Design of a methodology to determine the specifications of a cyber-physical human system. Case study: supply chains

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Engineering Design Summary

Currently, the labor force is being affected by changes in the production systems presenting in the industry. These changes lead to employees being replaced by machines and robots. Because of this, there is a need to consider how technological advances are impacting workers, which remains as a vital resource in manufacturing companies. Therefore, Colombia is at a low level of technification, which means, there are numerous manual operations in companies, the study will focus on this knowledge gap, to improve integration of workers in cyber-physical systems in the country. To achieve the desired integration between humans and machines, this project proposes the creation of a methodology that aims to determine the specifications required in the configuration of a cyber-physical human system. Be part of the identification of the specifications that the system needs to reach to define the requirements of both the client and the product and considerations for the well-being of the human in the mention system. With the identification of these parameters, the characterization of the system is carried out to determine different alternatives of the components, structure, behavior, and dynamics, based on the systems modeling. In conclusion, the validation of the preliminary methodology created with experts and with the implementation is carried out of the system in a case study of the supply chain. Through the configuration of three Workstations according to the desired level of automatization, under a controlled simulation environment.

Key words: *cyber-physical human systems (CPHS), human-machine interface, methodology, decision-making process, mental workload, reaction times, human factor, supply chain, controlled simulation environment.*

1. Problem statement.

Due to rapid technological advances, manufacturing companies face major developments in the production systems present in the Industry. Consequently, the workforce is being affected by possibly being replaced by machines and robots, given the progress of industrial automation (Pinzone, Albè & Orlandelli, 2018). Because of this, there is a need to consider how this trend will affect workers, who remain a vital resource in modern production systems. These systems are immersed in a movement oriented towards a significant change in the industry and in the way, things are done today. Today, partially automated production systems are due to a new revolution known as Industry 4.0. This term of German origin is used to describe the start-up of intelligent factories and is driven by the introduction of digital technology in the industry. The Industry 4.0 paradigm and the issues associated with the digital transformation of the industry can be considered a special case of cyber-physical systems (CPS) (Mládková, 2018). CPS are systems of collaborative computing entities that are in connection with the world and physical processes (Boone, 2019).

The control architecture of a CPS integrates structures and behaviors of the system. Within the structures or control systems there are centralized and hierarchical, semi-heterarchical and heterarchical approaches. Meanwhile, the behavior of the system components depends on the level of intelligence that is given to each component present within the CPS (Trentesaux, 2009). The components of a CPS can be modeled by agents or by holons, among others. Each of these components is represented by the creation of a digital twin, where a virtual representation of a component or physical aspect is constructed. Now, when a process involves not only machines, but also human operators, this type of system is known as cyber-physical human systems (CPHS). CPHS consist of interconnected systems that share information with each other through space and time and allow other systems to connect and disconnect (Sowe, Simmon, Zettsu, De Vaulx, & Bojanova, 2016). When the human is involved in a digital twin, it can be integrated with holonic manufacturing systems. There are two architectures for human integration in holonic systems, these are: the holon architecture interface and the holon work architecture (IHA and WHA), respectively (Leuvennink, Kruger, & Basson, 2019).

For the WHA, a holon is defined in terms of the individual human worker. Each human worker is represented and managed by a dedicated holon. The holonic system can communicate directly with workers through their personal interfaces (Leuvennink, Kruger, & Basson, 2019). Therefore, this architecture is aimed at companies that understand the potential generated by the intersection and conjunction of the characteristics of the human resource and the elements of the computer system (Villalonga & Romero, 2018). Thanks to this vision, companies can benefit by becoming intelligent factories capable of adapting to new needs and can more efficiently allocate resources in their production processes. However, when companies make modifications to the current production process, workers may experience greater complexity in developing their tasks, therefore, they must be flexible in adapting to a more dynamic work environment (Fantini, Pinzone, & Taisch, 2018). However, although greater responsibility and technological control are required, the challenge of companies is to generate a work environment where the human remains a key card within a CPS and jointly consider the uniqueness of human work with machines within an integral framework. For this reason, in the emerging context of Industry 4.0, a great opportunity arises for workers to be part of an intelligent system to achieve the desired synergy (Steusloff, 2016).

The challenge for companies is how to govern this synergy and intentionally guide the process of integration of workers within CPS to move towards the desired scenario. Indeed, it is desired that manufacturing companies can create a computer-assisted user interface, also known as the human-machine interface (HMI). The HMI allows the work to be facilitated to the human, identifying alarm situations and intervening directly in the process through the execution of command actions (Katore & Bachute, 2016). The directive actions in an HMI are imposed by the worker, who sends information to the digital twin to be processed and obtain an action response through actuators. Every human operation must be understood within a work system. A socio-technical system is composed of activities and organizational processes that involve the relationship between the human and the machines. This conceptualization covers methods, tools and disciplines that allow to improve the conditions of the system. Ergonomics is one of the scientific disciplines that includes the interaction between workers and other elements of a system, applying techniques and methodologies for the design and optimization of working conditions and system performance. Within Ergonomics, there is an emerging branch called Cognitive Ergonomics that emphasizes the analysis of mental processes, such as perception, memory, reasoning and motor response to determine how they affect the interactions between workers and other elements of the system (Gomes, 2014).

When manual operations begin to be technified in the system, factors that influence the worker's behavior arise and can affect variables such as mental load, stress, decision making, operator performance, human reliability and times of reaction. It is particularly true that, in complex work environments, humans may experience stressful situations due to the large amount of information that their work demands. This stress situation is evidenced in physiological changes, for example, altered heart rate, encephalograms and galvanic response of the skin, which can affect the daily performance of workers' activities (Dong, Lee, Park, & Youn, 2018). The productivity of a worker can be affected because of the introduction to new technologies, therefore, the question of how these impacts current manufacturing companies is generated. Therefore, it is necessary to review how the manufacturing sector, both internationally and locally, is adapting to this change. In the first instance, perspective analysis of Latin America arises, mainly in Colombia, compared to other countries that handle technologies with different characteristics. According to statistics presented by the National Association of Entrepreneurs of Colombia (ANDI), technology is growing strongly in Colombia, especially within the automotive industry, robotics and automation (Ovalle, 2013).

With respect to industrial automation in Colombia, a study conducted by the Autonomous University of Manizales identified the technological gaps in industrial automation of companies in the metalworking sector in Colombia. The identification of existing automation levels was carried out where the higher the level of human intervention, the lower the level of automation and vice versa. The levels were identified in the different stages of the value chain: supply, production process, packaging and packaging, storage and logistics. The automation levels in 40% of the companies were average. 10% are among the world-class middle-high category and the remaining 50% have low levels of automation and a greater technological gap, due to the manual nature of value chain operations (Ovalle, Ocampo, & Acevedo, 2013). According to the results obtained regarding the failures in technological management of organizations in Colombia belonging to a specific sector, it was possible to identify that the country tends to have a low level of technification, which allows to conclude that, currently, there are still quite a few human operations in most of the productive processes of companies throughout the country. For this reason, this project will focus on this knowledge gap framed in a socio-technical system in Colombia, since little has been said about the integration processes of workers with cyber-physical production systems. This document highlights the possibility of improving the integration between human beings and intelligent manufacturing systems.

In view of the above, the intention of this project is to address this challenge by designing a methodology that involves all the specifications required for the configuration of a cyber-physical system that includes not only machines, but also human operators, that is, cyber physical human systems in manufacturing companies in Colombia. The validation of the functionality and replicability of the proposed methodological guide is intended to be carried out through the configuration of three work states, under a controlled simulation environment, with different levels of participation for the human according to the level of automation that is desired to be achieved. The purpose of the application of this project is framed in the following question: *What are the specifications necessary to consider the configuration of a cyber-physical human system to implement them within a methodology?*.

The problem discovered in this project that is intended to be resolved is that, from all the literary review carried out, it was found that there is not enough evidence to demonstrate the existence of a methodology that specifies the procedure for the configuration of a CPHS in manufacturing companies, mainly In Colombia. In this way, the benefits that come with the development of this project is to address the need of companies interested in creating a cyber-physical human system by providing them with an step-by-step instruction that they must follow to achieve this synergy in a way successful Additionally, the novel aspect that the creation of this methodology entails is that the considerations for the well-being of the human being are taken into account when engaging in said system, that is, it concentrates on the behavior of the human when he has the power to make decisions depending of the role it plays in the performance of the requested task.

