Smart workstation of a Cyber Physical production system with digital human awareness

Mónica Juliana Pérez Morales [a,c] , José Fernando Jimenez Gordillo [b,c]

[a]*Estudiante de la Maestría en Ingeniería Industrial*
[b]*Profesor, Director del Proyecto de Grado, Departamento de Ingeniería Industrial*
[c]*Pontificia Universidad Javeriana, Bogotá, Colombia*

Abstract

The fourth industrial revolution, or also known as the digital revolution, is a transformation of the manufacturing and service models through the application of digital technologies in the economic and societal world. This revolution permits the creation of new markets and the efficiency improvement in industries operations. In fact, industries seek high customer satisfaction and efficient supply chain management to tackle the continuous uncertain and volatile environment market. Cyber Physical Systems, an enabling technology that potentiate the digital revolution, is a system responsible for the coordination and management of virtual and physical components for solving certain global goals. However, including humans in this system represents a challenge in the development of the digital revolution. Certainly, the contribution of human operator in production processes is needed to execute certain industrial processes. Unfortunately, few advances have been made for integrating humans into the productive systems in the fourth industrial revolution. This paper aims to contribute to a deeper understanding of the interaction of human in the 4.0 industrial environment for small companies. The project presents a representation of human being in a digital twin model for a Cyber Physical System.

Keywords: *Industry 4.0, digital twin, smart workstation, cyber physical production system, cyber physical human production system, human awareness, digital twin model.*

Resumen

La cuarta revolución industrial es una transformación de los modelos de manufactura y servicios mediante la aplicación de tendencias digitales y nuevas tecnologías que permitan la flexibilización de los procesos y la creación de nuevos de mercados en las compañías. Las industrias actuales buscan una satisfacción elevada del cliente y un manejo eficiente de la cadena de abastecimiento que le permita permanecer en el entorno incierto y mercado volátil en el cual se encuentra. Mediante este enfoque nace los Sistemas Ciberfisicos, encargados de la coordinación y manejo de los diferentes componentes, siendo una tecnología habilitadora en el contexto de la transformación digital. Por otra parte, es innegable el aporte del capital humano en los procesos productivos. A pesar de esto, son pocos los avances que se tienen para la integración de los humanos dentro de los sistemas productivos de la cuarta revolución industrial. Mediante la articulación entre los sistemas ciberfisicos y nuevas tecnologías como lo es el Digital Twin, el presente trabajo busca brindar un modelo que tenga en cuenta el comportamiento del humano dentro del sistema sin afectar la eficiencia operativa.

1. Justification and problem statement

In the global economy, the development of technology and the continuous balance between products demand and supply have a considerable impact on several industries, such in manufacturing aeronautics, logistics, health, etc. Nowadays, new technologies allow an efficient and flexible management for optimizing operational time and minimizing production cost (Nikolakis, Alexopoulos, Xanthakis, & Chryssolouris, 2019a). In fact, the rapid implementation of technology in last decades is known as the digital revolution. The digital revolution is the develop and application of information technologies and numerical control (Ji, Yanhong, Baicun, & Jiyuan, 2019). This revolution has integrated processes and technologies into a globalized world to affect the entire society, the social transition, the economics aspects. Therefore, it is clear that the digitalization and automation in the industries processes are a firsthand obligation in manufacturing processes (Angelopoulou, Mykoniatis, & Boyapati, 2020).

In specific, the digital revolution in the manufacturing industry is known as Industry 4.0, or the 4th industrial revolution. This term is an initiative of the German government in 2011 to identify the new industrial revolution that strengthens the manufacturing operations (de Paula Ferreira, Armellini, & De Santa-Eulalia, 2020). Benotsmane (2019) defined the Industry 4.0 as: interconnect technologies that are flexible and adaptative for the unique costumers needs, where each element works in the same interaction. However, the Industry 4.0 is now used to refer as a set of technologies that allows to connect smart and decentralized production (Kosacka-Olejnik & Pitakaso, 2019) for optimality and reactivity objectives (Jimenez, Bekrar, Zambrano-Rey, Trentesaux, & Leitão, 2016). Some key technologies in the Industry 4.0 are: Digital twin, Big Data, Cloud computing, robotics, smart factory and Cyber Physical Systems (Melesse, Pasquale, & Riemma, 2020; Zhong, Xu, Klotz, & Newman, 2017).

A key aim of Industry 4.0 is the integration of new technologies to automatize processes (Gil, Albert, Fons, & Pelechano, 2019). The industrial scenario has tasks that are difficult to automatable. Also, a range of industrial activities are linked to the human and even in an automated scenario is human intervention (Katiraee, Battini, Battaia, & Calzavara, 2019). In contrast, in Industry 4.0 has an abandonment in the subject of human interaction with the production system (Angelopoulou et al., 2020). Most studies in the field of Industry 4.0 focused on models without the human interaction or a weak interaction. Within the supply chain, humans are direct consumers of products or services (Katiraee et al., 2019).

In Industry 4.0 context, the activities are divided in two: cognitive and physical. The cognitive activities imply the use of intellectual effort for responding to humans senses, also the physical tasks are where humans use their body to do any action in the physical environment (Paredes-Astudillo, Jimenez, Zambrano-Rey, & Trentesaux, 2020). In traditional factories, the humans' operators focus their time on physical activities. Nowadays, manufacturing systems present the human operator in cognitive tasks (Rauch, Linder, & Dallasega, 2019). Recent studies have been carried for a successful incorporation of the human within the industry, focusing on the well-being of the human as a complex system. Some most studied approaches are: Safety management, Ergonomics and human factors, Learning and training, and Work- Life Balance (Pinzone et al., 2020).

Currently, implementing new technologies is not considering an advantage, but it is considered a requirement in the manufacturing processes. The influence of implementing recent technologies in the industry lies in three attributes as full connectivity, collective cooperation, and customized personalization. Firstly, the full connectivity refers to the ability of machines, products and external agents to communicate with each other and transfer information to ensure individual needs in a competitive behavior (Benotsmane, Kovács, & Dudás, 2019). Secondly, the collective cooperation refers to the intelligence between companies, machines and products and entities to improve collective efforts and increasing operations functionality (Aceto, Persico, & Pescapé, 2019). Finally, the customized personalization of products allows customers to select features that suit their needs and interests (Mourtzis, Vlachou, Dimitrakopoulos, & Zogopoulos, 2018). Indeed, these attributes are needed in new markets specifications but are also essential drivers for enabling technologies of industry 4.0.

From the enabling technologies, there are two developments that improve enormously the industrial operations: cyber physical systems and digital twins. A Digital Twin (DT) is a representation of physical entities that describe the condition and behavior for simulation and analysis (Erkoyuncu et al., 2020). NASA used one of the first applications of the DT for monitoring and simulate the behavior of a satellite (Stark, Fresemann, & Lindow, 2019). In production systems, the integration with DTs has been focused on the representation of entities, like robots and machines, to support and monitored the process (Cimino, Negri, & Fumagalli, 2019; Nikolakis et al., 2019a). Nowadays, the DT is defined as a tool that facilitates the integration of smart manufacturing (Ding, Chan, Zhang, Zhou, & Zhang, 2019).

The Cyber physical system (CPS) is a physical and virtual engineering system that, through centralized communication, operate, control and integrate all the tasks that are programmed (Rajkumar, Lee, Sha, & Stankovic, 2010). CPS allows the creation of physical and virtual models that integration with each other (Ding et al., 2019; Kotronis, Routis, Tsadimas, Nikolaidou, & Anagnostopoulos, 2019). Also, the CPS can manage the physical and virtual entities allowing the implementation of other 4.0 technologies in different scenarios. This distinction in CPS context is further exemplified in studies using for reduce the traffic congestion and delays, energy-aware buildings, and manage the evacuations lines (Rajkumar et al., 2010). There is a growing body of literature that recognizes the importance of CPS in the Digital transformation (Berry & Barari, 2019; de Paula Ferreira et al., 2020; Lee, Bagheri, & Kao, 2014).

The CPS can be specified depending on unique spheres and purposes (Paredes-Astudillo, Moreno, et al., 2020). Considering the above point of view were defines such as Cyber-Physical Production Systems (CPPS) and Cyber-Physical Systems centered on humans being like Human Cyber-Physical Systems (H-CPS) and Human Cyber-Physical Production System (H-CPPS). An example of CPPS advances is for process automation, sensors supervision and network communication (Romero-Silva & Hernandez-Lopez, 2019).

On the other hand Human Cyber-Physical Systems (H-CPS) create a scenery where humans and interconnected systems work in harmony (Kotronis et al., 2019). The role of humans within these structures is that of creation, management and operation (Pinzone et al., 2020).

HCPPS are human-focused production models based on their complex thinking and learning characteristics. These models must be flexible and adjustable in order to facilitate the interaction between the physical components of models (Paredes-Astudillo, Jimenez, et al., 2020).

Under the conceptual framework of Industry 4.0, the companies have carried out integrations for the measurement of factors. One tool implemented has been the use of digital representations of humans in CPPS. The replication, analysis and prediction of behavior is allowed human based on internal or external factors (Katiraee et al., 2019). Although, the most studied external factors are ergonomic factors, evaluating posture and environmental conditions of the workplace. In fact, internal factors as workload, cognitive capabilities, human awareness, and stress are the most complex to measure. Human awareness can broadly be defined as determine the agents and activities that are happening in the physical environment through the intervention of a person. This awareness allows a wide collaboration between the agents and the understanding of the environment (Lim Tek Yong, 2011).

Most of the research on human-based production models has been carried out considering that including human factors within CPPS allows the improve the efficacy (Chen, Cook, Guo, & Leister, 2017). In addition, having a human awareness inside allows an intelligent interaction within the production processes (Ruiz Garcia, Rojas, Gualtieri, Rauch, & Matt, 2019).

In Latin America, it is a need to increase the commitment between the government and the community to improve the possibilities of entering new markets. For this reason, it is necessary to open spaces for discussion on the special management of medium and small companies so that they can compete (Mendoza P. & Cuellar, 2020). This thesis is a contribution to solve the technological gaps, creating a digital representation to include operator in the industrial environment.

However, the one challenge faced by many researchers is the difficulty in integrating the human being within cyber-physical systems because of the complexity that it represents within the systems. Thus, is basic to suggest research challenges focused on the factors needed for a close representation. So, this dissertation focuses on answering the following research question:

Which factors should be including as representation of a human-operator in a H-CPPS?

To contribute to the improvement of this research, it should be answered the following three sub-questions. Firstly, this research proposes to determine the kinds of ergonomic factors exist that degrade the human wellbeing in the production context. Also, is important to evaluate *How can the human well-being is measured?* And finally, the correlation between human-centered tasks and humans well-being. These questions will help to understand the behavior and factors required to consider in a human digital representation within an industrial production environment.

2. Background information

Currently, the needs of the market are in a constant change of scene, where consumers demand greater customization of their products in a short time. For this reason, Industry 4.0 seeks the implementation of new technologies that allow making production processes more flexible, allowing high levels of operational efficiency (Jimenez, Bekrar, Trentesaux, & Leitão, 2016). Among the tools most used by the industry 4.0 for the transformation of organizations is artificial intelligence, digital systems, simulation, and data analysis (Kosacka-Olejnik & Pitakaso, 2019). Industry 4.0 accentuates digitalization as a developing pattern, to accomplish, through coordination and collaboration among frameworks and individuals, the ideal methods altogether potential angles.

Incorporating these production methods allows you to perform a real-time measurement of the processes and perform an analysis that allows you to generate optimal processes focused on the needs of the users. These analyzes leverage decision-making, cost reduction, and product quality improvement (Nikolakis et al., 2019a). Some most used techniques to carry out these analyzes are simulation. The simulation allows creating plausible scenarios where these are evaluated through the conditions of the organization's environment (de Paula Ferreira et al., 2020). Within the framework of the technologies of Industry 4.0 we find the DT, which is a virtual dynamic model that reconstructs a physical entity (Wu et al., 2020).

Also, the creation of new personalized products behaves complex, the use of simulation allows a revision of the procedures generating cost efficiency environment (de Paula Ferreira et al., 2020). For this reason, implementing new technologies for the control and analysis of the processes is an advantage.

Despite the current context, there is still a domain of complex manufacturing processes carried out by humans that are difficult to automate (Mahmood, Karaulova, Otto, & Shevtshenko, 2019). For this reason, the human being is still an indispensable part of the productive models. Some of these activities in which operators interact are inspection and maintenance (Nikolakis et al., 2019a). The operator is considered as a complex system, difficult to predict because of the unique characteristics that compose it (Nikolakis, Maratos, & Makris, 2018). Terms such as fatigue and ergonomics are necessary terms when speaking of human behavior within the industry. There are many studies, referring to revolve around the human being and its practice within automated systems (Costa Mateus, Claeys, Limère, Cottyn, & Aghezzaf, 2019).

Throughout this thesis, the term operator is used to refer to a human who performs actions, with physical and cognitive loads, of vital importance for the aim of the production system.

As an implementation of Industry 4.0 technologies to the current industry context, advances have been seen in incorporating humans into CPS with simulation creating HCPS. Because of the digital representation of the human, the companies can improve in assembly processes, reduce the costs of implementing digital systems, and improve the ergonomic component of human-centered operations (Nikolakis et al., 2019a). The

Reference	Integration of human	Integration goal	Obervation
(Ruiz Garcia et al., 2019)	Natural human-machine interface	Human decision-making capabilities	This paper presents a collaborative framework between human and robots through a natural human-machine interface coordinate by a CPS. This approach highlights the need for the integration of a CPS in for a human-machine iteration.
(Paredes-Astudillo, Jimenez, et al., 2020)	Human decisional entities	Evaluate the human role in systems	This work represents the human like a holon for a digital implementation focused on the human well-being.
(Ansari, Hold, & Khobreh, 2020)	Human cyber physical system	Design a methodology of human-machine interaction	The author talks about the complexity of workspaces and task and how it can share between entities.
(Liu & Wang, 2020)	Cyber physical system	Design a flexible system for human-robot collaboration	This paper is dedicated to proposing a remote Human-robot collaboration system for hazard manufacturing environments.
(Nikolakis, Alexopoulos, Xanthakis, & Chryssolouris, 2019b)	Digital Twin	Enable the optimization of the planning of human-based production processes	The article demonstrates the feasibility of the proposed approach, by enriching the simulation of manual assembly operations.
(Kotronis et al., 2019)	Human cyber physical system	Explore the applicability of the proposed approach in the design of a Remote Elderly Monitoring System	This work evaluates a formal model that include common critical requirements.

