, no. 2, pp. 137–150, 2018.

[14] A. Ahmadi *et al.*, “Evolution of 3C - Cyber-Physical Systems Architecture for Industry 4.0,” *8th Work. Serv. Orientat. Holonic Multi-Agent Manuf. (SOHOMA 2018)*, no. May, 2018.

[15] D. Gorecky, M. Schmitt, M. Loskyll, and D. Zühlke, “Human-Computer-Interaction in the Industry 4.0 Era,” pp. 289–294, 2014.

[16] L. Bibby and B. Dehe, “Defining and assessing industry 4.0 maturity levels–case of the defence sector,” *Prod. Plan. Control*, vol. 29, no. 12, pp. 1030–1043, 2018.

[17] A. Amaral, “A Framework for assessing manufacturing SMEs Industry 4.0 maturity,” 2019.

[18] E. A. Lee and S. A. Seshia, *Introduction to Embedded Systems: A Cyber-Physical Systems Approach*. 2015.

[19] E. A. Lee, “Cyber physical systems: Design challenges,” *Proc. - 11th IEEE Symp. Object/Component/Service-Oriented Real-Time Distrib. Comput. ISORC 2008*, pp. 363–369, 2008.

[20] A. R. Al-Ali, R. Gupta, and A. Al Nabulsi, “Cyber physical systems role in manufacturing technologies,” *AIP Conf. Proc.*, vol. 1957, no. April 2018, 2018.

[21] L. Monostori *et al.*, “Cyber-physical systems in manufacturing,” *CIRP Ann.*, vol. 65, no. 2, pp. 621–641, 2016.

[22] M. Burns, C. Greer, D. Wollman, and E. Griffor, “Cyber Physical Systems and Internet of Things in Industry,” pp. 2839–2840, 2019.

[23] S. Thiede, M. Juraschek, and C. Herrmann, “Implementing Cyber-physical Production Systems in Learning Factories,” *Procedia CIRP*, vol. 54, pp. 7–12, 2016.

[24] H. J. La and S. D. Kim, “A service-based approach to designing cyber physical systems,” *Proc. - 9th IEEE/ACIS Int. Conf. Comput. Inf. Sci. ICIS 2010*, pp. 895–900, 2010.

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

[26] J. R. Jiang, “An improved Cyber-Physical Systems architecture for Industry 4.0 smart factories,” *Proc. 2017 IEEE Int. Conf. Appl. Syst. Innov. Appl. Syst. Innov. Mod. Technol. ICASI 2017*, vol. 10, no. 300, pp. 918–920, 2017.

[27] L. Hu, N. Xie, Z. Kuang, and K. Zhao, “Review of cyber-physical system architecture,” in *Proceedings - 2012 15th IEEE International Symposium on Object/Component/Service-Oriented Real-Time Distributed Computing Workshops, ISORCW 2012*, 2012, pp. 25–30.

[28] Y. Liu, Y. Peng, B. Wang, S. Yao, and Z. Liu, “Review on cyber-physical systems,” *IEEE/CAA J. Autom. Sin.*, vol. 4, no. 1, pp. 27–40, 2017.

[29] National Academies of Sciences Engineering and Medicine, “A 21st Century Cyber-Physical Systems Education,” *Natl. Acad. Press*, 2016.

[30] L. Pires, “Sistemas ciber-físicos: o futuro da Manutenção Industrial ?,” *Inst. Educ. Técnica*, no. November 2016, 2018.

[31] G. Karsai and J. Sztipanovits, “Model-integrated development of cyber-physical systems,” *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, vol. 5287 LNCS, pp. 46–54, 2008.

[32] J. C. Jensen, D. H. Chang, and E. A. Lee, “A model-based design methodology for cyber-physical systems,” *IWCMC 2011 - 7th Int. Wirel. Commun. Mob. Comput. Conf.*, pp. 1666–1671, 2011.

[33] E. A. Lee and S. Seshia, *Introduction to Embedded Systems - A CPS Approach*. 2017.

[34] V. Prasad and S. H. Son, “Design suite for deeply embedded cyber physical systems,” *ACM SIGBED Rev.*, vol. 5, no. 1, pp. 1–2, 2008.

[35] C. Zheng, J. Le Duigou, P. Hehenberger, M. Bricogne, and B. Eynard, “Multidisciplinary integration during conceptual design process: A survey on design methods of cyber-physical systems,” *Proc. Int. Des. Conf. Des.*, vol. DS 84, pp. 1625–1634, 2016.

[36] S. Eppinger and K. Ulrich, *Product Design and Development*, 5th ed. New York: McGraw-Hill, 2012.

[37] R. Machado, “Aplicação de MFCA e métodos lean para o diagnóstico e melhoria de sistema produtivo no setor metalomecânico,” Instituto Superior Técnico, 2019.