2. Background.

Industry 4.0 is a trend towards where the industry is going, and its evolution depends on all the technological advances that have emerged over the years. With cyber-physical systems it is expected that modifications will be made in the manufacturing sector, which should know how to handle the changes that arise when introducing these systems. The challenge for the industry is to find the best way in which the process of integrating people into cyber-physical systems is adequate in which, both worker and machine, can be in the same process in a desired scenario (Fantini , Pinzone & Taisch, 2018).

Industry 4.0 brings with it the interaction between man and machine as one of the pillars for its development and implementation. Due to this, it is necessary to understand and analyze the repercussions in the collaborators of the companies when they are in a position that implies human-machine interaction. For this, there are several methods, which are responsible for measuring the level of mental workload that a person suffers while performing a task (Fallahi, Motamedzade, Heidarimoghadam, Soltanian, & Miyake, 2016). Currently, the mental workload and its analysis are a key point in the research and development of man-machine interfaces. This in order to find higher levels of comfort, satisfaction, efficiency and safety in the workplace, these being the most important objectives for ergonomics (Rubio, Díaz, Martín, & Puente, 2004). Additionally, to ensure the above objectives, it is necessary to regulate the tasks assigned to the operators so as not to generate in them sub loads or work overloads. Since they depend on the productivity of companies and the success of the implementation of Industry 4.0 within manufacturing companies.

In manufacturing systems, changes reflected by market requirements have been seen, which is why cyber-physical production systems have achieved greater benefits such as autonomy, self-organization and interoperability (Yao, Zhou, Wang, Xu, Yan & Liu, 2018). This makes it possible to combine the strength of the robot with the knowledge of the human, a trend that is emerging in the industry, due to the increasing requirements of manufacturing systems being flexible and knowing how to recognize drastic changes in market requirements. In Industry 4.0, there is a close relationship between the human being and the physical cyber systems, for the decision-making process, which has a variation according to the level of autonomy that the human has. This is achieved by establishing a VCA collaboration and autonomy vector (IEEE Technology and Engineering Management Society. Conference (2018: Evanston, Institute of Electrical and Electronics Engineers, & IEEE Technology and Engineering Management Society, nd), which identifies the degree of collaboration that exists between the human and the physical cyber systems during the decision-making process, which may vary depending on the level of automation of the machine in the decision-making process and the role that the human takes in the process. The following graph shows the different levels of VCA according to the variation in the degree of autonomy and the level of competences that the human being has, according to the variables used to measure the VCA, which are the level of autonomy in the X axis and the level of competence in the axis.

The problem discovered is that, the integration between technology and automation, what it seeks is for machines to perform tasks that humans previously developed. That is why we have tried to develop new systems that combine human and automation. As in the design of automation in man-machine systems, which focuses on cognitive tasks, which are based on previous work on human factors (Fantini, Pinzone & Taisch, 2018). Therefore, the decision-making process is referred to as a sequence of stages, in which the situation analysis, value judgment, planning and execution are found. This can be introduced in manufacturing systems by the processes that are handled in the sector. In order to perform the analysis in the decision-making process, the mental workload must be considered, it is necessary to use a measurement methodology, for this case there are two types. First, there are physiological measurements, which are manifested as a response of the body to certain stimuli, for example, the assignment of a task that generates cognitive effort. Secondly, there are subjective measurements, which are based on the perception that the person has regarding a task that is performed, achieved through methodologies that use surveys for this purpose. There are several methodologies that are used to measure the mental workload, either from the physiological point of view or from the subjective point of view. In the first case, the most important measurements are HR heart rate, electroencephalogram and galvanic response (Wu, Miwa, & Uchida, 2017). In the case of subjective measurements, the most important is the Nasa task load index, which, through the application of a questionnaire to an operator, allows a measurement of the mental workload that is generated in a person (Wu, Miwa, & Uchida, 2017). In studies carried out, there is a kind of methodology, in which it is sought to generate a relationship between mental load measurements, through physiological and subjective measurements (Fallahi, Motamedzade, Heidarimoghadam, Soltanian, & Miyake, 2016).

Depending on the type of workload, a controlled environment is designed that is focused on the type of workload that is of interest for its measurement. For example, if you are looking to perform mental workload measurements, you are looking to minimize physical activity, in order to face the measurements. Once the simulated controlled environment is designed, experimentation is carried out, causing the individual to perform a task that is of interest for evaluation. Given the above, as a first step, physiological measurements (heart rate, electroencephalogram, eye tracking, galvanic response, etc.) are performed during the task, in order to characterize the workload from a physiological point of view.

In work positions that involve decision-making by the operator, such as the traffic control center of a city, the physiological responses in the operators vary according to the complexity of the decision-making process (Fallahi, Motamedzade , Heidarimoghadam, Soltanian, & Miyake, 2016). In this way, physiological and subjective measurements were applied for several moments, depending on the level of traffic congestion, which generates conditions of stress on the worker, since the proper functioning of city traffic depends on their decisions. Additionally, it is evidenced that, at different traffic levels, the mental load measured from the physiological and the subjective, presents significant changes in the operator.

A flexible manufacturing system (FMS) is the one that provides certain levels of variations within a production line. When a product has some flexibility in its life cycle, it is considered as a flexible system. To verify that a manufacturing system is flexible, the following aspects should be considered: Variety of parts, Time change, Error recovery and New part test. A FMS allows for its capacity that the automatic production of different parts is flexible. Additionally, the flexible manufacturing system allows modeling techniques to be used, such as: mathematics, artificial intelligence, hierarchical method of decision making with multiple criteria, petri nets and simulation (Yadav, A., & Jayswal, 2018). Figure 3 shows seven of the most prominent design methodologies found with their respected criteria. These are considered the best practices of the methodologies for the design of processes that are compatible with the design of a methodology.

3. Objectives.

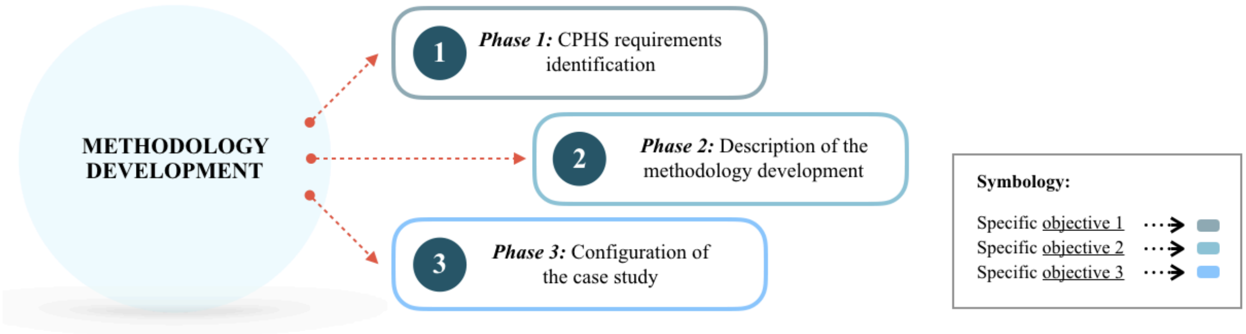
Design a methodology to determine the specifications of a cyber-physical human system, inspired by the best practices of the methodologies for design of existing engineering processes. Case study: human activity in decision making within a supply chain.

3.1 Specific Objectives:

- Identify the possible requirements of a cyber-physical human system.
- Create a methodology for the construction of a cyber-physical human system, based on the modeling of systems.
- Validate the proposed methodology through the emulation of a cyber-physical human system in a link in the supply chain.

4. Methodology development.

Figure Description of the document body phases.



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4.1 First phase: CPHS requirements identification.

The main purpose of this phase was the development of a document which, after identifying the requirements of a cyber-physical human system, it provides an approach to the requirements for CPHS that must be considered to develop a CPHS. **Annex A** shows a document called *Requirements for CPHS*. Considering a CPHS as a multi-agent system, these requirements were divided into six different groups according to the components of this type of system to show the CPHS requirements.

