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Technical Considerations for the Conformation of Specific Competences in Mechatronic Engineers in the Context of Industry 4.0 and 5.0

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Abstract: The incursion of disruptive technologies, such as the Internet of Things, information technologies, cloud computing, digitalization and artificial intelligence, into current production processes has led to a new global industrial revolution called Industry 4.0 or Manufacturing 4.0. This new revolution proposes digitization from one end of the value chain to the other by integrating physical assets into systems and networks linked to a series of technologies to create value. Industry 4.0 has far-reaching implications for production systems and engineering education, especially in the training of mechatronic engineers. In order to face the new challenges of the transition from manufacturing 3.0 to Industry 4.0 and 5.0, it is necessary to implement innovative educational models that allow the systematic training of engineers. The competency-based education model has ideal characteristics to help mechatronic engineers, especially in the development of specific competencies. This article proposes 15 technical considerations related to generic industrial needs and disruptive technologies that serve to determine those specific competencies required by mechatronic engineers to meet the challenges of Industry 4.0 and 5.0.

Keywords: Industry 4.0; competency-based education; cyber-physical systems; specific competencies; engineering education

1. Introduction

Today's industrial production, characterized by globalization and uncertainty, is being affected by the rapid development and application of various technologies, including Information and Communication Technologies (ICT) [1], and is also pressured by market demands for increasingly specialized and differentiated products. The incursion of frontier technologies in production lines makes the changes in industries and in society in general accelerated, and has wide repercussions in industry value chains and in contemporary cities. It can be said that the world is undergoing a transition between two major industrial events. To meet the challenges facing companies, a new industrial paradigm known as "Industry 4.0" (I4.0) has emerged. This new industrial production proposal involves generating new organizations and proposals for control of high value-added systems [2].

Consequently, the industrial world is in a phase of accelerated transition between the industrial revolution characterized by electronics, computing and automation (Manufacturing 3.0 (I3.0)) to another industrial revolution characterized by digitalization, cloud computing, the internet of things and cyber-physical systems (CPS), and in another less rapid transition phase between I4.0 characterized by the displacement of humans from production systems and Industry 5.0 (I5.0) which seeks closer collaboration between operators and machines.

The effects of I4.0 are felt in companies, universities, cities and modern society in general. I4.0, so conceived in 2011 in Germany [3], is similar to the era of mechanization characterized by steam power; it is also similar to the era where production lines and electricity were the engine of the economy, as well as to the era where computing and automation improved and optimized production systems. This means that I4.0 is a new industrial revolution and its effects are global and disruptive, mainly in companies and production processes.

Changes in industries are driven by the incursion of new technologies, such as the Internet of Things (IoT), Collaborative Robotics, Artificial Intelligence (AI), Augmented Reality (AR), CPS and Digital Twins (DT), among others [4].

I4.0 is a philosophy of the large-scale integration of methods, tools, systems, knowledge and technologies whose purpose is to enhance production chains by improving and optimizing processes. In fact, an important objective of the fourth industrial revolution is to optimize the third computerized industrial revolution (I3.0).

I4.0 proposes the digitization of the entire value chain through the integration of physical infrastructure into systems and networks associated with frontier (disruptive) technologies to create added value [5]. In this way, a production plant that is ready for I4.0 may be conceived as a system of systems, where elements of those partners that are part of the value chain (e.g., suppliers, manufacturers, and factory employees) must operate together to achieve the stated goals [6].

I4.0 is used to mutually interconnect the following three factors [7]:

1. The process of integration and digitization of simple technical-economic relationships into complex networks.
2. The process of digitalization of product and service offerings.
3. In venturing into new market models.

Today many activities performed by mankind are interconnected in various ways with the help of communication systems. It is highly likely that I4.0 will improve the lives of human beings in many aspects and in various areas of opportunity. I4.0 is initiating various dynamic changes in the way companies envision and the ways products are manufactured, which will involve changes at all levels of manufacturing and supply chains, as well as changes in manufacturing line workers, engineers, and CPS developers, as well as changes in customers [8]. In the same way, education, and especially engineering education, will have to adjust to the new industrial paradigm seeking to provide graduates capable of facing the challenges required by the companies of today and the near future.

On the other hand, digitization is a process of high value and interest within I4.0. However, the core technologies of this new industrial revolution are CPSs [5]. These systems are of utmost importance in I4.0, since they act as a means to relate the physical world, integrated by elements such as mobile devices, sensors, mechanical systems and actuators, with the Internet seeking to simulate or reflect the events of reality in a digital or computational environment called cyberspace, with the aim of processing inspection and time management [9].

Currently, CPSs have diverse applications in critical situations where it is required to have reliable, protected and safe functions, and where the synchronization is subject to specific and strict requirements, such as in homes and universities or in automated systems where human operators work, or in modern production systems where there are collaborations between humans and robotic systems [10]. CPSs represent the core technology of I4.0, so the characterization and study of CPSs are of great importance for industry and engineering education.