Table 1: Human's integrations found in the literature

formulation of HCPS could have two contrasting viewpoints, the System view and the human centered. The system views the human provided benefits or tasks and the system supports them, subsequently the human center is concentrated in the human's tacks (Kotronis et al., 2019).

As can be seen in the Table 1, references are made to human's interactions found in the literature. Likewise, in the table there is a column dedicated to the observations for the documents found, making specific reference to the conclusion on the integration. Also, there can find the mechanisms and goal of the integrations.

Nowadays is impossible to separate the human being or operator from his direct interaction with a digital environment. The academy has made several advances in integrating product systems to digital systems, but the human being has been relegated to secondary manual activities within the production chain. With Industry 4.0, the human-machine paradigm is a term increasingly closer to the production systems. This integration is also called Operator 4.0, where the human is no longer considered as a secondary actor and establishes relationships with the rest of the entities in the production chain (e.g., machines, products, resources). Through these relationships, the human and his knowledge take special relevance in the processes.

DTs are one pillar of H-CPS (Bousdekis, Apostolou, & Mentzas, 2020) as they facilitate the interoperability of processes. The DTs can support different communication between entities in the production chain. As a DT concept, there is no accepted definition, providing several debates. The concept used for the present work is: "machines or computer-based models that are simulating, emulating, mirroring, or "twinning" the life of a physical entity, which may be an object, a process, a human, or a human-related feature" (Barricelli et al., 2019). DTs move away from simulations by allowing a detailed analysis of the data and proposing optimal scenarios for decision making.

Thanks to this representation of physical entities within complex systems, the Human Digital Twin (H-DT) is born as an adaptation of this technology to H-CPS. H-DT can be fully integrated with different topics and technologies widely referenced in Industry 4.0. Bousdekis (2020) enunciates one role that H-DT has taken within H-CPS, along with the application of other enabling technologies. These roles are listed below:

- Personal assistant: The H-DT performs predictive tasks on human behavior but does not interfere in the activities that the latter performs in the environment. It can predict how the operator may respond to system disruptions and provide potential solutions based on advanced data analytics models, blockchain and other technologies.
- Personal monitor: In this model, the H-DT performs only monitoring tasks, where it learns from human behavior when performing actions. It cannot give feedback.
- Personal coach: This is the only model capable of providing feedback, where the system's optimality is sought and that allows it to complete the activities in the best way. The relation human-machine takes special relevance to this model.

3. Consistency with master syllabus

This section seeks to show the contribution of the master's degree in Industrial Engineering of the Pontificia Universidad Javeriana to this degree project. Initially, it should be noted that the syllabus of the master's degree has two components: common cycle and elective cycle. The common cycle are those subjects that are seen by all students and are part of the construction of the added value of the master's degree. The subjects of the elective cycle are those subjects that are freely chosen by the students to focus on their development during the master's degree.

The human has been presented throughout this project as an important agent in the supply chain, being complex and flexible. Taking this concept into account, its incorporation into production systems points towards an improvement in the efficiency of processes based on techniques to improve productivity. This development is framed by the process improvement and optimization methodologies.

These methodologies are key thematic of the master's degree in industrial engineering, such as: production models, where current production perspectives and their impact on productivity were observed; Supply Chain Management where the behavior of the different actors within the supply chain was observed; Advanced Optimization Models for problem solving through the application of complex algorithms.

By the elective cycle subjects, it was possible to deepen in the structure of multi-agent systems and the new technological tendencies. For the deepening of the cognition in cyber-physical systems, the subject "Sistemas Multiagentes" was taken, from which the conceptual bases of the agents, their interaction and programming are shown in this work. Subjects such as "Tendencias Tecnologicas" and "Gerencia de la innovación de tecnológica" complemented the deepening of the problems and openness to success cases within the industry. Finally, the subject "Diseño de Experimento" provided tools for the realization of the experimental protocol and the ultimate validation of the data. These different topics helped in the structuring and implementation of the work presented here.

4. Objetives

Design a model of a Digital Twin for the integration on a human being to a CPPS, allowing the balance between productivity of the system and the well-being of the operator.

- Define the key requirements for a Digital Twin model that considers the human representation within a cyber-physical production system.
- Build a conceptual model of the Digital Twin for a human in a cyber-physical production system, considering the components, attributes, and interactions.
- Propose a Human Digital Twin model for the integration on a human operator to a H-CPPS, seeking a trade-off between the system productivity and human well-being.
- Implement the proposed Digital Twin model in a smart workstation with physical work-load awareness.
- Evaluate the Human Digital Twin model in the CP factory laboratory, considering a usability and functionality validation tools.

5. Methodological Development

To complete with the different objectives presented, the use of a 5-phases methodology was determined. Figure 1 shows the steps in order of development and the interrelation between them.

Figure 1: Project Methodology

Each of the steps of the method will be listed below. In addition, emphasis will be made on what each one of them contributes to the work and the aim they aim to fulfill.

- *System Requirements:* In this step of the method, there are two different approaches. The first stage is a literature search on the representation of humans within manufacturing systems. Through this, a segmentation in clusters based on chronological order is shown. Taking this information into account, a list of last requirements for the H-DT to be developed is determined. These requirements are the basis for the design of the development prototype. This step of the method covers the specific aim.
- *Conceptual framework of system architecture:* This step seeks to provide a conceptual framework for the construction of the H-DT. For this purpose, the general framework on which the development to be delivered is based will be determined. This stage will help to merge the previously defined requirements into a framework, resulting in a conceptual framework for H-DT construction. Also, the framework will show the consolidation of the requirements and background of the system.
- *Detailed design:* The aim objective of this stage is detailing the multi-agent system as the communication systems, the attributes of the agents and the information from which they will be fed. This step comprises the development of the specific's objectives two and three of the work developed.
- *Implementation of the Digital Twin:* Based on the conceptual design developed in the previous step, the development and implementation of the H-DT in the virtual environment is carried out.
- *Validation of the model:* For fulfillment objectives four and five of this project, a validation of the model will be performed in a workspace with integrating a human. This step involves the design of the workspace and the experimental protocol used for the validation of the H-DT model developed in this degree work. Thanks to this, conclusions can be drawn on the use of the DT for the virtual representation of the human.

5.1. Phase 1: System Requirements

This section shows the process carried out for the definition of the H-DT requirements. For this purpose, a literature review was carried out to identify the characteristics and features of the digital representation of the human being. After that, a list of initial criteria was determined and added to an evaluation. Finally, the requirements for the H-DT that will frame the entire development of the project were listed.

5.1.1. Literature review of digital representation of human operators

This section presents a literature review of the digital representation of human operators within manufacturing systems. Human operators are considering the principal actor because has a direct involvement in the shop floor. The aim of this review is acknowledging the virtual human operator component within the manufacturing system to get insights into the role, interaction, involvement, and human capabilities related to this collaboration. As a result of this section, the author identifies the key characteristics of the human components on the manufacturing system to create a H-DT that represents the human operator. This review is organized as a chronological evaluation of the human digital representation. A chronological evaluation recognizes the evolution of this representation and understanding the improvements over the years.

This review started with a preliminary evaluation of 196 scientific papers extracted from Springer Link, Science direct, and IEEE databases. These papers were selected using the following logical expression of keywords: (simulation OR "digital twin" OR "digital representation" OR "virtual system") AND (physical OR "ergonomic characteristic*" OR productivity OR measurement* OR indicator*) AND ("smart station" OR workstation OR workplace) AND (human* OR worker OR employer*). Thereafter, it was extracted the structured metadata of each paper getting such as authors, title, publication dates, keywords, and abstract. From the set of papers, it was trimmed to 38 papers considering the instances that displayed at least a single characteristic of a human representation in the virtual system (e.g., manufacturing controls system, manufacturing execution system, manufacturing management, etc.). For this section, a virtual system is considered a set of entities such as hardware devices, software applications, production activities, and human-machine interfaces intended to involve the human in a production scheme.

For the filtering the set of papers, the inclusion criteria were based on the following factors: (1) Digital Representation and Human are part of the main research effort, (2) Any kind of system that introduces concrete scenarios of the Digital Human Representation in production systems, (3) Describes the use of measurements or indicators of operators physical or cognitive factors. In addition, the exclusion criteria were based on the following factors: (1) The inclusion of the Human in the activity was not explicit or the Human was only used to control an automatic system, (2) The Human performance was not measured, (3) Full text could not be assessed, or it is not in English, (4) Published before 1990, (5) Systems with application in logistics. The reason for choosing this time frame is that the 1990s saw the implementation of distributed systems in production (Thentesaux, 2009). This application of distributed systems applied to improve the reactivity of the systems. The filtering step trimmed the set to a sub-set of 38 papers. These papers were used to identify the chronological evaluation of human digital representation.

To explore the sub-set of 38 papers, it was identified the features of each paper according to the following six characteristics: inclusion of the human within the virtual system, human-virtual environment communication, human factors indicators, virtual representation, purpose of the virtual representation and devises and measurement to human factors. For the first three characteristics, it is defined as a limited category for indicating the characteristics based on terms defined previously. In the remaining three categories, the identified characteristics were extracted directly from the information got from the paper. For a better understanding of the categorization characteristics, it is defined each characteristic criterion. First, including the human within the virtual system is a characteristic that identifies the role and approach for including the human operator within the virtual system and how is perceived the human operator in the interaction with the digital environment. It is considered three categories: resource, monitoring and complex actor. A resource refers that the human is recognized as an element that performs activities as a service-oriented task which will affect the system. Thus, the operator is equal to those of other physical resources, such as machines. A monitoring refers that the human operator is taken as a physical entity that capture and monitors the manufacturing environment and takes part in the decision making on tasks performed by other entities. Finally, the complex actor refers to when the human is an entity capable of performing joint and complex activities in the workplace. In addition, complex actor serves as an entity that monitors activities and triggers decision-making processes. In this sense, the categories are organized according to the level of participation and intelligence featured by the human operator. Second, the Human-virtual environment communication category is the characteristics that evaluate the type of communication within the virtual system. Two categories are established: limited communication and real-time communication. The limited communication refers to the ability of the information system to capture information, transform and create a digital representation of the environment. However, in specific, the human operator does not receive the data in short-term feedback, and this could be partial or delayed information. The real-time communication refers to an interaction between the human and the virtual system, where it is possible to have feedback from the task, operations activities or human actions, and the information is received simultaneously or in a small delay manner for a potential decision making. Third, the Human factors indicators are a characteristic that seeks to evaluate the human indicators for evaluating the human operator. These evaluation variables can be task-based indicators, physical indicators, and cognitive indicators. The task-based indicators measure the completion time, the status of the tasks, and control metrics. In the physical indicators are human factors such as workload, posture, workspace, visual fatigue, and loads that can be generated to the physical characteristics of the operator (i.e., noise, light, and temperature). Finally, cognitive indicators are human factors that include elements such as stress, mental fatigue, concentration, skills, and motivation. Fourthly, the Virtual Representation is a characteristic that has the objective of determining which technological development, technology, architecture or model the representation of the human being within the virtual environment was carried out. These characteristic permits visualizing the tendency of the application of technology within cooperative environments between the human operator and the virtual system. Fifthly, the Purpose of the virtual representation is a characteristic that seeks to demonstrate the trend or impact required with the implementation of this representation. This feature is added for evaluating the range of options available during the system interaction and the role that represents within the production environment. Finally, the devices and measurement to human factor is a characteristics that presents the devises o tools that permit capturing the information from the human operator for the construction of the digital representation (e.g., sensors, scanners, vision systems). Through this feature, it is possible to determine the evolution of technological applications into shop-floor workspaces and include the assessment of human performance in the workplace.

Figure 2 shows the chronological segmentation was made. The first cluster, named as Basic integration, comprising the dates from 1990 to 2000. The dominant characteristic of this cluster is the type of measurement of the human being is the work performed. In this cluster, the operator is determined as a resource. The operator performs a certain number of activities in which neither physical nor cognitive loads are measured. In

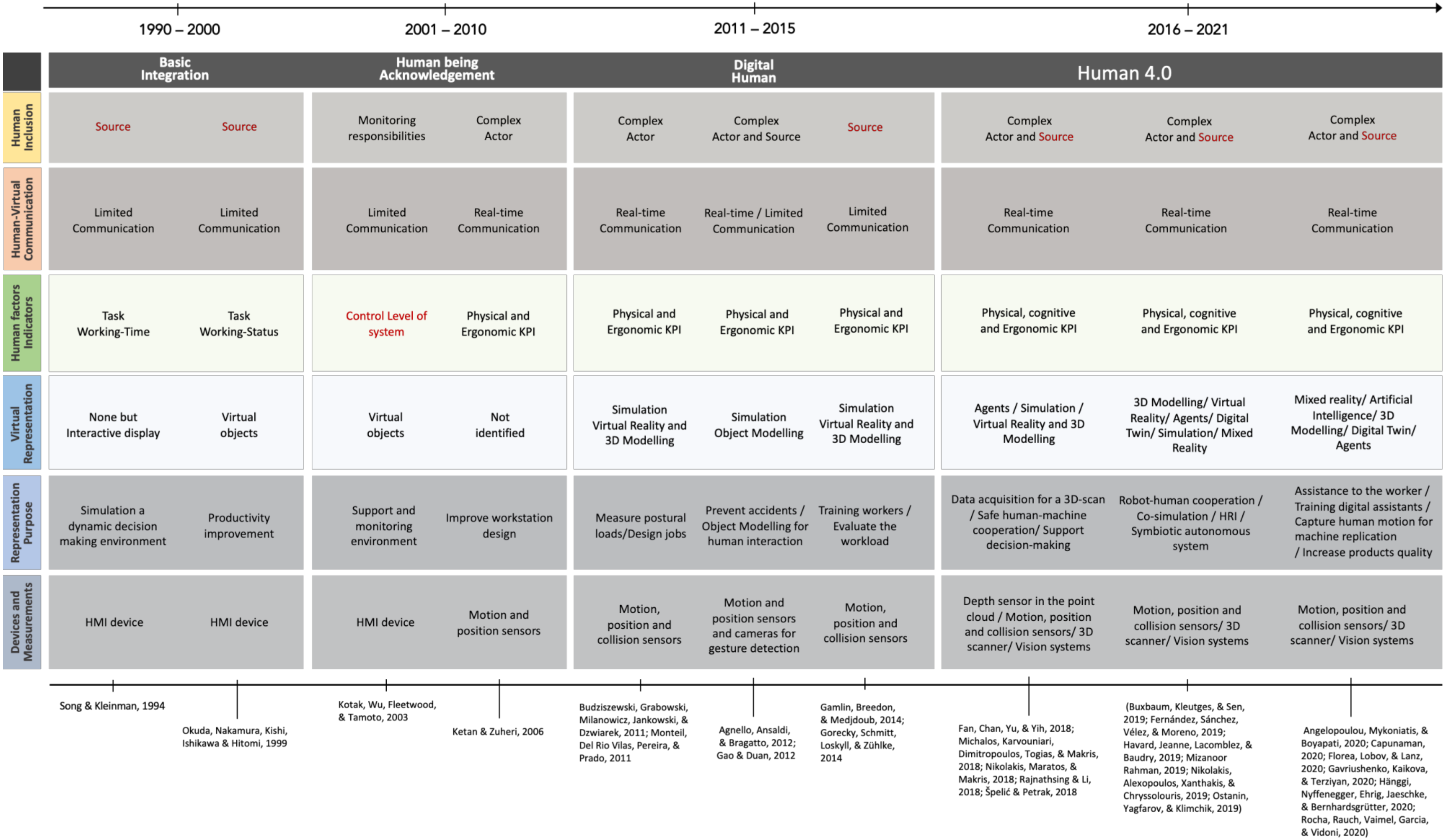

Figure 2: Evolution of the human being on virtual systems of manufacturing environments