To identify the requirements of a CPHS, a literature review was carried out, in which it was found that the CPHS behaves as a multi-agent system (Wooldridge, 2009). These requirements were addressed in six different groups (types of environments, agents, human-machine interface, features of CPHS, HDE, and applications) according to the components of a multi-agent system Each of them tackles the CPHS from a different point of view depending on the company's needs. First of all, there are different properties of environments that might be analyzed depending on the complexity level of the CPHS. Table 1 shows a summary of different properties to be used when a company desire to design a CPHS based on the properties of environments in multi-agent systems.

Table 1 Summary of properties of environments.

Property	Description
Accesible	The information is complete and is available at all times without restrictions for the agent. It provides an easier manner to create agents that may operate effectively within the environment.
Deterministic	The environment in which any action has a single guaranteed effect.
Static	• This environment remains without changes, except for the performance of the agent's actions. • In this environment, its agents have to perform an information-gathering process in order to make decisions.
Discrete	A discrete environment is one that can be guaranteed to only ever be in a finite number of discrete states.
Episodic	This environment, the performance of an agent depends on a series of discrete episodes, with no link between agent performance and different episodes. The agent decides what decision to make based solely on the current episode and does not analyze further future episodes such as the reagent.

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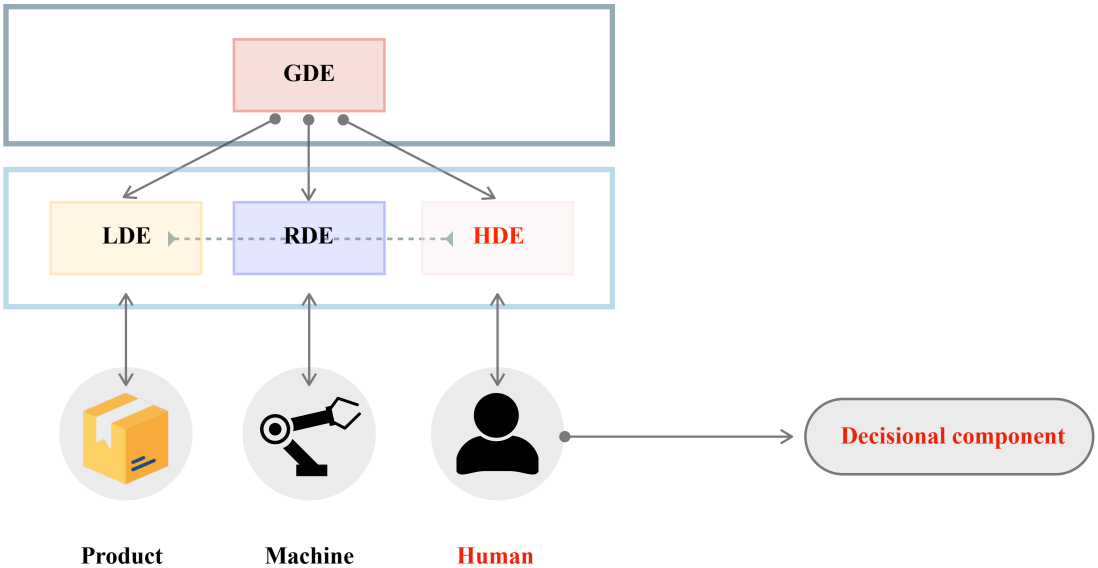
Then, the agent was considered as a group, taking into account its definition as a computer system located within an environment or atmosphere that can act autonomously in the environment to meet its design goals, its characteristics, and aspects of the interaction between agents and the environment. Thereafter, considering a CPHS as a multi-agent system, the characteristics of a human-machine interface were listed followed by the features of a CPHS.

Figure 1 Architecture of the CPHS.
Content from: *Cyber-Physical Production System with Human Fatigue Awareness (2019)*.



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Besides, regarding the human factor, a human decision entity was defined with its own characteristics. A Human Decision Entity (HDE) represents an individual human operator in the digital world in charge of the activities between the human tasks and the control system being these tasks of a physical or cognitive nature (see Figure 1). The communication of the HDE is done through physical and cognitive interphase in order to command posteriorly changes to human tasks (Paredes-astudillo, Jimenez, & Zambrano, 2019). Subsequently, it was identify the requirements that a company must considered, as follows.

- The sensing and monitoring of different human physical and cognitive indicators are indispensable in the configuration of CPHS.

- In the configuration of a CHPS, it is needed to identify: the effectiveness-oriented objectives, which corresponds to the achievement of the completion of the jobs, and the well-being-oriented objectives, which aim to minimize the degradation of the well-being (Paredes-astudillo, Jimenez, & Zambrano, 2019). Table 2 presents the possible objectives and indicators of the HDE that could be measured in a CPHS.

Finally, a list of possible applications of multi-agent systems was presented in which there are some uses that can be applied to a CPHS. The applications were classified into two different groups as shown in Table 3.

Table 2 A human decisional entity.
Content from: *Jimenez, Bekrar, Zambrano-Rey, Trentesaux, & Leitão, 2017.*

Effectivity-oriented objectives	Well-being oriented objectives
Productivity indicators: production to be made, earliness, tardiness, throughput time.	Balance cognitive and physical workload.
Primary results: improve in progress product and finalized product.	Cognitive and physical fatigue.
	Knowledge, skill and, abilities as cognitive (speed perception and memory), personality (emotional stability), and psychomotor (motion coordination)
	Well-being indicators: cognitive demand, physical demand, fatigue, frustration, electrodermal activity, heart rate, response time, etc.

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Table 3 Types of applications of agents.
Content from: *An Introduction to Multiagent Systems (2009).*

Distributed systems	Personal software assistants
Agents become processing nodes in distributed systems.	Agents play the role of proactive assistants
Special emphasis on multi-agent systems.	Special emphasis on individual agent systems.

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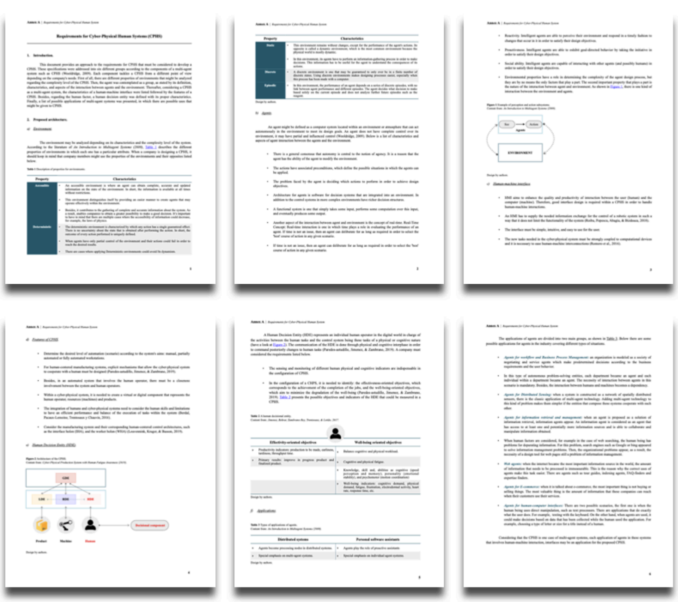
In light of the above, Figure 2 exposes the tangible creation of CPHS requirements. The document *Requirements for CPHS* represents the final result of specific objective 1.

Figure 2 Thumbnail view of the requirements's document content (Annex A).



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4.2 <u>Second phase</u>: description of the methodology development.

4.2.1 Declaration of design.

The main design of this project was to create a methodology that exposes the step-by-step process for cyber-physical human systems configuration in conventional manufacturing systems. The result was a process design methodology that provides a solution-based approach for solving industrial automation problems. This methodology will empower anyone to apply methods to solve complex processes as is the configuration of a CPHS in their companies. **Annex B** shows a document called *A Generalized Methodology to Develop CPHS for Production Environments* that provides an eight-stage methodology model to help companies implement partially and fully automated systems for its manufacturing processes.

4.2.2 Design process.

To build the methodology, it was necessary to identify the best practices of existing design methodologies. A methodological chart was made to point out the most relevant characteristics, objectives, and stages of each selected methodology as shown in Figure 3. Seven methodologies of process design were chosen (Co-Design, Design Thinking, Simple Design Cycle, ABET, Scientific Methodology, Complex Design Cycle, and Goal-Directed Design) to achieve an overview. Fourteen target factors (see 'Objectives' in Figure 3) emerged from them to provide a multi-step model for performing a complex process as is the configuration of a CPHS, but the process can be made easier by formalizing its steps. The methodology is intended to be comprehensive enough to cover the full range of performance for a process and stimulate reflective thought about the performance.

Figure 3 Summary of seven existing design methodologies.

Design methodology	Authors	Criteria													
		Sequence of steps for its development	*Expert Opinion*	*Team Work*	*Applicable in process design*	*Product specifications*	*Innovative solutions*	*Multidisciplinary work*	*Identification of necessities*	*Evaluation or validation process*	*Benchmarking*	*Product implementation*	*Iterative process*	*Validation Opportunity*	*Prototyping*
Co-Design (Tambien conocido como estrategia de diseño colaborativo)	(Gherardini, et al., 2019)	x	x	x	x	x			x				x		
Design Thinking	(Hehn & Uebernickel, 2018)	x				x	x	x							
Simple Design Cycle	(Adin et al., 2014)	x	x		x				x	x				x	
ABET	(ABET, 2015)	x		x	x	x			x	x				x	x
Scientific Methodology	(Jaime-Mirabal & Ladino-Luna, 2018)	x			x	x			x	x		x	x	x	
Complex Design Cycle	(Gherardini et al., 2019)	x			x	x			x	x		x	x	x	x
Goal Directed Design	(Laila, et al., 2016)	x			x	x			x			x			x

Symbology:

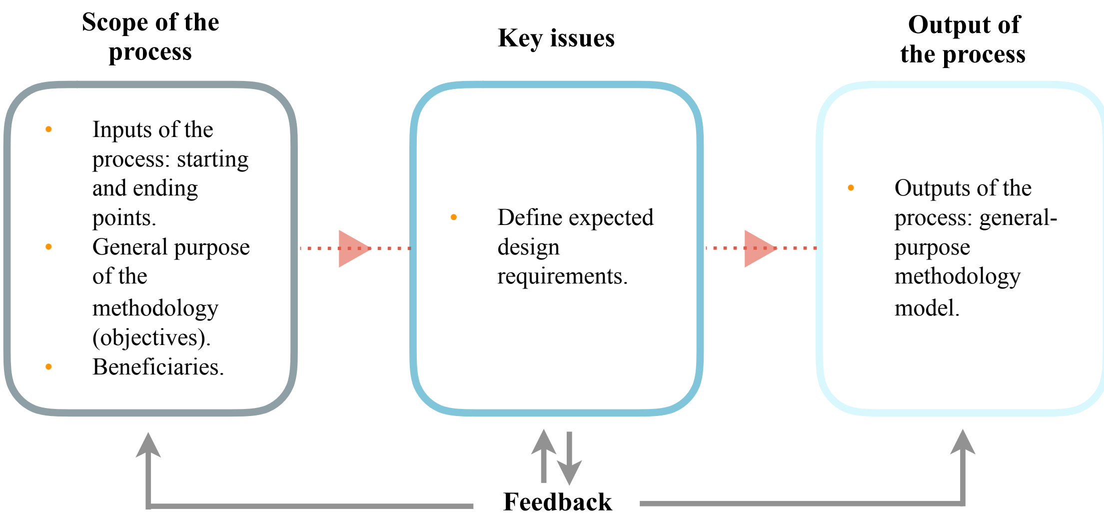
Seven methodologies of process design ····>

Fourteen target factors ····>

Design by authors.

The three steps that were considered to create the proposed methodology are based on *A Methodology for Creating Methodologies Research* (Science, 2006), which provides a step-by-step procedure for constructing methodologies (see Figure 4). The first one was about setting the scope of the process by establishing its starting and ending points as well as identifying the purpose and who benefits from it. The second step was to identify key issues and to set criteria that will be used to assess the quality of the process and its results. The last step was to organize the process into a methodology by logically ordering the steps, adding feedback loops.

Figure 4 Description of the process to create the proposed methodology.



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Once executed the three steps mentioned in Figure 4, the goal was to have the minimum number of steps while at the same time keeping each step manageable. Further, it was important to assume the mindset of a person performing the methodology for the first time. This was achieved by executing the process using the methodology as a guide. It is worth mentioning that as the methodology was tested, it was paid attention to any confusion that a first-time user may experience in performing each step and it was thought how the step might be rewritten to make it clearer.

Once the methodology was deemed sound and it achieved the objectives identified in Step 1, it was asked both an expert (the director and associate members of the Industry 4.0 Research Seedbed) and a novice (industrial engineering students) to test the methodology. Besides, the effectiveness was tested by choosing a context in which to facilitate to measure performance in "real-time". The goal at this step was to improve the quality of the methodology as seen both in the effectiveness of following the methodology and in the product that results. For this particular case, the methodology was tested within the manufacturing stage of the supply chain (see the third phase). Finally, it was collected the data from the experience and it was ensure to ask the participants to assess every step while the activity is being facilitated.

In light of the above, Figure 5 exposes the tangible creation of the methodology (Step 3). The document *A Generalized Methodology to Develop CPHS for Production Environments* represents the final result of the engineering design component proposed. However, to a better understanding of the proposed methodology, the application process of the methodology is summarized in Figure 6.

Figure 5 Thumbnail view of the methodology's document content (Annex B).

Design by authors.

4.2.3 Performance testing.

To validate the proposed methodology, an emulation of a cyber-physical human system was created as a case study of this study. It is based on a supply chain manufacture link emulated in the Industrial Automation Technological Center (CTAI) in the Pontificia Universidad Javeriana (Bogotá, Colombia). For better knowledge about performance testing, the 'Third Phase' provides a full description of the tests that were performed to ensure that the methodology meets the performance requirements. Furthermore, this phase shows the analysis of the data that resulted from the performance tests.

4.2.4 Design restrictions.

The objective of this section is to demonstrate the methodology complies with the general restrictions listed in the Degree Project. The restrictions were classified into three types, (A) restrictions that may limit the design, (B) restrictions for implementing the proposed case study, and (C) restrictions of an academic nature that limit the level of experience and learning of volunteers who are recruited for the study. Table 4 shows a comparative table to demonstrate that the process respects the stipulated design restrictions regarding type A.

Figure 6 The application process of the methodology.