contrast, just the time and status of the tasks are measured. For example, Okuda (1999) present a cooperative model of autonomous people in a human- oriented production process, applied the cooperation model to production simulation, and evaluated it. The measurement of these activities is done through the information provided by the human and there is no evidence of integrating sensors. Because of the above, it is observed that one of the most important indicators in this stage is productivity, decision making and coordination within the production scenarios that have human operators (Okuda, Nakamura, Kishi, Ishikawa, & Hitomi, 1999). Finally, in the basic integration stage, the communication human-system is unilateral. The human operator does not find continuous feedback from the system. This could be considered the initial stage of the digital representation of humans within manufacturing production systems. Where, despite the basic integration of the operator, there is an intention to monitoring and control the human indicators as productivity. From an automation perspective, monitoring and control is one of the basic steps of systems such as MES.

The cluster of Human being Acknowledgement from 2001 to 2010 is characterized by an empathizing of the interaction of the operator within the systems and its importance. The human is integrated into the systems as an element different from the resource and becomes an actor within the system. In addition, understanding of the human being cluster can be considered as the transition stage between human information gathering and the use of sensors to capture information. Also, this cluster shows the trend towards the search for resource optimization and the importance of including manual activities in system planning This begins the interpretation of the physical factors in the design of a workplace that considers the needs of the human being, focused on productivity. Ketan & Zuheri (2006) show how determining the optimal design for limitations stacking workstation by the application of ergonomic analysis, discrete-process simulation, and multi-response optimization. Some technologies that are being considered, because of the start of trends such as Industry 4.0. For example, Kotak et al. (2003) describe a practical system framework for holonic design and operations in a distributed manufacturing environment using multi-agent systems (MASs) and simulation techniques.

The third cluster is the Digital Human, period from 2011 to 2015, this period is characterized by an improvement in the capture of information for the construction of the representation of the human. Therefore, the capture of accurate information becomes one of the determining factors in the construction of 3D virtual models. A trend is observed in the inclusion of emerging technologies, such as virtual reality, and the improvement of the use of motion and collision sensors. As an illustration, Gamlin, Breedon, & Medjdoub (2014) show a Virtual Reality Technology as a training tool within Lean Manufacturing Environments, integrating indicators other than productivity within the objectives for virtual human representation. Another technology that saw its beginnings in this stage is the use of computer vision for the reading and analysis of gestures, which would later be used in the next stage for the measurement of factors other than physical ones. In addition, this use of computer vision allows a reconstruction of the environment, movements, and interaction of the operator in real time (Gao & Duan, 2012). The variables that are measured in this cluster are physical-ergonomic, leaving behind task-based measurement.

This transformation is the prelude to the last cluster of Human 4.0. This cluster comprises from 2016 to 2021, where the implementation of enabling technologies for Industry 4.0. For example, the authors introduce terms like artificial intelligence, digital twin, robotics, and simulation. Therefore, under this technological framework, human-robot interactions are observed in the same workspace, with activities developed collaboratively. Thanks to these interactions, the need for digital representations of humans that are faithful to their physical counterparts is amplified. Also, this cluster has the largest number of papers, with an exponential growth compared to the clusters explained above. Another highly relevant feature is the inclusion of cognitive variables and attributes (stress, fatigue, etc.) in the representation of the human being. This reinforces the transformation of the human being as a resource to merge it as a complex actor within the systems. In addition, the importance of real-time communication between the human and the virtual environment is recognized, which allows for timely and dynamic feedback. For example, Rocha, et al. (2020) design a model for a vision-based worker real time help system for assembly.

This research has mainly two findings. Firstly, the evolution presented in section 6.1 found the adjustment of the human representation though the ages. It changes from considering humans as resources that provide service to considering a human as virtual or digital representation that collaborate within the production process. The importance of this new consideration is that the human is seen as an advance entity that need to execute the task assigned but also that need to minimize the degradation on the physical and cognitive characteristics. On one side, this permit evaluating production environments where human not only execute manual tasks, but also involves a cognitive workload that adds value to the production process. But, on the other side, this creates a specification need in control systems as the compliance of the human well-being demands protocols and mechanism to minimize the human degradation. For this reason, it is considered in this paper the need of creating a H-DT for assuring the representation with the virtual system. Secondly, the entities on production systems, either digital or physical entities, are synchronized to fulfil the physical process need. Traditionally, the human was an external entity that interact with the system. Still, the creation of a H-DT engages the system to consider the human capabilities and the maintenance of the human well-being. Certainly, a H-DT as a differential technology from industry 4.0. The H-DT allows a continuous and control and real-time feedback on the human task.

5.1.2. Challenges of Human Integration in Cyber-Physical Systems

Before postulating the final requirements of the project, it is important to evaluate the problems, drawbacks, and challenges to which the project will be confronted. For this purpose, the classification of Defty et al. (2021) will be presented, where he defined three different categories of challenges for integrating humans in CPS: Representation, Communication, and Interfacing.

5.1.2.1. Representation

The challenges encountered in the representation of the human within CPS are one point that could generate more discussion. Because the human being a completely complex actor has multiple attributes and perspectives, ranging from physical characteristics to ethical concepts. Therefore, it is necessary that the representation of the human be flexible and modular (Desfty et al., 2021).

The human in a production process have contact with the other physical entities of the system. These interactions can be human-human or human-machine, with simple stimuli such as visuals or complex collaborative interactions. Because of this, the representation must capture and represent these interactions of the human with its physical environment (Desfty et al., 2021).

5.1.2.2. Communication

Defty et al. (2021) establishes as communication the interaction between two or more virtual entities that share information between them. The CPS base their behavior on the interaction between all the entities of the system where through this synergy, decisions can be taken. Thus, it is certain to establish communication between the discrete entities of any system. But the challenge is to integrate these communication channels (Desfty et al., 2021). This challenge can be overcome by properly implementing protocols or methodologies in the structure of human representation.

5.1.2.3. Interfacing

Communication between the digital representation and the human is indispensable for the correct functioning of the system. The challenges in terms of human-machine interfaces are not recent. Because of the intrinsic complexity that comes with the transformation of software into a language that humans can understand (Desfty et al., 2021). In addition, it must be adaptable and simple, a language that allows practical decisions to be made for the human. This coincides with an interface that is adaptable to the different needs of both the environment and the human and their workstation.

Another challenge that we can identify that suits this project is the amount of information, the latency, and the connection of the communication. When talking about a virtual representation of a machine, the communication is direct, and the processing capacity of both computers is known. For representations of a human, it is necessary to have an interaction mediated by other devices (Desfty et al., 2021). This means that communication is not between the components. Defty et al. (2021) stress the importance of considering the reaction time of the human to the stimuli, since it is necessary for the human to register, understand, and act under the stimulus. Someone should especially consider this last point when the stimuli can affect the wellbeing or safety of the human within the production line.

5.1.3. Analysis of Digital Twin Requirements

In this stage, the requirements stated in the literature review are evaluated in such a way that the list is condensed to have consolidated and real guidelines to follow. By narrowing down the list set forth in the previous paragraphs, we seek to determine the priorities of the project for the development of the H-DT. For this purpose, it was decided to evaluate by criteria, using a prioritization matrix.

The design criteria are divided into three different criterion types which are: relevance, resources, and impact. Relevance category refers to whether the item in the list of requirements contributes to the development of the project's objectives. This criterion ensures that the requirements chosen are relevant and do not generate a flaw in the choice that could affect the result. On the other hand, the type of criterion that refers to resources is to determine whether the requirement can be carried out with the equipment or capacity that the project has available. For this criterion, it is important to consider resources, such as the time available and the level to be managed within it. Finally, the criterion is the impact of including this requirement within the project. Although it can be confused with the criterion, it may resemble in definition the relevance criterion, the main difference is in the approach, since the relevance criterion has a focus on the project. While the focus of the impact criterion is a more global approach and seeks to determine whether this requirement fits the market and look of Industry 4.0. These three criterion types were subdivided in a final criterion and given a weight within the evaluation shown in Table 2.

Criterion type	Criteria	Weight
Relevance	It fits to the scope expected.	2.5%
	Conforms to the complexity required.	2.5%
	Conforms to the specific objectives set out in the job.	20%
	Contributes to the achievement of the general objective.	20%
Resources	Requires viable resources.	5%
	Can be developed in the estimated time.	25%
	Can be developed on multi agent platform.	10%
Impact	Provides relevance within the frame of the Industry 4.0	10%
	It is related to Nowadays industry	5%

Table 2: Weight assigned to the criteria for choosing the requirements

From the weighting shown in the previous table, the proposals with a score over 4 were chosen as a requirement, the final requirements are shown below together with the score obtained.

Requirements	Score
Easy to use, requires that the software allow natural interaction facilitating more intuitive production control.	5,0
Easy of learning, allowing the easy incorporation of new users.	4,7
Quickness, perform certain activities in a desirable time.	4,5
Simple interface, allows a quick reading of the information.	5,0
The interface displays information in real time.	5,0
Compliance with international standards.	4,5
Dynamic feedback.	5,0
Real-time communication.	5,0
Real-time worker movement recording.	5,0
Easy installation-software on a computer.	4,6
Communication between the different software components.	5,0
Allow to run a production by the user.	4,5
Provide an interactive user interface.	5,0
Physical worker characteristics.	5,0

Table 3: Initial requirements

Considering the initial criteria, the following requirements were grouped and described in the functional and usability requirements for the proposed H-DT.

Requirement 1: A software that allows to perform activities in an intuitive and user/worker friendly way is required. For this, the colors, graphics, and texts used must be easy to understand, and contain an easy application in manufacturing workplaces. In addition, the DT must comply with international technical standards.

Requirement 2: The DT must have the ability to provide real time feedback to the worker, to have a correction of the actions and elements needed for the job. The feedback must be done in a way that is accessible to the user. The workstation must be adjusted to provide feedback through different senses (e.g.: visual, auditory, sensory).

Requirement 3: The DT must be able to contain and replicate the physical characteristics of the worker's behavior through integrated vision systems that allow real-time reception of the worker's positions and actions at the workstation.

Requirement 4: The DT must seek a balance between the well-being of the worker and fulfillment the task. This, so that it does not interrupt the behavior, planning and structuring of production within the company. The DT is a tool in search of efficiency and comfort.

5.2. Phase 2: Conceptual framework of system architecture

In this phase, we will develop a structuring of the framework in which the H-DT will be developed. Initially, it is shown how it is a human interaction in a cyber-physical environment and the role that the H-DT develops within the system. After that, the methodology for the development and implementation of the framework is mentioned. Based on the methodology, the agent-based structure that will be used for the development of the H-DT is developed. In addition, the concept of agents and their characteristics is deepened. Finally, the development of the agents that make up the development is carried out.

5.2.1. H-CPS conceptual framework

This section shows the conceptual design of the H-CPPS in which the H-DT to be developed in this work is involved. Therefore, this section will show a global view of an inclusion of H-DT with other elements of the production chain.

The H-CPPS focuses on the concept of the human being as an essential and convergent part of the processes. However, it is currently observed that this concept has a low inclusion in CPPS, generating a gap where the human can be categorized as another intelligent object or physical entity of the system. A virtual representation of the human helps to reduce this gap and brings benefits such as increased productivity. To have a broader framework for the application of H-CPSs, and including H-DT within these virtual environments, Figure 3 shows the four dimensions of integration of the proposed framework for the application of the H-DT model of this work. These four dimensions are fundamental for H-CPSs and the potential construction of a cyber-human symbiosis.

Dimension 1 *Digital modules serving human operators:* digital modules are those additional tools that support human information processing. This processing can have several functions and, depending on the tool used, can also have different purposes. Among the purposes that are highlighted are: (1) modules for monitoring human activities (Emmanouilidis, C., et al., 2019), (2) predictive tools for human behavior (Zhou, J., Li, P., Zhou, Y., Wang, B., Zang, J., & Meng, L, 2018) (3) new modules that support learning to improve human skills (Riedl, M. O., 2019). In addition, other secondary modules, such as internal or on-net storage, allow for extensive information management and access of various physical entities for processing. This is especially beneficial when dealing with large amounts of data.

Dimension 2 *Hardware / software devices for human-system interconnection*: Interconnection can be defined as the elements required for active communication that serve as a bridge between physical and virtual systems. Given this, it can be divided into two parts: (1) Software where the virtual systems in charge of the intercommunication can be found and (2) Hardware of the physical systems, also called human machine communication. From the software perspective, measures have been included in the human digital representation such as the H-DT, which have easily mutated towards the inclusive construction of the human perspective within productive environments. Hardware tools such as vision systems, 3D environments, electromyographs, have allowed the capture of information that helps for virtual entities.

Dimension 3 *Role and capabilities of the human operator:* The role of the human operator is one of the broadest perspectives in this spectrum and is certainly far from being concluded. Despite this, the human being must be considered within production lines. Moreover, it must be represented as an entity completely different from any physical entity. This, considering the complexity of their attitudes, attributes, and capabilities. Unlike the other entities, the abilities vary among humans. This gives us a variable, unpredictable scenario in which the rest of the dimensions must adjust.