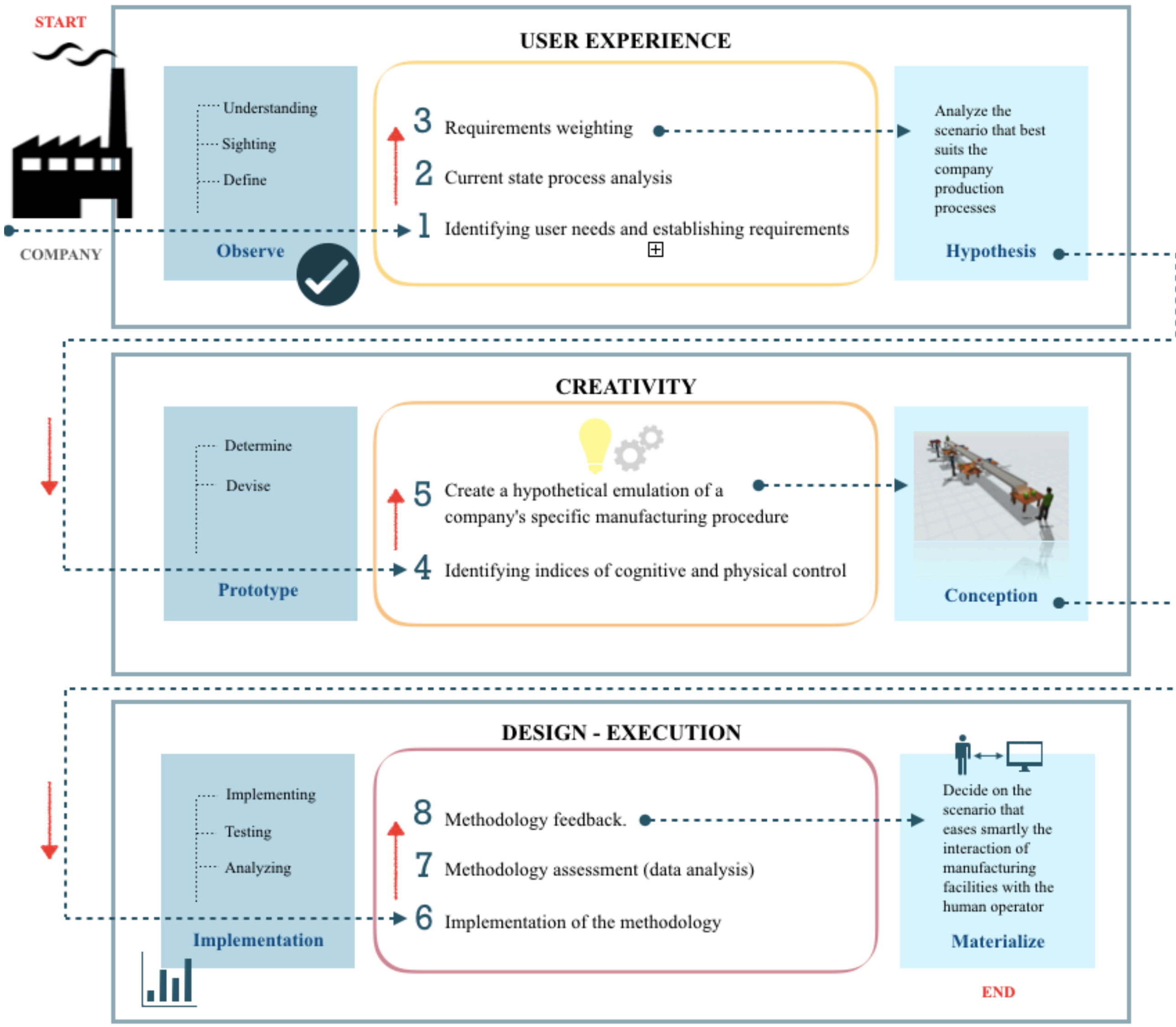

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Table 4 Comparative table of the design restrictions type A.

Restriction type	Description	How the methodology complies with the restriction?	Fulfillment percentage
A - #1	The design of the methodology is based on the modeling of Lemoigne Systems.	The design of the proposed methodology was conformed to the design and modeling characteristics regarding Lemoigne Systems.	100%

Restriction type	Description	How the methodology complies with the restriction?	Fulfillment percentage
A - #2	The methodology will be designed to be implemented in a case study of a supply chain, with the collaboration of a group of engineering students.	The case study created is based on a manufacturing link's emulation in the supply chain. This emulation is composed of two workstations with a single machine each (i.e. M1 and M2) and its respective HDE, placed and connected through a material transportation system. Therefore, each HDE was performed by a volunteer within a sample of 30 people (volunteers recruited from The Pontificia Universidad Javeriana), all of them were the collaborators of the study.	100%
A - #3	The design of the methodology is designed to offer a service, but not a tangible product.	This was achieved by executing the process (case study) using the methodology as a guide (see **Annex B**).	100%
A - #4	In fully manual or automated processes, the proposed design cannot be implemented. The methodology is designed to be applied to cyber-physical systems that contemplate human intervention.	The methodology was designed to be implemented in partially automated manufacturing systems, which are characterized by having a certain percentage of collaboration for the human operator in terms of task control.	100%
A - #5	For both types of validation, a replica can only be made for the time and scope of the degree project.	Only one case study was created and executed to validate the performance and design of the methodology (see **Annex C**). In addition, the proposed methodology was tested and approved by the director and associate members of the Industry 4.0 Research Seedbed (experts).	100%
A - #6	Only one iterative process can be done for the corrections that arise from both validations.	Besides of as mentioned above, Step 2 of the 'Design process' regards the iterative procedure to improve the quality of the methodology as seen both in the effectiveness of following the methodology and in the product that results.	100%
A - #7	This methodology will serve to create the human cyber-physical system of conceptual engineering and not detailed engineering.	The design of the proposed methodology considered the manufacturing system and their corresponding human-centered control architectures, such as the interface holon (IHA), and the worker holon (WHA), which regards to conceptual engineering.	100%

Design by authors.

4.2.5 Need for this methodology.

It should be mentioned that it is a complex process to create a methodology, but the process can be made easier by formalizing its steps. *A Generalized Methodology to Develop CPHS for Production Environments* is intended to help companies configure human-centered cyber-physical systems in their manufacturing processes. This methodology promises to be comprehensive enough to cover the full range of performances for the process and stimulate reflective thought about its performance. The proposed methodology is classified as a discovery analysis due to the absence of an a-priori model.

4.3 Third phase: configuration of the case study.

4.3.1 Design statement.

In order to validate the proposed methodology, an emulation of a real assembly line was created considering a manual activity of human operators in which task load increases the mental effort of the operator. This case study was centered on a manufacturing link's emulation in the supply chain. **Annex C** shows a document called *Guidelines for conducting the case study: a manufacturing control system in the supply chain* that explains in detailed the carrying out of the study.

The case study was conducted and tested in two moments. The first was the execution of a pre-test (i.e. pilot test), in which the experimenters were able to observe the reaction of volunteers performing the labeling tasks assigned. Meanwhile, it was identified whether the operators could handle the labeling procedure while being connected to the galvanometer. Besides, this pilot test aimed to determine the adequate number of references to be labeled per operator during the real assembly line. A list of possible recommendations for the final experiment was created to easy the establishment of the design requirements to be considered. Some of the decisions made were a) determine the location of the conveyor belts, b) decide which part of the operator's hand to place the galvanometer, and c) the shipping frequency at which the references should enter the system. The second moment was the development of the final tests considering the recommendations mentioned above.

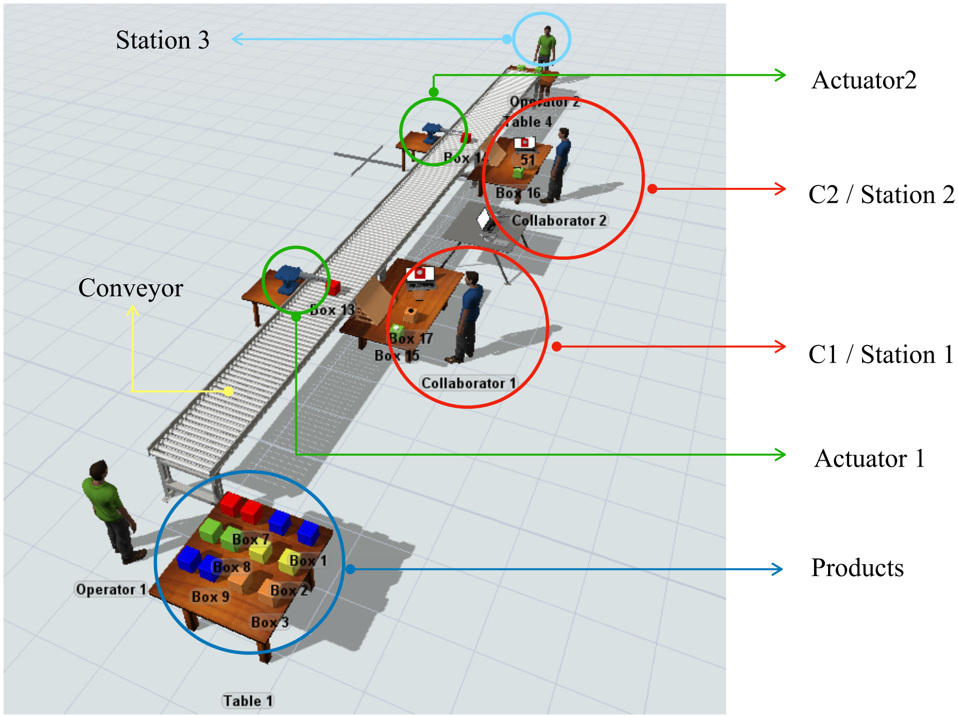
4.3.2 Design process.

To build the case study, an emulation of the proposed human-centered manufacturing system was designed. This flexible manufacturing system (FMS) considered a manual labeling station managed by two human operators working in parallel. The study was assembled in the Industrial Automation Technological Center (CTAI) at the Pontificia Universidad Javeriana (Bogotá, Colombia). This emulation is composed of two workstations with a single machine (actuator) each, and its respective HDE (i.e. C1 and C2), placed and connected through a material transportation system (conveyor).