Dimension 4 *Well-being factors of human operators:* considering the above mentioned, the human possesses differentiating characteristics and factors different from those considered with the other physical entities must be considered. Well-being factors are three different denominations: physiological, physical, and cognitive.

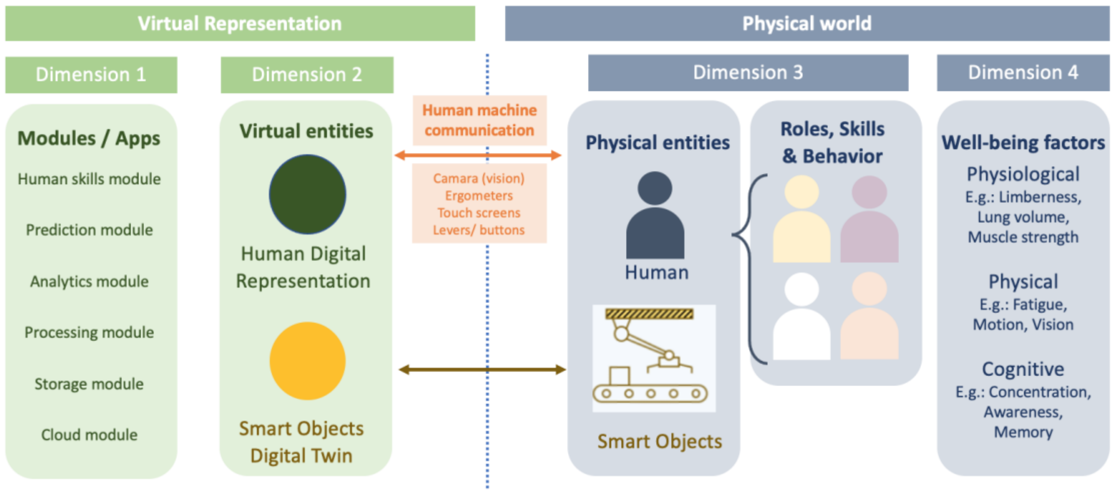

Figure 3: Cyber and human interaction

Considering the above, the current project is going to focus on the design of the virtual entities of dimension 2 named as "Human Digital Representation".

5.2.2. Conceptual analysis of Multi-Agent Systems for H-DT

As second part of the conceptual design, this section describes the conceptual components of the H-DT model. The proposed model is realized by a Multi-Agent System (MAS) that allows a programming like object-oriented programming. MAS programming allows having virtual entities, called agents, that work together to solve complex problems. By the agents, a division of labor can be realized that allows an efficient utilization of resources. The main features and elements of MAS are described below, where an overview of the development of the proposed H-DT.

An agent is defined as an autonomous, rational, and social entity, which has a defined aim and seeks to maximize its result. For this reason, we can have 3 specific characteristics of the agents, which will be defined below and will be extended in the application to the model. These characteristics were taken from the behavior of humans and how they can interact in societies.

- *Agent as an autonomous entity*: The term *autonomy* based on agents refers to: *the encapsulation of the knowledge, resources, services, and behavior of the entity.* This characterization allows the individuality of the different agents and avoids the non-duplication of information. This is one principle of agents since it does not allow the subordination or management of one agent by others. Through autonomy, the agents can make independent decisions that contribute to fulfillment the aim they have. Therefore, the decisions taken by different agents, but from the same family, in the same situation, may be different.
- *Agent as a social entity:* Although agents are autonomous entities, agents can generate relationships or forms of communication. Also, that behavior allow to the agent reach the global or individual target. This type of communication, based on norms and rules, is called cooperation. Communication between entities can be limited or extensive, depending on how they are configured to interact. There can also be a mediator between two agents who are to be a channel and filtering the communication between agents. This mediator role helps to avoid saturating the information system.
- *Agent as a rational entity:* This characteristic is given as a complement to the other characteristics. In the decision-making step, based on the information of the environment and its autonomy, the agent can act looking for the maximization of the goal. The rational thinking of agents can be derived in two ways: system interaction or intelligent systems. First, rational thinking based on system interaction is one where agents based on rules and their cooperation with the system decide. Intelligent systems-based behavior is one where the decision is supported by adjoint systems such as AI systems or neural networks.

Agents' performances are based on two components: Perception and Decision. Perception is the virtual construction of the environment that the agent can perform, considering the information provided by sensors or other agents. This information from the environment can be processed to perform a more complex sketching of the environment. This understanding of the environment makes it possible to understand the consequences of the actions performed by the agent on the environment. By creating a world based on perception, the agents can assume the behavior of this and of the other agents that remain in it, this is called the process of creation of beliefs.

Also, the decision stage is defined as the actions taken by an agent to interact with the environment. These actions can be taken under a strict system of rules, which regulate the agent's communications and behaviors regarding the rest of the system and environment. Through this model, the agent depends on its beliefs and goals. Another important component is the behavior, this refers to the actions that are possible to develop. The agent must be able to identify these options.

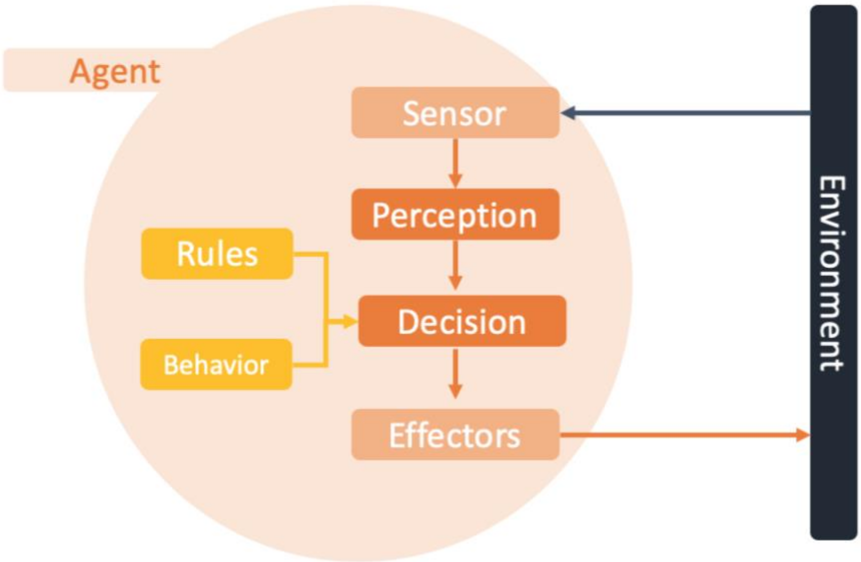

Figure 4: Basic agent performance

Considering all the above, a MAS could be defined as the cooperation between two or more agents capable of deciding in favor of a joint goal. Thanks to this definition and unification of criteria, we can carry out the definition of the proposed architecture.

5.2.3. GAIA Methodology

Based on communication challenge shown in section 5.1.2.2, it was used an additional methodology focused on H-DT development. This methodology aims to provide support for the evaluation of the levels and channels for communication between the distinct entities.

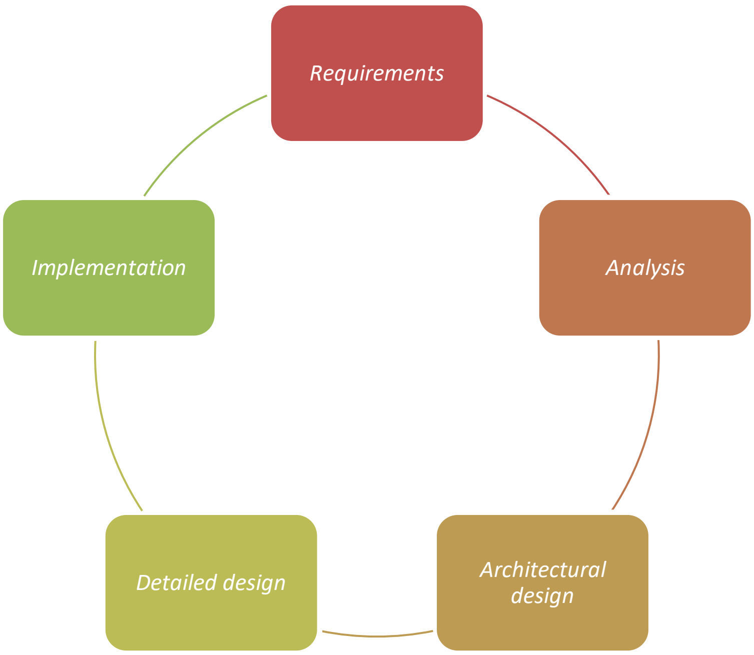

Figure 5: GAIA methodology

The H-DT model is framed in an interaction between a physical model and a virtual model, with multiple components of external analysis, it is proposed that the agent methodologies of a distributed system are the best approach to the problem. For this, the GAIA methodology for the development of multi-agent systems is presented (García-Ojeda, De, Pérez-Alcázar, & Arenas, 2004). This methodology allows to decompose complex interactions in simple suborganizations of agents (Huang, El-Darzi, & Jin, 2007). Figure 5 shows the steps proposed in the GAIA methodology.

The GAIA methodology is a systems engineering methodology based on object-oriented programming methodologies. Multi-agent systems and object-based systems have several similarities, although objects do not have the same characteristics as agents. Therefore, methodologies such as GAIA have been developed to enable robust agent structuring. In addition, GAIA is a design-centered methodology, because it takes care of the first stages to prevent errors or inconveniences in the implementation stage. The steps or stages that make up the methodology are:

- *Requirements:* In this stage, the system is established, and the constraints of the project are integrated. These requirements are a list like the one shown in table 3. This list can have requirements that, because of the current limitations of the project, may have a negative influence on the system. The requirements for this project were determined in section 5.1.3.
- *Analysis:* In this step, the functionality of the requirements and their importance in the system's development is analyzed. Its aim is to evaluate, classify and determine the last requirements, objectives, tasks, and actors for the development.
- *Architectural design:* For this process, the general framework of the multi-agent system on which it will be based, and the objectives of the different agents involved will be defined.
- *Detailed Design:* The communication channels, attributes, behavior, and cooperation actions within the system will be defined in depth.
- *Implementation:* This is the development stage, where the proposed design will be implemented. The required libraries and software resources must be evaluated at this stage.

5.2.4. Agent analysis

Implementing a DT based on agents allows the response of the components to be agile and allows an easy integration between the different components of the same perspective. As observed throughout this section, an MAS has a joint aim that allows the agents to maximize their performance. For this proposal, the aim defined for the MAS is: *realize a digital representation of a human that allows the coordination of activities, decrease of fatigue and improvement of the operator's well-being, without affecting productivity.*

To determine the functions and tasks of the different agents in the MAS, the use of the organizational analysis given by the GAIA methodology was determined. This organizational analysis, the objectives to be targeted were defined, considering the requirements and the general aim already established. In this stage of agent analysis, the role of the different agents within the system is determined and how they can have different objectives but contribute to development. Table 4 shows the definition of the three main objectives and their secondary objectives. Using secondary objectives is to break down an objective that is very broad for the system. It is important to specify that these objectives are those of the system. Given this, the objectives of the different agents in the model will be determined in a later process.

Target ID	Target description
o.1	Represent the state of the human
o.1.1	Calculate human indicators
o.1.2	Capture the necessary information
o.2	Production control
o.2.1	Evaluate the efficiency of the process
o.3	Provide performance feedback to the human

Table 4: Breakdown of target

After the list of system objectives, we can find the description of these in tasks for the system. Therefore, each task aims at a minimum of one objective, either general or specific. Breaking down the objectives into tasks as presented in the table allows us to evaluate the use of the objectives and to specify the tasks for later implementation.

Task ID	Target ID	Task description
T1	o.1.2 - o.2	Collect the information from the human
T2	o.1.1 - o.2.1	Debug and validate the data
T3	o.1.1 - o.2.1	Store a history of the data
T4	o.1.1	Calculate human indicators
T5	o.1.1 - o.2.1	Evaluate the indicators
T6	o.1.1 - o.2.1	Transform the data for the indicators
T7	o.2	Capture process information
T8	o.2.1	Calculate process indicators
T9	o.3	Evaluate break times
T10	o.3	Send information to the HMI

Table 5: Definition of agents' tasks

Finally, tasks that were like each other or that allowed the development of a role within the system were grouped together. This previous step resulted in three different actors within the multi-agent system. These roles are listed in table six and will be developed and deepened in the following sections.

Actors	Assigned tasks
Perception agent	T1 - T7
Information agent	T2 - T3 - T6
Decisional agent	T4 - T5 - T8 - T9 - T10

Table 6: Assigning tasks to actors within MAS

5.2.5. Architectural design in the Digital Twin Integration

A DT allows real-time monitoring of the activities and ergonomic factors of the worker. For the acquisition of this information, the model will be equipped with an integrated vision system in charge of acquiring information from the environment. The human has real-time interaction with its digital counterpart through real-time feedback through visual and auditory aids. The following sections describe the characteristics and behaviors of the agents and their interaction with the system.

The model is based on agents at three different hierarchical levels. As can be seen in the Figure 6, there is a communication between the hierarchical levels with the upper and lower level of the model. Also, each hierarchical level is composed of a different type of agent. This means that the digital representation of the human is composed of a minimum of three agents that interact, cooperate, and decide.

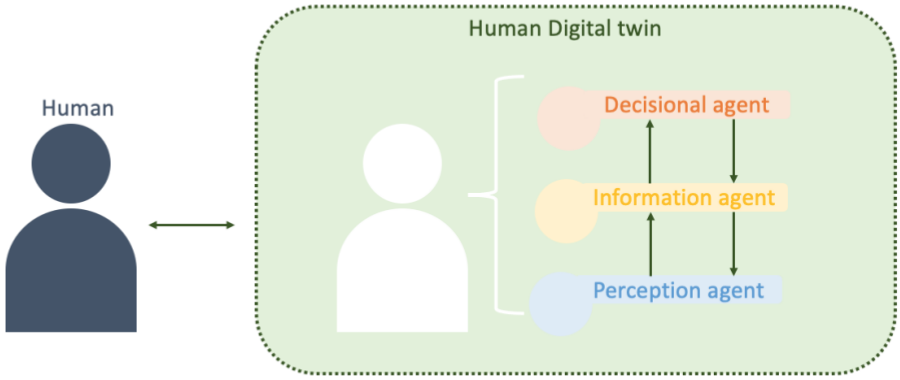

Figure 6: Digital Twin Model

5.2.6. Human Digital Twin Agents

This section shows each of the agents that make up the hierarchical levels and the role they play within the DT.