This FMS is able to label one type of product with five references, depicted in colors (Red, Green, Blue, Yellow, and Light Brown), where each has a specific type of label (e.g. black or white) depending on the product's reference. For processing the references, a wooden cube (the physical representation of the product) enters the FMS and moves through the transportation system to be labeled by the operators. As mentioned above, an emulation of a real assembly line was created considering a manual activity of human operators in which task load increases the physical and cognitive fatigue of the operator. The objective of this system is to process a fixed production order and the KPI metric is and the electric current every 0.5 seconds (i.e. GSR in µSiemens). Figure 7 illustrates the FMS used.

To validate the potential of this proposal and the understanding of the methodology, various experiments in the assembly line were conducted. The main goal of this case study was to compare stages of automation to explore the reactiveness of the system with the human-machine integration in both C1 and C2. For that purpose, three scenarios were designed to compare the proposed re-allocation of the task and a control no-reallocation scenario (see Table 1 shown in **Annex C)**. For each scenario, a percentage of decision-making was measured for the two types of agents (please verify the percentages in **Annex B**-Figure 3). This study considered a sample of 30 collaborators for being considered human operators in the assembly line. The volunteers were recruited from the Department of Industrial Engineering of Pontifical Xavierian University. Groups of 2 people were formed to execute the production order for Scenario A, B, and C (see Section 2 in **Annex C**). The used application for this case study is process analysis, classified as a discovery analysis due to the absence of an a-priori model.

Figure 7 Illustration of the manufacturing case study (simulation design on FlexSim).



Design by authors.

On the other hand, a brief description of the FMS configuration is explained as follows. However, the detailed labeling process execution is documented in **Annex C**-Section 4, as well as the objective of the FMS proposed (see **Annex C**-Section 3). The labeling process starts when the Operator 1(see Figure 5) allocates the task to each station (i.e. Station 1 and Station 2). Once the Operator 1 enters a reference to the conveyor belt, this is transported to Station 1 or Station 2 depending on the Operator 1 decision. When the reference is about to arrive at the station, a single effect pneumatic cylinder dispenses the product to its respective collaborator to start the labeling process required. After the product being dispensed, the human operator task is to place the first label on the greater length of the cube and the second label should be located on the opposite side of the first one. Once collaborators have finished the labeling process of references, each operator must place the reference labeled in the corresponding storage for that type of labeling. Figure 8 illustrates the real assembly line, workstations, products, and human operators for an instance.

Figure 8 Illustration of the real manufacturing case study. Photography by authors.

4.3.3 Performance requirements.

The performance requirements of the methodology's case study design were as follows:

- The design must be replicable, reproducible, and affordable. This was fully fulfilled since the methodology may be used in any manufacturing process of a company.

- The design of the methodology must be understandable to users. The effectiveness was tested by choosing a context in which to facilitate to measure performance in "real-time", this was the case study. This requirement complied by asking both an expert (the director and associate members of the Industry 4.0 Research Seedbed) and a novice (industrial engineering students) to test the methodology. The volunteers of the experiment were asked to assess every step while the activity is being facilitated. This feedback resulted in 90.7% of the people fully understanding the methodology, a 4.3% of people almost completely understood the methodology and the remaining 5% did not understand the methodology.

- The design of the methodology must guarantee to meet the majority of company's needs. Therefore, the methodological guide starts by identifying and gaining an empathic understanding of the problem the user is trying to solve.

- Once the company follows all the steps provided for the methodology, it must be guaranteed that the company could implement the CPHS for its current manufacturing process. As a result, the design of the methodology proved to be a general-purpose methodology in which various scenarios of possible hypotheses, indices of cognitive and physical control, and measuring types of equipment were explained. This aims to support companies in solving industrial automation problems regarding their specific needs.

- The measuring equipment used for the case study proved to not being invasive for the collaborator. For that reason, the proposed tool in the methodology guaranteed not causing physical or emotional damage to people in the study.

- It is important to highlight that the test duration was reasonable and complied with the estimated time interval in the pilot test requirements. Consequently, the time factor was considered insignificant in the data collected during the test.

- Regarding the space conditions, the case study was executed under appropriate conditions in terms of lighting, temperature, and noise.

4.3.4 Performance test.

Regarding the data collected in the case study, a descriptive analysis of the data was developed through the Cassy Lab 2 software. This aimed to obtain relevant information from the sample in order to acquire significant conclusions of the test. On the other hand, it was performed an analysis of variances to validate the hypotheses raised in the methodology, and consequently, a simultaneous study of the factors that influenced the test of the case study. The section 'Results' provides a complete explanation of the data analysis collected in the experiment.

4.3.5 Design restrictions.

The objective of this section is to demonstrate the case study complies with the general restrictions listed in the Degree Project. Table 5 shows a comparative table to demonstrate that the process respects the stipulated design restrictions regarding types B and C.

Table 5 Comparative table of the design restrictions type B and C.

Restriction type	Description	How the methodology complies with the restriction?	Fulfillment percentage
B - #1	For reasons of time and scope of the project, with respect to the level of automation, only three scenarios can be established to identify the level of decision-making of the worker, according to the role he plays.	The case study was developed under the configuration of three scenarios, such as manual, semi-automatic and automatic. Each scenario is characterized by presenting a certain level of automation, which assures a difference between them.	100%
B - #2	The scenarios must be simulated within a controlled environment.	The simulation environment presented the same environment conditions during both the pilot test and the final test, thus, no alterations in the data were generated when measuring.	100%
B - #3	The environmental conditions lighting, temperature and noise of the environment must be typical of a real workspace.	As the case study was carried out in the Industrial Automation Technological Center (CTAI), the environmental conditions of the space are proper from the academic environment. Consequently, lighting, temperature, and noise were considered similar to a working environment.	100%
B - #4	The controlled environment where the simulation of the scenarios will take place cannot be changeable. Therefore, it is necessary to have a space where several jobs can be put online for simulation and, even more important, to have that space available for a whole week.	Both the pilot test and the final test were executed at the CTAI. The instruments and tools used for the experiment remained the same for both studies.	100%
B - #5	Volunteers must enter the controlled environment after having a period of 5 minutes of relaxing.	Before starting the experiment, a format with the test instructions were given to the volunteers. While reading and understanding the test conditions, 10 minutes was granted to do so.	100%
B - #6	There are restrictions of the human being in terms of limited response capacity that are based on age, learning level, fatigue status, personality characteristics, attitudes towards a task, emotional instability, sleep disturbances and psychosomatic alterations (Mandrick, Peysakhovich, Rémy, Lepron, & Causse, 2016). For this reason, the study requires that volunteers recruited for the validation of the methodology are healthy, that is, without any medical diagnosis that may disturb it.	It is worth mentioning that experiment volunteers were under the same mental and physical conditions to perform the test. This aimed to collect data without alterations due to illness, age, learning ability, fatigue, and personality status.	100%
C - #1	Volunteers must be active Industrial Engineering students of the Pontificia Universidad Javeriana	This study considered a sample of 30 collaborators for being considered human operators in the assembly line. The volunteers were recruited from the Department of Industrial Engineering of P Pontificia Universidad Javeriana	100%

Design by authors.

4.3.6 Compliance with standard.

The design of the methodology was fully accomplished since all the objectives were achieved as proposed. The characteristics required to apply the case study such as environmental conditions, temperature and lighting were the same for data collection. Besides, it was taken into account that the test volunteers were people of similar ages and maintained the same level of learning.

From the above, it was allowed to obtain a quantity of 261 data per person, preventing biases in the measurement of data and generating a lower percentage of error and reliability in the information. This aimed to analyze the information easily maintaining the same standards previously established. At the time of performing the information analysis it was observed that, when generating a graph of the galvanic response vs. time, volunteers present a similar trend between each pair of curves. This reflects that the data maintained the same cycle and validate that the environment where the test was carried out maintained the same standards and characteristics specified throughout the data collection process. Furthermore, this proved that the methodology was comprehensive enough to cover the full range of performances for the process and stimulate reflective thought about its performance.

5. Results.

This module introduces a methodology for cyber-physical human systems configuration in manufacturing systems. Within the literature reviewed, it was not found a model that provides companies a configuration detailed guide to ease smartly the interaction of manufacturing facilities with the human operator. Therefore, the proposed methodology was classified as a discovery analysis due to the absence of an a-priori model.