5.2.6.1. Perception agent

The Perception agent is the agent that collect the information for the human by sensors and additional systems. This means that for each additional element of information acquisition from the environment, a new perception agent will be created. Therefore, the information kept in the attributes is transient and does not remain in the agent. This agent is the closest understanding of the environment. From the analysis of the information in it, the creation of the system will be carried out. Considering all the above, the aim of this agent can be defined as the acquisition of information from the environment, processing it, and distributing it to the information agent.

5.2.6.2. Information agent

The role of the information agent is to merge and coordinate the acquisition of information from the perception agents. Besides receiving the requests from the decision agent, the information agent keeps a record of the sensor data with a time delta regarding the data provided by the perception agent, which is in real time. Therefore, it can be assumed that the information agent is a merging bridge between the information acquisition and decision-making phases. The main objective of this agent is to provide the decisional agent with the necessary data for decision making and to coordinate the existing perception agents.

5.2.6.3. Decisional agent

The decision agent is to calculate and evaluating the different indicators in the system based on human behavior. Therefore, this agent depends on the input given by the information agent. Its chief aim is to transform the data to determine the state of the physical counterpart. Thanks to this agent, decision making can be centralized. Therefore, the decision taken by the decisional agent is in search of the human's well-being. Therefore, the decisional agent will evaluate the human's rest time and its duration.

5.3. Phase 3: Detailed Design

The detailed design shows the behavior and cooperation between the different agents and physical entities involved in the MAS. Figure 7 shows that the initiator of the activities is the decisional agent, which requests the updating of its parameters for the calculation of the indicators. This is so that the perception agent can capture this information. After this information capture by the perception agent, an update of parameters is made to the information agent. The information agent cleans the information and saves the history against a ΔT, where T is the time variable.

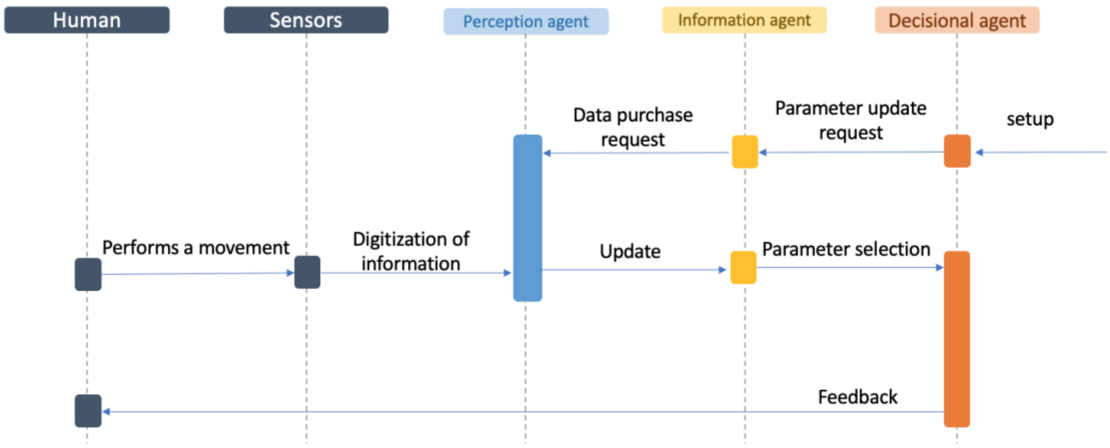

Figure 7: UML diagram of the functionality and behavior of interactions between layers

After these steps, a response is given to the request of the decisional agent, which is to evaluate the indicators of both the human wellbeing and the productivity of the system. Through these indicators, the decisional agent can decide and project feedback to the human. This feedback is by an HMI and the signals are auditory and visual. The HMI allows a communication in real time between the virtual representation and the physical entity that for this case would be the human.

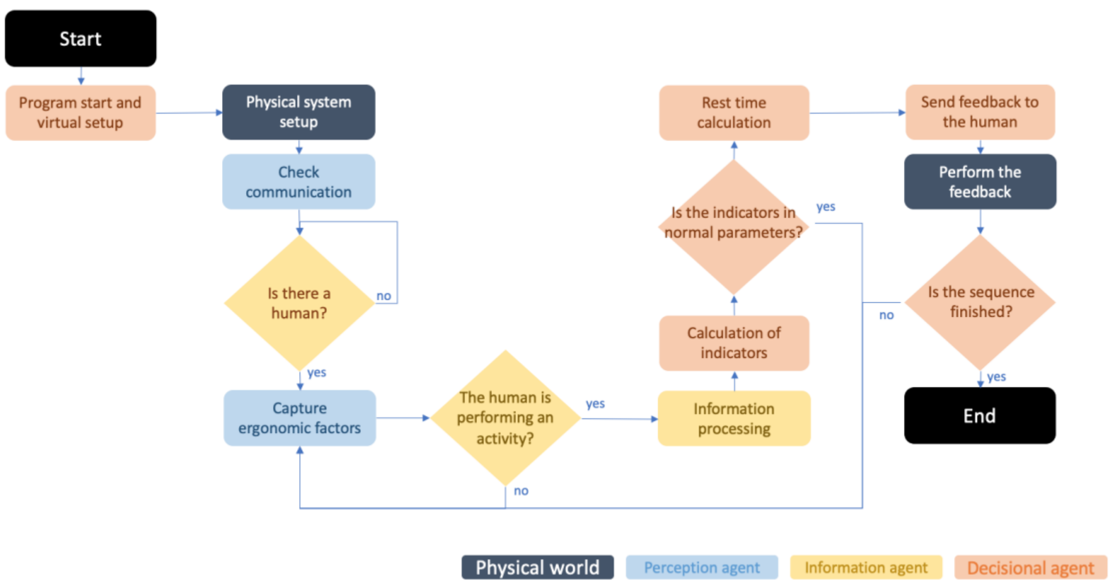

Figure 8: Flow diagram of H-DT

5.3.1. Cooperation

One of the most essential elements within a MAS is the cooperation between entities. With H-DT there are two types of cooperation: cooperation between virtual entities and cooperation between physical and virtual entities. These two subdivisions are of utmost importance within the project since the consistency of a DT depends on them. For this reason, the different interactions between entities and their behavior will be explained below.

5.3.1.1. Cooperation between virtual entities

Figure 9 shows the different interactions of the MAS for the realization of the different activities within the H-DT. As can be seen in these interactions, the model is quite like a heterarchical scheme among the entities of the system.

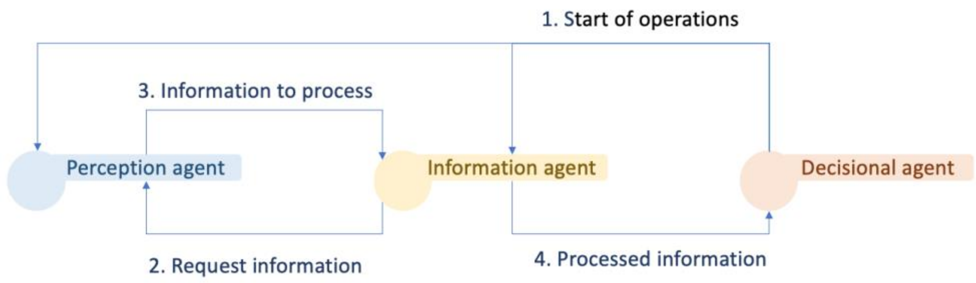

Figure 9: Diagram Cooperation between Virtual Entities

To understand the interactions in depth, each one of them will be explained below:

1. **Start of operations**: It is the System setup performed by the decisional agent. This setup is like a cooperation button between the different agents. In the case of the information agent, its setup is to check the communication channels with both the decisional agent and the Perception agent and of creating the attributes depending on the number of Perception agents that have been created. The agent is to confirm communication between the physical entities so that it is possible to capture the information required by the system. Finally, the decisional agent receives a confirmation of the setup. If the setup is successful, the information agent proceeds to the next step of cooperation. If the setup was unsuccessful, the agent sends an alarm to the user requesting to solve the problem, either with the physical or virtual entities. After the user's confirmation, the agent setup is re-launched.
2. **Request information:** In this interaction, the information agent is to request the update of the human information to the perception agent. This information request is made every ΔT, where T is the time variable.
3. **Information to process:** The perception agent collects the information of the human's posture points and this transitory information is passed to the information agent. Considering the request made in the previous step. If no human is found in the reading of the points of the human or cannot identify, the information passed to the information agent is empty.

4. **Processed information**: In this step, the information agent gives the processed data to the decisional agent. When talking about the processed data, it is understood as the points required for decision making. For example, if the activation performed by the human only involves the upper extremities but the perception can capture additional information to that required, the information agent will only pass the information of the relevant points of the upper extremities to the decisional agent. On the other hand, if the human cannot be captured in the reading, the information agent informs the decisional agent will receive a warning about this case and the latest data on the human.

5.3.1.2. Cooperation between virtual and physical entities

For the development of cooperation between physical and virtual entities, there are three main interactions, as shown in Figure 10.

1. **Check communication**: This step is the first interaction of the agents with the physical entities. This step verifies the perceptions are interacting correctly with their virtual counterparts. It is important to consider that the H-DT model will have as many perception agents as there are physical perceptions to supervise the behavior of the human inside the workstation.
2. **Send information:** After checking the information, a request for information is made, which is captured from the physical entity and stored temporarily by the perception agent. This data is the essential part of the cooperation behavior previously evaluated.
3. **Notify actions:** Finally, after the decisional agent decided based on the real-time indicators of the human. The decisional agent notifies when to take a break time and when to restart the activities. These alarms are displayed visually to the human through HMI and audible support.

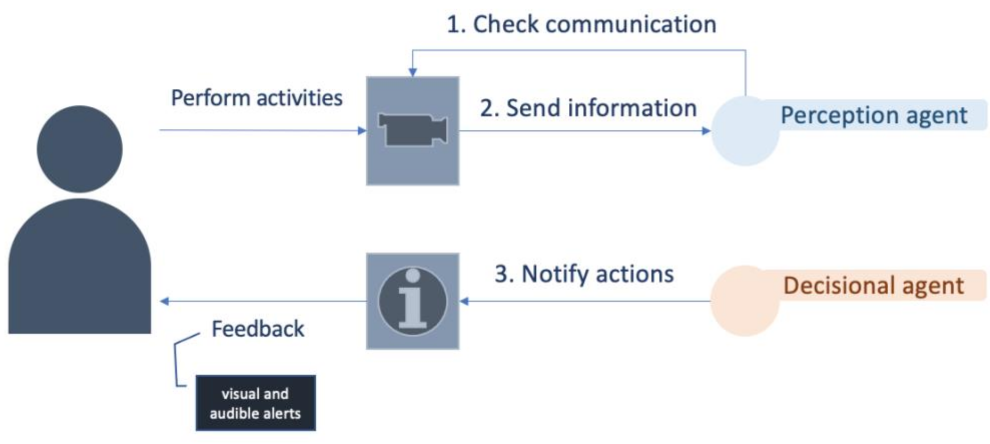

Figure 10: Diagram Cooperation between Virtual and Physical Entities

5.4. Phase 4: Implementation of the Human Digital Twin

The purpose of the H-DT implementation stage is to articulate the previous stages with the human activity within the production chain. In this way, the indicators calculated in the decisional agent will be established and used to make decisions within the model. This phase completes the model design process.

5.4.1. Human Task Description

The human task considered for the realization of the model was one of classification, visual recognition and decision making by the human. Therefore, a cognitive and physical load is observed in the activity. The task is explained below.

The products, which are wooden cubes of five different colors: blue, green, red, yellow, yellow, white, quickly arrive at the human workstation. The operator must recognize the product and change it for another one, considering the following rules: (1) the color of the cube must differ from the current cube (2) he cannot choose the same color twice. This means that the operator has two limitations, the color of the previous cube and the color of the current cube. The product changeover decision is made entirely by the operator and there is no intervention to the H-DT. Therefore, this is a repetitive task that also generates cognitive exhaustion and stress on the operator, because of the speed with which he must decide.

5.4.2. Indicators of Human Digital Twin

As mentioned throughout the paper, the decisional agent is to calculate the indicators and evaluate the human recovery times. Considering the above, it is necessary to evaluate the task to determine these indicators.

For the task described in the previous section, it is observed that there are two types of ergonomic factors present: physical and cognitive. To evaluate these factors, it is necessary to determine the method to be used, based on the risk factor represented by the task performed. When the physical aspect is observed in depth, it is concluded that the activity has an ergonomic risk factor of repetitiveness. A repetitive task, according to the UNE1005-5 (2017) standard, is one that comprises manual actions in work cycles that are performed with a continuous sequence. These tasks result in musculoskeletal wear and tear on the operator. ISO 11228-3 and EN 1005-5 recommend the use of the OCRA (Occupational Repetitive Action) method, or the simplified OCRA checklist method, for the evaluation of this risk factor. Since the OCRA method results in a long process, for the present project, the OCRA checklist method was chosen since it proves to have an accurate result without the complications derived from the initial method (Diego-Mas, 2015).

To evaluate the risk factor derived from the cognitive aspect of the task, we seek to assess the levels of human fatigue and stress based on the rate of errors per cycle of the activity. Given this, the Performance analysis indicator was proposed, which evaluates the cognitive loads of the human within the model. In conclusion, to determine the rest times, the decisional agent evaluates two indicators: the performance analysis and the OCRA checklist.

5.4.2.1. Performance analysis

This is an indicator created to evaluate the human inside the model, considering the following factors:

- *Number of pieces per cycle (P):* For the model, it was defined that there is a maximum number of pieces per cycle, which for this case is 12 pieces executed. Therefore, after each cycle, the worker or user must take a break. This factor gives the worker a proper rest time, so that he does not reach a high level of fatigue before taking a break.
- *Number of errors made (W):* This factor is evaluated considering the errors made in the last three cycles of the model. If the sum of the errors committed in the last cycles is greater than 1.5P, which for this validation is 18, an extended rest time should be taken. Thanks to this factor, we seek to quantify signs of stress or cognitive fatigue.
- *Back posture (B):* Seeks to prevent long-term injuries in a worker. If it is identified that the operator's back is bent over 30 degrees compared to the back of the chair, the operator should be instructed to improve his posture at the next break.

As can be seen in Figure 11, the behavior of the performance analysis indicator, where a cyclical rest time is given. This cyclic rest is given by the factor P and prevents the worker from reaching fatigue more quickly. But if the condition of factor W is fulfilled, the worker is given an extended rest time.

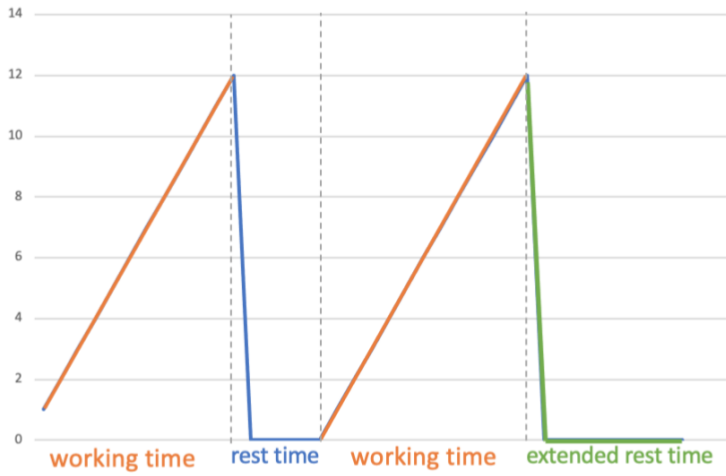

Figure 11: Rest time based on performance analysis indicator

5.4.2.2. Check list OCRA

The OCRA checklist is an abbreviated method of OCRA. OCRA checklist allows to evaluate a job and conditions of the operator in a much more efficient and faster way than with the original method. Therefore, this method is widely used within the different fields of industry (Diego-Mas, 2015).

The evaluation of this method is through 5 factors multiplied by a multiplying factor (MD). From the values of the scores of each factor, the OCRA Check List Index (ICKL) is got, a numerical value that allows classifying the risk as Optimal, Acceptable, Very Slight or Uncertain, Mild Unacceptable, Medium Unacceptable or High Unacceptable.

The following are the different factors and some values that are kept constant because of the conditions of the Workstation proposed for the model validation:

$$ICKL = (RF + FF + FFz + FP + ARF) * MC$$

- *Recovery Factor (FR):* This factor seeks to determine if the employee has the required breaks to perform his actions without being tired. The ideal ratio is 5:1, where for every 5 minutes of work there is at least 1 minute of recovery. In addition, these recovery times should not be included in lunch schedules.
- *Frequency Factor (FF):* Evaluates the frequency between the movements performed, since the more frequent a movement is, the more it can weaken a certain bone structure over another. The qualification of this factor will depend on the number of actions per minute the person performs.
- *Force Factor (FFz):* Considers the force exerted by the hands or arms when performing a certain action. Because the activity performed for this validation is almost null, this factor will not be considered.
- *Posture and Movement Factor (PF):* This analysis includes the evaluation of whether the hand, wrist, elbow, and shoulder have the support. It also considers the timing of the different actions.
- *Additional Risk Factor (ARF):* This factor encompasses other risks that may affect the operator's performance. Since the pace of work is determined by a machine, the factor here is constant at 2.

5.4.3. Decision evaluation

This section shows how the integration of the two indicators previously mentioned was carried out for the decision-making process by the decisional agent. First, although the OCRA Checklist provides an indicator approved by the UNE EN 1005-5 standard, it does not vary constantly so that a decision can be made on the worker's rest time. But it allows us to evaluate whether the recovery time is correct. Therefore, it was determined depending on the risk classification given by this indicator was going to be the recovery time of the worker. These recovery times are referenced in the Table 7.

Risk Level	Rest time (s)	Extended rest time (s)
Optimum	5	15
Acceptable	7	18
Uncertain	10	20
Unacceptable Mild	15	25
Unacceptable Medium	17	18
Unacceptable High	20	30

Table 7: Rest times based on OCRA checklist risk levels

To determine the rest time and extended rest time values shown in Table 7, an initial test was performed. The test involved several users and determined an average of the rest times required by the human depending on different risk level scenarios.

5.5. Phase 5: Validation model

This phase details the design process of the Smart Workstation, in which the model will be validated. In addition, this section also details how the human intends to interact with the layout and the activities to be performed within this design.

5.5.1. Smart workstation

A design of a Smart workstation that complied with the design parameters of the H-DT was carried out. The current model sees system composed of two cameras: hands and posture that act as sensors. Besides an HMI, which is the physical component that allows feedback from the H-Dt to the human. Finally, it has a conveyor belt that provides the human with the product. The *Figure 12* shows the components that are detailed below where the functionality of each one of them within the system is evidenced.

- *Hands camera:* it is the camera in charge of taking the movement of the hands inside the workspace. It also captures the products in movement on the conveyor. This camera is in the upper part of the Smart Workstation assembly, which allows a wide view.
- *Posture camera*: this camera is on the side and is to measure the posture of the human's upper extremities.
- *HMI (Human Interface Machine):* is the mechanism that allows communication between the human and the MAS, through this the human knows his rest times.
- *Conveyor:* performs the distribution of the products (buckets) in the workstation. This conveyor belt has a constant speed.

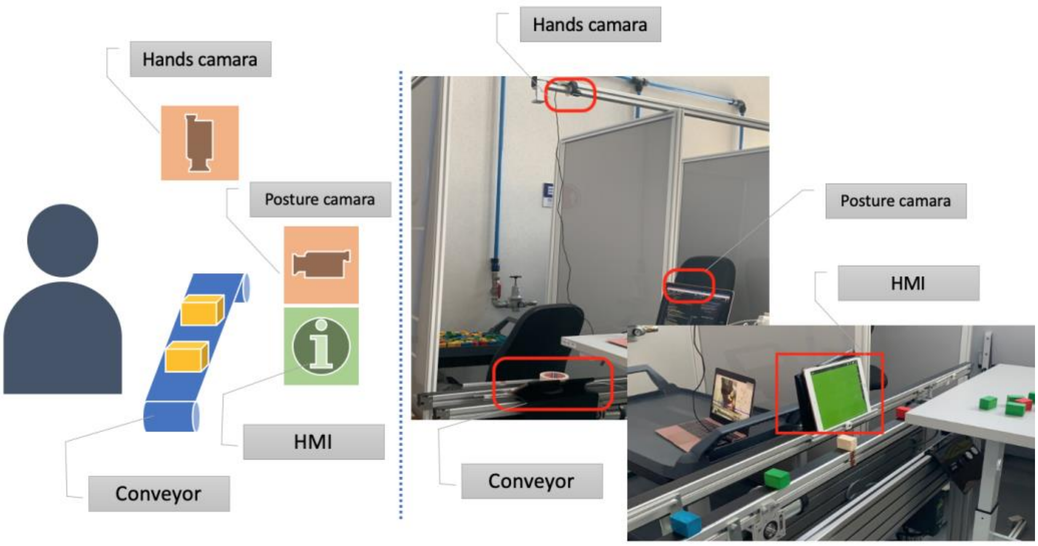

Figure 12: Smart Workstation Diagram

Other secondary components of the designed workstation are a chair and a table. The table has the purpose of having products in case the human needs to perform the activity and it is next to the chair and close to the reach. In addition, the vision system and the HMI are connected to the H-DT through a computer that does not interfere in the operator's work area.

The feedback received through the HMI is visually aided by colored indicators on the screen and has auditory aids that reinforce the instruction. In this way, the user easily perceives the sign regardless of the level of cognitive fatigue. For integrating these components described with the H-DT, it was established that the data gained by the perception agents is given by the vision system integrated by two cameras.

5.5.2. Experimental protocol

The experimental design to be presented below has the objective of evaluate the effects of the application of an H-DT.

To evaluate the effects of the H-DT application, the user was exposed to two scenarios. Instance A, where the user himself was to take his break times. In this instance there was no break time limit or any stimulus to remind him of this possibility. Instance B, which allowed the human to interact with the H-DT through the HMI, which allowed him to know his break times. The number of products to be processed by the human is kept constant. Table 8 shows the instances and variables that were kept constant.

Instance	Description	Variables
Instance A	No H-DT intervention.	**Number of products**:120 **Product color distribution:** random **Product delivery speed:** constant during testing
Instance B	H-DT determines human rest times.	

Table 8: Instances for H-DT experiment

Considering that in the Instance B is the integration with the H-DT, the distribution was carried out in cycles. The distribution of the 120 products was carried out in 10 cycles. This means that the variable P of the performance analysis indicator is 12 products.

For this aim of the experimental protocol, an additional indicator of those previously explained was included. This was an indicator of perception, where the human expressed the system with the instance in which he felt most comfortable. For this indicator, several statements were prepared where users would evaluate how much they agreed or disagreed with the statement and give a final rating of the models.

- I felt that the display helped me meet the goal.
- I felt less tired when I had the display.
- I felt that I took less time with the display.
- The colors on the display were intuitive.
- I made fewer mistakes with the display.

Finally, he gave a rating to each of the instance of the experiment. To avoid any input bias, the user had a quick test session with both scenarios. In addition, the order in which the instances were performed was randomly assigned to the users.

6. Results

This step shows the results got from the application of the experimental protocol in the proposed H-DT. For the application of the experimental protocol, 12 users were used for validation. These users were evaluated using the same workstation and activity conditions. In addition, the application of the probes was randomized to avoid bias in the data. Finally, the users had a test session prior to data collection, which allowed them to become familiar with the experiment and its implementation.

Initially, the behavior of the systems proposed in Experimental Protocol will be evaluated. For this experiment, there were two instances: Instance A and Instance B, the latter being the one involving the use of H-DT. The average total execution time of the 120 products in Instance A was 3,72 minutes with a standard deviation 0,69. Instance B got a mean of 3.26 minutes and a standard deviation of 0.14. Thus, as shown in Figure 13, Instance B had a lower variance among the test data and a lower mean than Instance B without the use of the proposed H-DT model. Despite this, it is also observed that there were users who got lower times in Instance A and 66% of the users did not have a variation greater than one minute between the two scenarios.

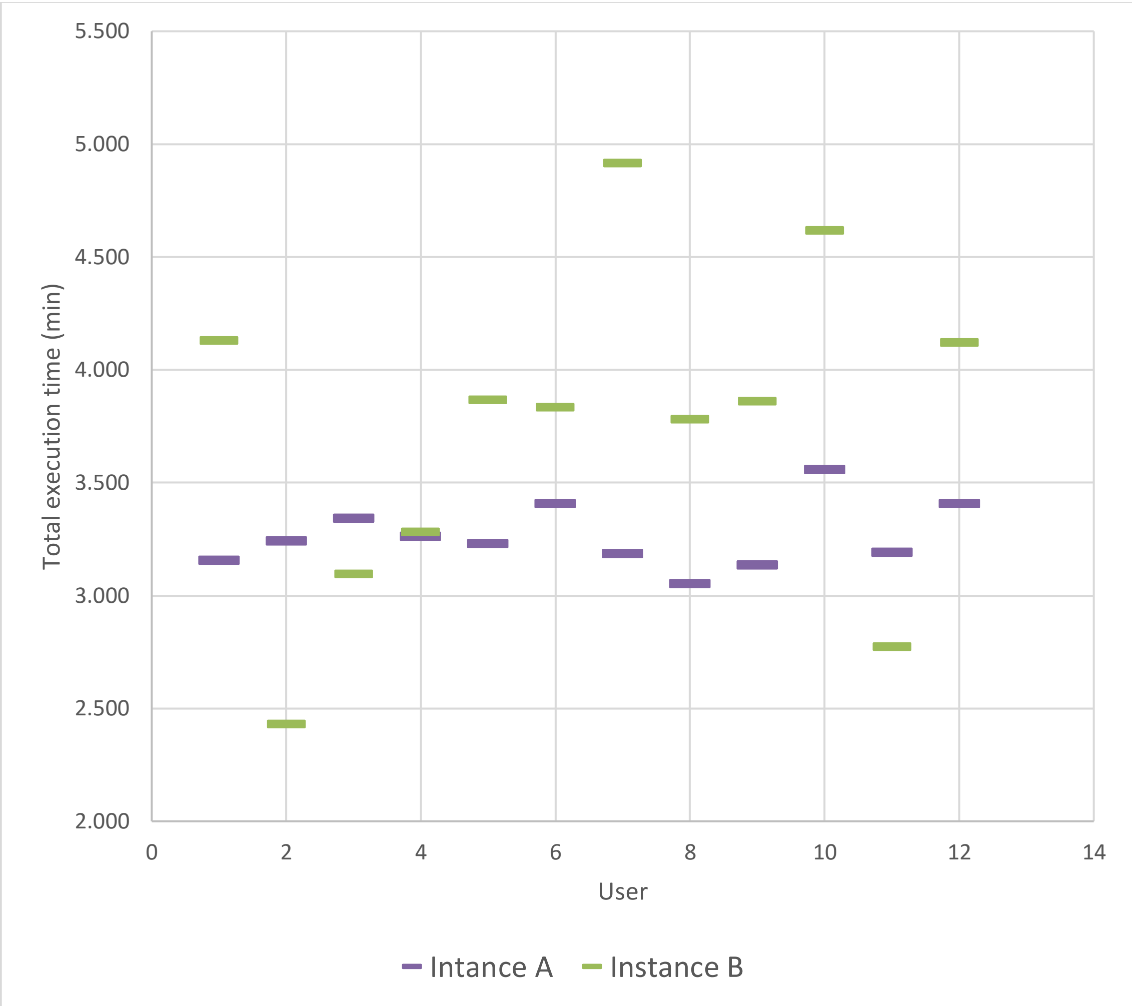

Figure 13: Total exclusion time graph of Instance 1.A and Instance 1.B

A different behavior is observed when comparing the rest times given in the different instances in Figure 14. It is observed that the instance without H-DT implementation, Instance A, has highly dispersed data with an average of 64,69 seconds. On the other hand, instance B has an average of 69,17 seconds. This means that users in the instance without H-DT implementation took on average less time to rest compared to the times designated by H-DT to rest.