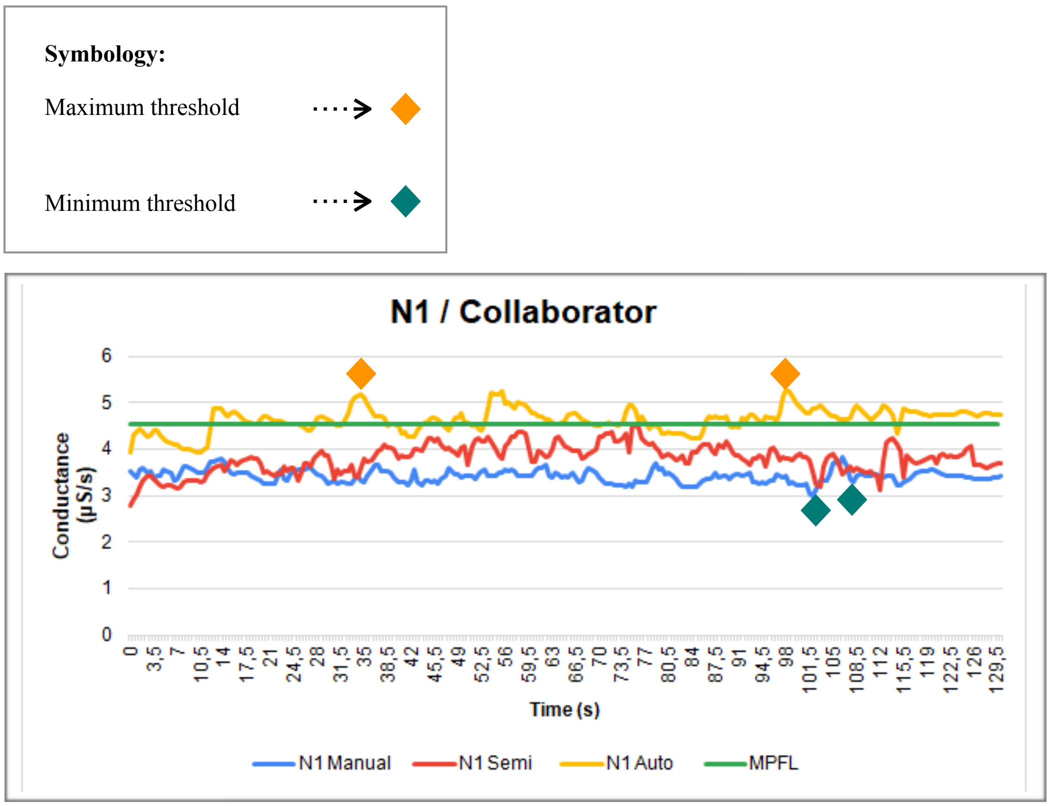
The document *A Generalized Methodology to Develop CPHS for Production Environments* represents the final result of the engineering design component proposed. This document provides a general-purpose methodological guideline to help companies implement partially and fully automated systems for its manufacturing processes. Besides, the steps considered within the methodology allowed users to gain a wider understanding of solving complex processes as is the configuration of a CPHS in their companies. The proposed model distinguished itself from others by adding an application case example for each implementation stage. This guaranteed that users internalized some of the steps with repeated use and from following them closely while using the methodology in a real-life context.

According to the design of the methodology, a validation of this was carried out, through a case study in a link in the supply chain, specifically in the labeling process of a company, in which two order orders were handled references on one level and on the other level five references were handled. The test included the emulation of a cyber-physical human system in the laboratory of the industrial automation technology center. For the development of this, samples were taken from 30 individuals who underwent six tests. These tests consisted of individuals having an interaction with the system. This interaction varied depending on the scenario and the level, at which the individual had to make different decisions depending on the challenges that he/she had to assume during the labeling process. The test was conducted under three scenarios (Manual, Semi-automatic and automatic) and each scenario had two levels, as mentioned above. Besides, for everyone, 261 data were obtained for each level and each scenario. Therefore, as the value of data obtained exceeds 30 data, the assumption of the Central Limit Theorem (CLT) is made, which in turn allows us to assume that they are distributed normally for each scenario and each level.

To verify the data that was obtained, the data obtained per person was plotted in two graphs, one for each level, in which it can be observed how the trend of the galvanic response of each person was in the three scenarios in each level. This allowed verifying which scenario generates greater incidents in the person. As it was obtained in the literary review, it is known that the galvanic response is a predictor of stress in people, thus, this may generate an impact on the performance of employees while performing their tasks at work. As shown in Figure 9 and Figure 10, it is identified which were the threshold of each scenario, which represents the the maximum and minimum critical points to the graph. This considers a higher or lower level of stress, depending on the limit observed. These were generated by a stimulus because of the tasks that were being performed during the process of labeling the cyber-physical human system.

By way of example, it was chosen an HDE (Collaborator 14) in order to explain the results obtained. For that case, it was observed that the collaborator's maximum critical points in level I (N1) were 5,29 and 5,26 µS/s, which occurred when the decision making and the reaction time of the moment were critical for the person. Being the cause of a prolonged effort for a certain time. In the opposite case, which is the minimum critical points that were the following 2,78 and 2,91 µS/s, it was analyzed that these moments are when the operators generates a lower level of stress, therefore, his/her performance tends to improve and does not affect their work performance. The mentioned information is presented in Figure 9.

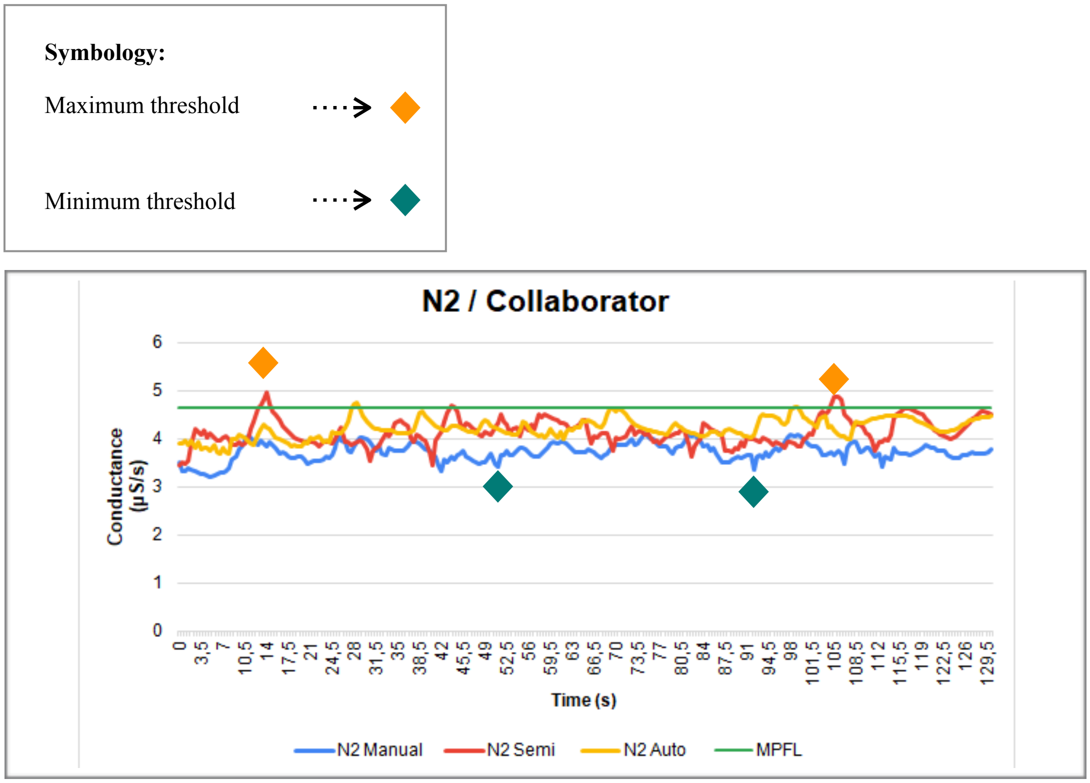
Figure 9 Galvanic response in collaborator 14 for Level I.



Design by authors.

Evenly, the same analysis may be observed for the collaborator at level 2 (N2). In this case, the collaborator obtained as maximum thresholds 4,95 and 4,86 µS/s, and as minimum thresholds 3,20 and 3,22 µS/s. This indicates the levels of stress that the employee handled during the labeling process at this level of difficulty, as shown in Figure 10.