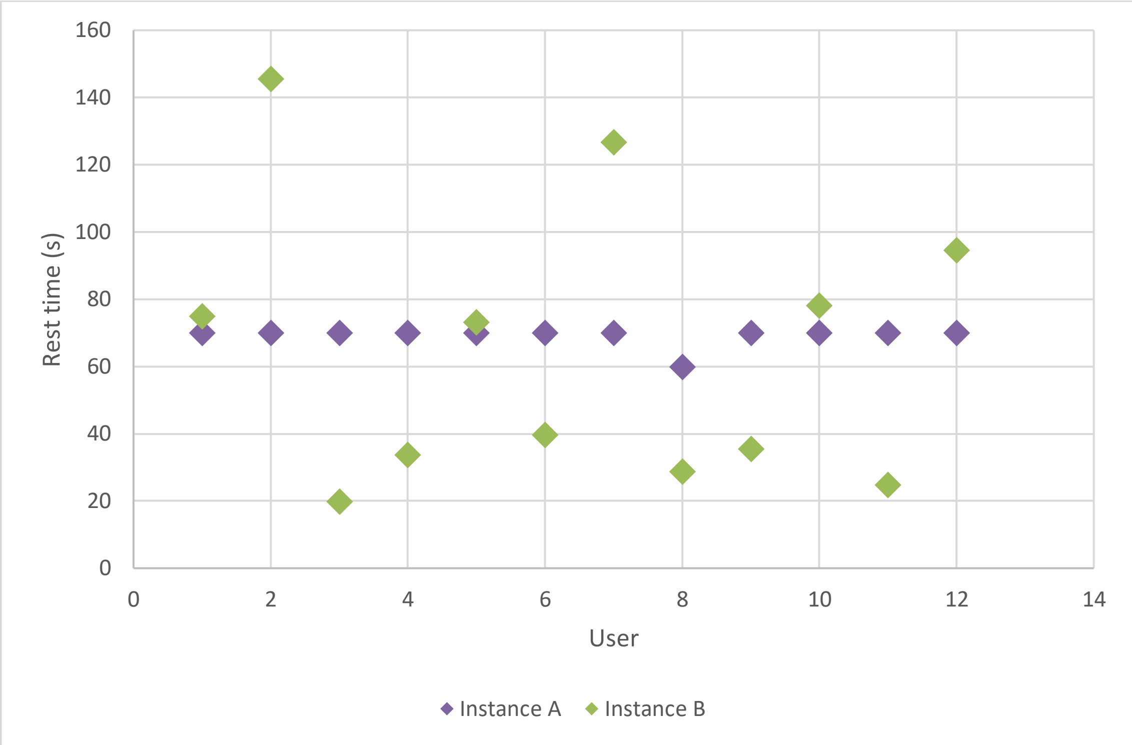

Figure 14: Total rest time graph of Instance A and Instance B

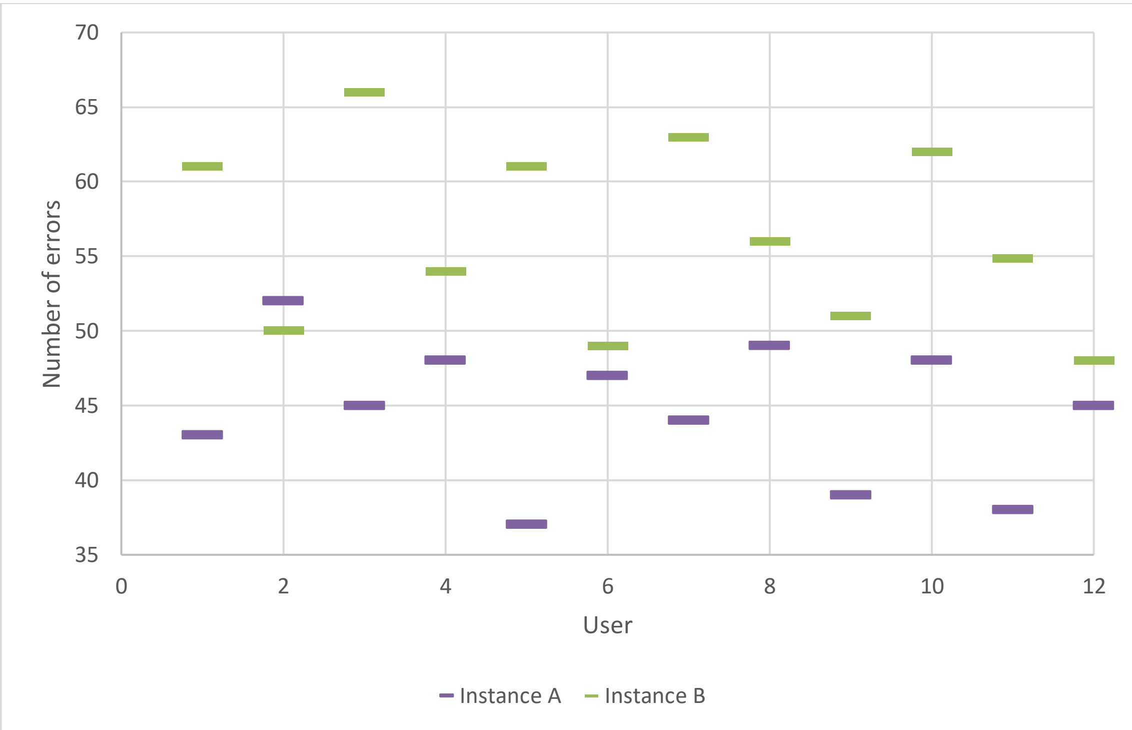

Figure 15: Number of errors graph of Instance A and Instance B

After the number of errors was evaluated, it can be observed that there is a difference of over 10 errors on average between instances of the experiment. Instance B had an average of 44,58 errors per user, and Instance A had an average of 56,31 errors per user. As shown in Figure 15, the dispersion of this variable was similar for both instances.

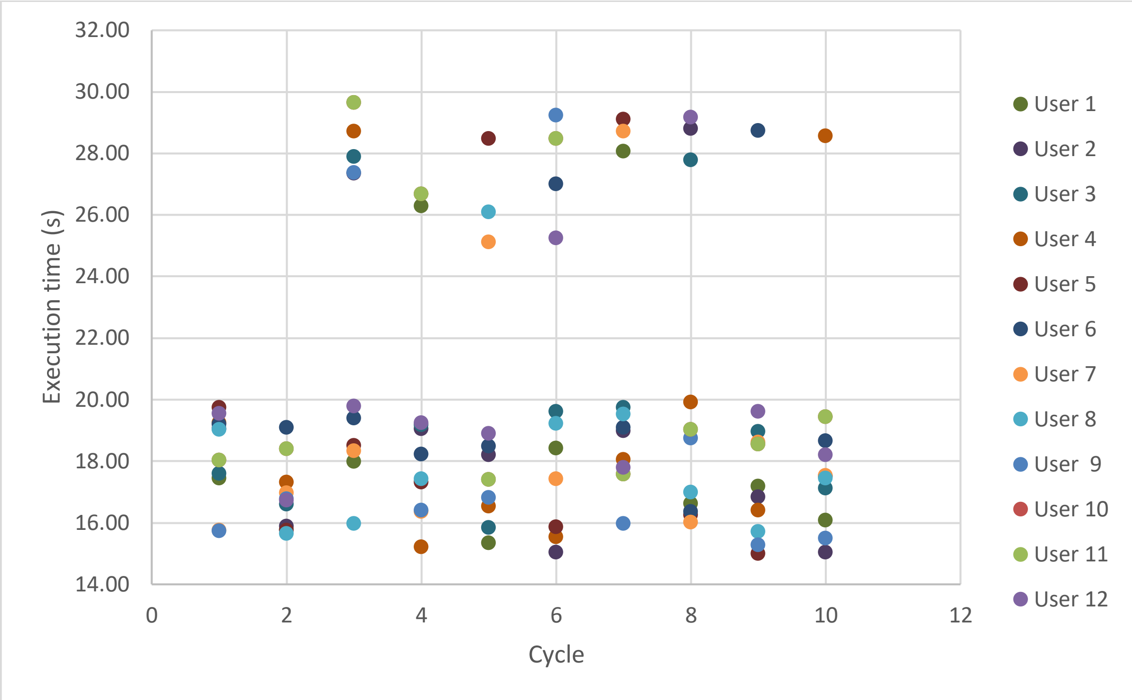

Figure 16: Total exclusion time graph by cycle of Instance B

Subsequently, the inter-cycle behaviors of Instance B were evaluated for the total execution time of the activities and the number of errors, Figure 16 and Figure 17 respectively. There are no marked trends among users regarding their behavior. Initially, it is shown that the average cycles have longer execution times, being the highest times the cycles where the users took breaks determined by the H-DT. The average value of the execution times in the cycles without rest time is 18,12 seconds, while the average execution time with rest time extended is 28,11 seconds. In addition, 92% of the users had two rest time extended cycles throughout the experiment. On the other hand, it is observed that after an extended rest time; the user had a decrease in the number of errors.

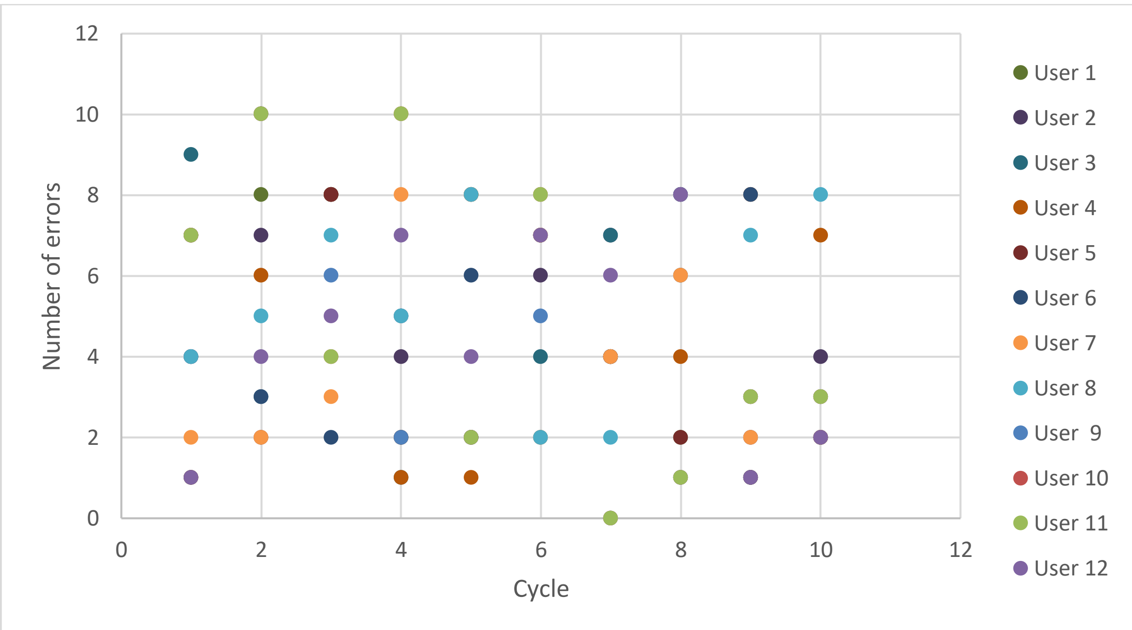

Figure 17: Number of errors graph by cycle of Instance B

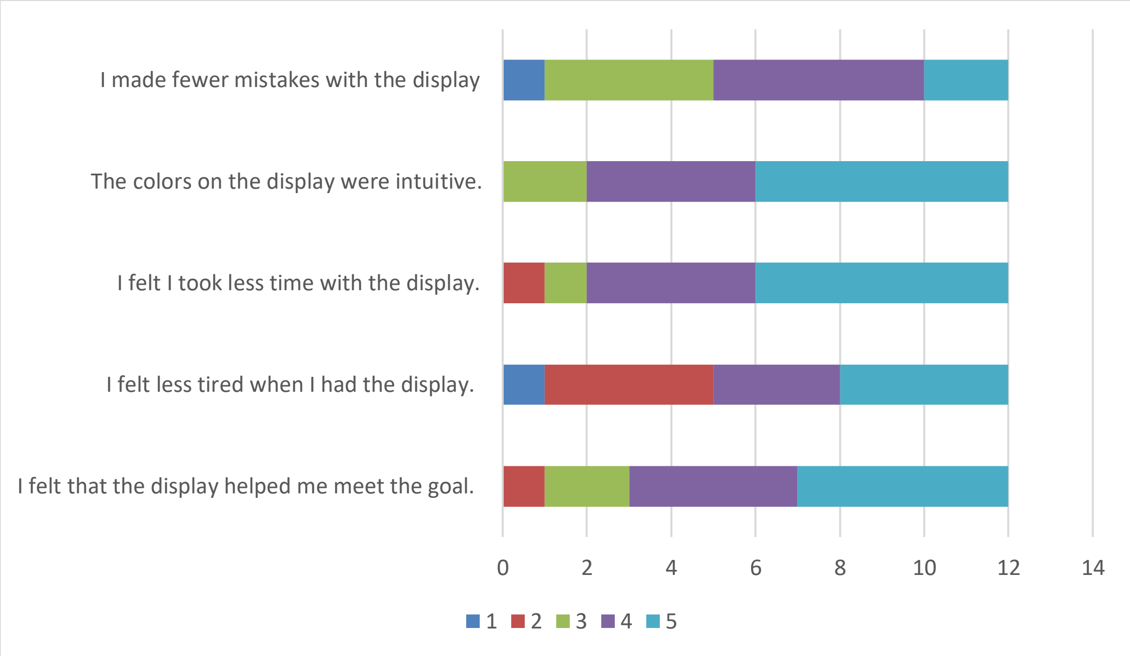

Figure 18: Perspective indicator results

Finally, the results of the perspective indicator are shown. Initially, the users showed they felt that the use of the instructions given by the H-DT through the display helped them to complete the activity in less time and make fewer errors. This is consistent with the ratings given to each of the models in which they took part. Users rated the instance with the use of the H-DT at 4,33 out of 5. In contrast, users rated their experience without the use of H-DT at 3,83 out of 5.

7. Conclusions and Future work

The realization of a digital representation of the human within a production system is not a recent issue. Since the 1990s, basic versions of the human have been integrated for analysis. What is relevant is the evolution of the virtual representation of the human over the following decades. Initially, the human was considered as another physical entity of the system in charge of performing activities within a system. This view has been transformed and has given way to a much more dynamic view of the human. Currently, the human is considered as a complex actor within the system that are far from being equal to any other physical entity of the system. Therefore, virtual representations of the human have essential requirements such as (1) Allowing real-time communication between the virtual entity and the human, (2) The valuation of physical and cognitive factors within the model. Including new Industry 4.0 technologies to realize these virtual representations has brought new challenges and opportunities. One of these new technologies is the DT, where the term H-DT is born when representing humans.