Figure 10 Galvanic response in collaborator 14 for Level II.



Design by authors.

Furthermore, with the 30 samples obtained from the case study, this data was statistically analyzed to verify the hypotheses. Which said that the null hypothesis describes that the means in comparison of two scenarios were equal and the alternate hypothesis says that the means in comparison of two scenarios are different. For that case, an ANOVA was performed to compare means between independent data with a 95% confidence, which allowed us to determine that the null hypothesis is rejected and that the means are different according to the data obtained in the case study. As illustrated in Figure 11, the analysis of the ANOVA rejected the null hypothesis in the three factors and in the interaction of the scenario with the level of difficulty is understood as if there is an incidence on the other, so it is not reject the null hypothesis. To carry out the statistical analysis, it was taken into account that the factor of the collaborators as a blocking factor, since it could affect the observed response and therefore does not allow the adequate analysis of the test, therefore the interaction with the other factors with this factor.

Figure 11 Analysis of variances for the case study sample.

Anova

Variable factor	SM	G.L	CM	F test	F critical	P Value	Ho
A (Scenario)	3,868492266	2	1,934246133	13,02384769	3,058486124	0,000006	Rejected Ho Null
B (Level)	1,049305071	1	1,049305071	7,06527943	3,906392403	0,008742	Rejected Ho Null
C (Collaborators)	827,884101	29	28,54772762	192,2202402	1,545812257	0,000000	Rejected Ho Null
AB	0,303640939	2	0,15182047	1,022251842	3,058486124	0,362362	Not rejected Ho Null
Error	21,53477958	145	0,148515721				
Total	854,6403189	179					

Design by authors.

Moreover, it was possible to identify which scenario and level of difficulty generated the highest level of stress in the sample of 30 people in the case of the methodology study. Figure 12 shows the percentages that each scenario obtained at each level for the entire sample.

Figure 12 Matrix of percentage per desired level of automation and difficulty.

Scenario	Level 1	Level 2
Manual	22%	26%
Semiautomatic	36%	36%
automatic	42%	39%

Design by authors.

However, from the data collected, it was identified that the highest levels of stress registered within the 30 collaborators, regarding levels of difficulty, were 23% for Level I and 77% for Level II. Finally, for a wider knowledge of the graphs that were obtained by each person per scenario level of difficulty, please see **Annex D**, which contains all the 30 results representing each collaborator of the case study.

6. Limitations, conclusions, and recommendations.

6.1 Limitations:

The proposed methodology was designed specifically to be applied to flexible manufacturing control systems. Therefore, its application in other scenarios is limited and the results may not be as expected. During the implementation of the methodology, measurements were made with the galvanometer, with which the mental workload was measured through a physiological response. Due to the availability of time, it was not possible to make measurements with other equipment instruments suggested in the methodology to measure mental workload and physical effort. On the other hand, in the case study, no measurements were made regarding the physical fatigue of the operator. Companies that want to implement the proposed methodology could conduct a case study including physical measurements in conjunction with mental workload measurements.

The time available for the realization of the case study together with the availability of space was sufficient to achieve the objectives. Nevertheless, there was no time slack in case of any unforeseen event. Throughout the development of the case study, there were limitations with the measuring instruments, due to problems with the software license that controls the instrument. There was no back up of the instruments, which put on risk the development of the measurements during the start-up of the case study, as happened in the pilot test.

6.2 Conclusions:

In the development of the methodology, it was identified in the literature review that there was no detailed guide that would allow an easier way to configure the interaction of the manufacturing facilities with the human operator. For this reason, it is concluded that the proposed methodology is classified in a discovery analysis for lack of having an a-priori model. The methodology aims to provide a guideline that helps companies to implement partially automated or fully automated systems in their manufacturing processes. Additionally, in the development of the methodology, it was possible to identify that the proposed steps allow users gaining a broad understanding of the resolution of complex processes as is the configuration of a CPHS in their production processes.

To validate the design of the proposed methodology, an emulation of a real assembly line was created considering a manual activity of human operators in which task load increases the mental effort of the operator. This case study was centered on a manufacturing link's emulation in the supply chain. Through this case of the study, it was possible to conclude that users could internalize the majority of steps that the methodology suggested. Moreover, the proposed case study provided a final conclusion regarding the scenario that generated the highest level of stress in participants while executing the tests. This scenario was Scenario C characterized by being a fully automated system. From the configuration of this scenario, it was concluded that when a collaborator gave only support to the system (30% of the suggested collaboration level for a human operator in terms of task control), he/she tented to have no control of the process due to the machine executes most of the labeling task. This caused the sample obtained results nearby 42% (Level I) and 39% (Level I) from the Scenario C.

Both percentages are above the suggested collaboration level for a human operator proposed in the methodology, which was considered the highest level of stress for individuals. It must be recalled that the analysis of results was developed based on the literature review, which proves the GSR is a predictor of stress and during the test, Cassy Lab 2 software was used as the tool for constant real-time measurement. Additionally, it was concluded that the level of difficulty that generated the greatest stress incidents in the sample was Level II (five references dispatched). This result contributes to the increment of references to be labeled in the process, which relates directly to an increase in the amount of information the collaborator had to processed compared to Level I. Therefore, operators at this level must handle a greater concentration regarding labeling tasks that causes a prolongation of his/her cognitive effort, affecting the operator's performance at his/her activities.

As shown in Figures 9 and 10, collaborators presented critical points during each test. This atypical data resulted in lapses of time where the volunteer was exposed to a pressure in the decision-making process that he/she had to perform while labeling the references. The peaks variated depending on the desired level of automation and the level of difficulty. Through the human-machine interface emulated in the experiment, all measures were collected in real-time with the support of a GSR. The measurements allowed authors to obtain the threshold presented in the results of this methodology's case study. This aimed to identify the exact moment when a collaborator raises his/her stress levels and, therefore, could make mistakes that lead to a decrease in the performances during the labeling tasks. Based on this finding, experimenters were able to identify the source of the problem regarding the KPI metrics and present future recommendations to prevent issues that may maximize the degradation of the operator in terms of cognitive fatigue. Finally, the core of this study was to guarantee and promote the well-being of the human while performing any manufacturing process within a company.

On the other hand, in the configuration of the case study proposed, it was taken into account that for the modeling of the multi-agent system for the labeling station it was not necessary to use this, since the main application objective stipulated in the development of the work it was that there was a human decision-making entity, which had the role of an operator within the system. For this reason, a multi-agent system was not used within the validation of the methodology for the emulated case study.

6.3 Recommendations:

6.3.1 From a methodology for creating methodologies.

- Lack of patience. When the methodology is being applied, the people tend to skip different steps across the methodology, risking the quality of the final product, in this particular case, the development of CHPS. For this reason, it is recommended to follow the order of the steps presented by the developed methodology.

- When people apply the methodology it is recommended to save the process by documenting it to have all the necessary data for future improvements.

6.3.2 From the proposed methodology.

- The proposed methodology was designed specifically to be applied to flexible control systems. The company that employs this methodology must have a flexible control system in which it can be applied to synchronize the machine capabilities and human operators to offset mutual deficiencies and exploit mutual advantages.

- It is recommended that the methodology must be applied in companies that have partially or fully automatic holonic manufacturing systems instead of fully manual control systems.

- For the application of the methodology step, it is recommended to use an instrument that gives a live measuring of the operator's physiological responses. On the other hand, the company that applies the methodology has to identify the maximum and minimum permissible measuring parameters of the instrument. In addition, it is necessary to use a measurement instrument from the list because the list contains different instruments that measure mental workload from a physiological perspective.

7. Annexes.

Table 6 describes the name and content of each annex presented in this document.

Table 6 Annex description.

Annex	Description
Annex A	**S**hows a document called *Requirements for CPHS*
Annex B	**S**hows a document called *A Generalized Methodology to Develop CPHS for Production Environments* that provides an eight-stage methodology model to help companies implement partially and fully automated systems for its manufacturing processes.
Annex C	**S**hows a document called *Guidelines for conducting the case study: a manufacturing control system in the supply chain* that explains in detailed the carrying out of the study.
Annex D	**C**ontains all the 30 results representing each collaborator of the case study.

Design by authors.

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