H-DT are tools that contribute to the operation of productive systems, such as cyber-physical production systems. In these environments, humans interact with the other entities of the system. Therefore, given humans, it is important to create an adaptive architecture that can adjust to changes in the environment and human behavior. Given all the above, this work presents a 5-stage methodology, which allows creating an architecture for H-DT focused on Smart Workstation of a CPPS.

First, a clear definition of requirements must be provided in order to project the project's needs, evaluate the capacity for the development of H-DT and measure if the project will generate contributions to the environment. For this project, three different criteria were defined to evaluate the criteria focused on relevance, resources and impact in order to cover the needs described above. In addition, it is important to consider the limitations that have been found in the evaluation of requirements.

Subsequently, a framework for H-DT is developed based on the described requirements. This allows the conceptual analysis of the components and the basic interaction between them to be clearly delimited before the implementation or prototyping phase. Therefore, in this step, the definition of the H-DT programming paradigm must be performed. For the project, the SMA programming paradigm was defined, which allowed the use of established tools in the GAIA methodology. This point can be very useful when including H-DT in a complex system with other physical entities.

The detailed design stage of H-DT is the design of behavioral and decision-making processes within the entities. When developing this stage, interactions within the virtual processes and interactions between the physical entities must be considered.

The fourth aspect of the methodology is the implementation of H-DT. This stage focuses on the development of the software and integrating this development with the physical world through the decision-making method. Decision making, since it is a representation of human behavior, can be done through indicators that adjust to the ergonomic or behavioral factor of the operator.

Finally, the validation stage of the model seeks to evaluate the proposal under different instances, which should corroborate the fulfillment of the requirements of the first stage. The model evaluation stage allowed us to observe that the communication from the virtual world to the physical world is one of the biggest barriers to the development of H-DT. This is because it is necessary to make feedback that is intuitive and easy to understand by the human, facilitating the taking of actions in the environment. Therefore, it is important to provide feedback that not only fits the human workstation but also the complexity of the activity being performed.

Future work may focus on searching for the representation of other human roles. Including cognitive factors, besides ergonomic and physical ones, allows for performing a DT in strategic roles. As DT is an emerging technology, it is important to explore other perspectives of the human being other than his role as an operator. This constant evolution in the virtual human representation will also allow the entry of new concepts, such as Industry 5.0 or technologies such as blockchain.

In addition, the proposed model could be implemented in the H-CPPS proposed. This model will include the construction of cooperative scenarios between other physical entities, such as machines and robots. With this, the field of application to human-machine interaction models is broadened. On the other hand, the inclusion of new indicators to the model and other measurement systems that help to extend the accuracy of the system could be performed.

8. References

Aceto, G., Persico, V., & Pescapé, A. (2019, October 1). A Survey on Information and Communication Technologies for Industry 4.0: State-of-the-Art, Taxonomies, Perspectives, and Challenges. *IEEE Communications Surveys and Tutorials*. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/COMST.2019.2938259

Angelopoulou, A., Mykoniatis, K., & Boyapati, N. R. (2020). Industry 4.0: The use of simulation for human reliability assessment. In *Procedia Manufacturing* (Vol. 42, pp. 296–301). Elsevier B.V. https://doi.org/10.1016/j.promfg.2020.02.094

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

Barricelli, B.R., Casiraghi, E., Fogli, D.:A survey on digita ltwin: Definitions, characteris- tics, applications, and design implications. IEEE Access. 7, 167653–167671 (2019)

Benotsmane, R., Kovács, G., & Dudás, L. (2019). Economic, social impacts and operation of smart factories in Industry 4.0 focusing on simulation and artificial intelligence of collaborating robots. *Social Sciences*, *8*(5). https://doi.org/10.3390/socsci8050143

Berry, C., & Barari, A. (2019). Cyber-Physical System Utilizing Work-Piece Memory in Digital Manufacturing. *IFAC PapersOnLine*, *52*(10), 201–206. https://doi.org/10.1016/j.ifacol.2019.10.023

Bousdekis, A., Apostolou, D., & Mentzas, G. (n.d.). A human cyber physical system framework for operator 4.0-artificial intelligence symbiosis. https://doi.org/10.1016/j.mfglet.2020.06.001

Chen, L., Cook, Di. J., Guo, B., & Leister, W. (2017, June 1). ssue on Situation, Activity, and Goal Awareness in Cyber-Physical Human-Machine Systems. *IEEE Transactions on Human-Machine Systems*. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/THMS.2017.2689178

Cimino, C., Negri, E., & Fumagalli, L. (2019). Review of digital twin applications in manufacturing. *Computers in Industry*, *113*, 103130. https://doi.org/10.1016/j.compind.2019.103130

Costa Mateus, J. E., Claeys, D., Limère, V., Cottyn, J., & Aghezzaf, E. H. (2019). Ergonomic and performance factors for Human-robot collaborative workplace design and evaluation. *IFAC-PapersOnLine*, *52*(13), 2550–2555. https://doi.org/10.1016/j.ifacol.2019.11.590

de Paula Ferreira, W., Armellini, F., & De Santa-Eulalia, L. A. (2020). Simulation in industry 4.0: A state-of-the-art review. *Computers and Industrial Engineering*, *149*, 106868. https://doi.org/10.1016/j.cie.2020.106868

Defty, TW., Kruger, K., & Basson, AH. (2021). Classification of Technical Challenges to Human-System Integration in Cyber-Physical Systems.

Diego-Mas, Jose Antonio. Evaluación del riesgo por movimientos repetitivos mediante el Check List Ocra. Ergonautas, Universidad Politécnica de Valencia, 2015. http://www.ergonautas.upv.es/metodos/ocra/ocra-ayuda.php

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

Erkoyuncu, J. A., del Amo, I. F., Ariansyah, D., Bulka, D., Vrabič, R., & Roy, R. (2020). A design framework for adaptive digital twins. *CIRP Annals*, *69*(1), 145–148. https://doi.org/10.1016/j.cirp.2020.04.086

García-Ojeda, J. C., De, J., Pérez-Alcázar, J., & Arenas, A. E. (2004). *Extending the*

Gaia Methodology with Agent-UML. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.108.7051&rep=rep1&type=pdf
Gil, M., Albert, M., Fons, J., & Pelechano, V. (2019). Designing human-in-the-loop autonomous Cyber-Physical Systems. https://doi.org/10.1016/j.ijhcs.2019.04.006
Huang, W., El-Darzi, E., & Jin, L. (2007). Extending the Gaia Methodology for the Design and Development of Agent-based Software Systems. In *31st Annual International Computer Software and Applications Conference - Vol. 2 - (COMPSAC 2007)* (pp. 159–168). IEEE. https://doi.org/10.1109/COMPSAC.2007.114
Ji, Z., Yanhong, Z., Baicun, W., & Jiyuan, Z. (2019). Human-Cyber-Physical Systems (HCPSs) in the Context of New-Generation Intelligent Manufacturing-generation intelligent manufacturing Human-cyber-physical system Human-physical system Cyber-physical system Knowledge engineering Enabling technology Manufact. https://doi.org/10.1016/j.eng.2019.07.015
Jimenez, J.-F., Bekrar, A., Trentesaux, D., & Leitão, P. (2016). A switching mechanism framework for optimal coupling of predictive scheduling and reactive control in manufacturing hybrid control architectures. https://doi.org/10.1080/00207543.2016.1177237
Jimenez, J.-F., Bekrar, A., Zambrano-Rey, G., Trentesaux, D., & Leitão, P. (2016). Pollux: a dynamic hybrid control architecture for flexible job shop systems. https://doi.org/10.1080/00207543.2016.1218087
Katiraee, N., Battini, D., Battaia, O., & Calzavara, M. (2019). Human diversity factors in production system modelling and design: State of the art and future researches. *IFAC-PapersOnLine*, *52*(13), 2544–2549. https://doi.org/10.1016/j.ifacol.2019.11.589
Kosacka-Olejnik, M., & Pitakaso, R. (2019). Industry 4.0: State of the art and research implications. *Logforum*, *15*(4), 475–485. https://doi.org/10.17270/J.LOG.2019.363
Kotronis, C., Routis, I., Tsadimas, A., Nikolaidou, M., & Anagnostopoulos, D. (2019). A model-based approach for the design of cyber-physical human systems emphasizing human concerns. In *Proceedings - 2019 IEEE International Congress on Internet of Things, ICIOT 2019 - Part of the 2019 IEEE World Congress on Services* (pp. 100–107). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/ICIOT.2019.00028
Lee, J., Bagheri, B., & Kao, H.-A. (2014). A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. https://doi.org/10.1016/j.mfglet.2014.12.001
Lim Tek Yong. (2011). A collaborative awareness framework for mobile tourist recommender system. In *2011 3rd International Conference on Computer Research and Development* (pp. 329–333). IEEE. https://doi.org/10.1109/ICCRD.2011.5764030
Liu, H., & Wang, L. (2020). Remote human–robot collaboration: A cyber–physical system application for hazard manufacturing environment. *Journal of Manufacturing Systems*, *54*, 24–34. https://doi.org/10.1016/j.jmsy.2019.11.001
Mahmood, K., Karaulova, T., Otto, T., & Shevtshenko, E. (2019). Development of cyber-physical production systems based on modelling technologies. *Proceedings of the Estonian Academy of Sciences*, *68*(4), 348–355. https://doi.org/10.3176/proc.2019.4.02
Melesse, T. Y., Pasquale, V. Di, & Riemma, S. (2020). Digital Twin Models in Industrial Operations: A Systematic Literature Review. *International Conference*

on Industry 4.0 and Smart Manufacturing (IS, *42*, 267–272. https://doi.org/10.1016/j.promfg.2020.02.084
Mendoza P., M. A., & Cuellar, S. (2020). Industry 4.0: Latin America SMEs Challenges. In *2020 Congreso Internacional de Innovación y Tendencias en Ingeniería (CONIITI)* (pp. 1–6). IEEE. https://doi.org/10.1109/CONIITI51147.2020.9240428
Mourtzis, D., Vlachou, E., Dimitrakopoulos, G., & Zogopoulos, V. (2018). Cyber-Physical Systems and Education 4.0 -The Teaching Factory 4.0 Concept. In *Procedia Manufacturing* (Vol. 23, pp. 129–134). Elsevier B.V. https://doi.org/10.1016/j.promfg.2018.04.005
Nikolakis, N., Alexopoulos, K., Xanthakis, E., & Chryssolouris, G. (2019a). The digital twin implementation for linking the virtual representation of human-based production tasks to their physical counterpart in the factory-floor. *International Journal of Computer Integrated Manufacturing*, *32*(1), 1–12. https://doi.org/10.1080/0951192X.2018.1529430
Nikolakis, N., Alexopoulos, K., Xanthakis, E., & Chryssolouris, G. (2019b). The digital twin implementation for linking the virtual representation of human-based production tasks to their physical counterpart in the factory-floor. *International Journal of Computer Integrated Manufacturing*, *32*(1), 1–12. https://doi.org/10.1080/0951192X.2018.1529430
Nikolakis, N., Maratos, V., & Makris, S. (2018). A cyber physical system (CPS) approach for safe human-robot collaboration in a shared workplace. https://doi.org/10.1016/j.rcim.2018.10.003
Paredes-Astudillo, Y. A., Jimenez, J.-F., Zambrano-Rey, G., & Trentesaux, D. (2020). Human-Machine Cooperation for the Distributed Control of a Hybrid Control Architecture (pp. 98–110). Springer, Cham. https://doi.org/10.1007/978-3-030-27477-1_8
Paredes-Astudillo, Y. A., Moreno, D., Vargas, A.-M., Angel, M.-A., Perez, S., Jimenez, J.-F., … Trentesaux, D. (2020). Human Fatigue Aware Cyber-Physical Production System. In *2020 IEEE International Conference on Human-Machine Systems (ICHMS)* (pp. 1–6). IEEE. https://doi.org/10.1109/ICHMS49158.2020.9209366
Pinzone, M., Albè, F., Orlandelli, D., Barletta, I., Berlin, C., Johansson, B., & Taisch, M. (2020). A framework for operative and social sustainability functionalities in Human-Centric Cyber-Physical Production Systems. *Computers and Industrial Engineering*, *139*, 105132. https://doi.org/10.1016/j.cie.2018.03.028
Rajkumar, R., Lee, I., Sha, L., & Stankovic, J. (2010). Cyber-physical systems: The next computing revolution. In *Proceedings - Design Automation Conference* (pp. 731–736). https://doi.org/10.1145/1837274.1837461
Rauch, E., Linder, C., & Dallasega, P. (2019). Anthropocentric perspective of production before and within Industry 4.0 Anthropocentric production Industry 4.0 Cyber-physical production systems Operator 4.0 Systematic literature review Human-centred production. https://doi.org/10.1016/j.cie.2019.01.018
Romero-Silva, R., & Hernandez-Lopez, G. (2019). Shop-floor scheduling as a competitive advantage: A study on the relevance of cyber-physical systems in different manufacturing contexts. https://doi.org/10.1016/j.ijpe.2019.107555
Ruiz Garcia, M. A., Rojas, R., Gualtieri, L., Rauch, E., & Matt, D. (2019). A human-in-the-loop cyber-physical system for collaborative assembly in smart manufacturing. In *Procedia CIRP* (Vol. 81, pp. 600–605). Elsevier B.V. https://doi.org/10.1016/j.procir.2019.03.162
Stark, R., Fresemann, C., & Lindow, K. (2019). Development and operation of Digital

Twins for technical systems and services. https://doi.org/10.1016/j.cirp.2019.04.024
UNE, Normalización Española. (2007). Safety of machinery - Human physical performance - Part 5: Risk assessment for repetitive handling at high frequency.
Wu, C., Zhou, Y., Vinicius, M., Pessôa, P., Peng, Q., & Tan, R. (2020). Conceptual digital twin modeling based on an integrated five-dimensional framework and TRIZ function model. https://doi.org/10.1016/j.jmsy.2020.07.006
Zhong, R. Y., Xu, X., Klotz, E., & Newman, S. T. (2017). Intelligent Manufacturing in the Context of Industry 4.0: A Review. *Engineering*, *3*(5), 616–630. https://doi.org/10.1016/J.ENG.2017.05.015