Digital Twin (DT) technology, similarly to CPS, has an extremely important role in I4.0. Since their conception, it was announced that DTs would give a revolutionary technological boost to companies and industries, since with them various operations and processes can be simplified [11]. A DT is a virtual copy or replica of a dynamic system composed of physical elements that fulfill a specific function. The physical system and its replica are directionally interconnected, so that there is a feedback between them composed of information from the physical elements (e.g., sensors), and from processed or evaluated information from the DT to the physical part.

DTs are the most important technologies with the greatest applications today in I4.0, providing industrial processes with efficiency and optimization, among other important benefits. The study and analysis of DTs are important and necessary for those companies or industries seeking to improve their processes under the I4.0 philosophy. It is important to note that the technologies of the DTs and CPS should be taught in universities to engineers as they represent the central basis of the fourth industrial revolution so that the design, construction and operation of the same will be crucial for the current and future industry.

From an operational point of view, I4.0 seeks to optimize I.30. In this sense, IA is a discipline that offers various algorithms to achieve the optimization of production systems. In fact, according to [12] the employment of Industrial AI towards process optimization in manufacturing is gaining rapid traction, enabling smarter, more efficient data-driven decision-making by leveraging both historical and real-time data. Thus, the application of Industrial AI for process optimization can contribute to make manufacturing processes more profitable, while also being more sustainable and efficient. Artificial Intelligence (AI) and its various algorithms are computational tools that greatly assist the development of intelligent equipment. In fact, it can be stated that AI is a cognitive science that is used for research, in image and natural language processing, in robotic systems and for automatic learning, among other applications related to I4.0 to conceive, design, manufacture and control systems considered intelligent. In addition, AI, in conjunction with Big Data, IoT, cloud computing, DTs and CPS, among other technologies, will make companies and industries of today and the future operate in an optimal, efficient, flexible, lean and green way. Currently, industrial AI (Artificial Intelligence with applications in industries) is in an initial or incipient phase, so it is necessary to study and propose techniques, structures, frameworks and methodologies for its correct use and implementation in the industrial sector [13].

AI is a field of knowledge that is not new, but that will now be a necessary input for those companies that want to operate under the context of the I4.0 and that, due to its great importance, should be a subject of formal study in engineering education. The adaptation of companies and universities to I4.0 must be in a certain sense accelerated because many companies already handle various disruptive technologies and therefore put pressure on other companies that make up the value chain to upgrade. Some countries, such as Germany and France are in an accelerated process of industrial reconversion, but other countries such as Mexico or Brazil do not present a substantive dynamic of change. The urgency for change is based on two facts: (1) Many companies have not measured the implications of I4.0 and, therefore, have not started upgrades and (2) It has begun to be discussed that there is already a fifth industrial paradigm known as Industry 5.0 (I5.0), which seeks to integrate human beings back into industrial processes, improve the environment, obtain better social benefits and implement resilient systems, among other innovations.

I5.0 focuses on the following basic elements [14]: (1) On human agency, (2) On sustainability, and (3) On the ability of a system to maintain important functions and processes in the face of stress by resisting and then recovering or adapting to change (resilient system). I5.0 will bring about relationships between systems of different classes and technological configurations associated with I4.0 that are linked together for mutual benefit and between skilled operators (symbiotic relationship between technology and humans), to create workplaces and work environments where the human being is at the center of the work and is able to generate high value-added, top quality and customized products. The I4.0 is characterized by the implementation of state-of-the-art technologies and with this, better and high performances are achieved; on the other hand, the I5.0 seeks to establish highly cooperative relationships of the synergistic type between production systems improved with new technologies and social systems, with the aim of seeking a more personalized and massive production of parts, products, solutions and services [15]. I5.0 should be considered in the education of today's engineers, since, similar to I4.0, I5.0 represents technological changes and challenges in companies and society in general.

Industry 4.0 is changing the world and teaching processes, so higher education needs to be innovated. In fact, higher education institutes are contributing to these changes through research and education [16]. I4.0 causes engineering education to undergo significant changes, requiring teachers to modify traditional engineering education. Teachers have to train their students under the guidelines of the new industrial paradigm so that they can cope with I4.0 and have the ability to continue research on the subject under lifelong learning conditions. In other words, it is required to establish such tangible engineering skills, both in processing and thinking that can be applied to emerging technologies [17].

The I4.0 vision seeks to train engineers who are capable of performing more complex activities, since robots with intelligence will replace operators and engineers in various industrial activities. Therefore, the education of professionals must be oriented towards obtaining information and improving their skills in tasks and activities that cannot be performed by robots. I4.0 causes a displacement of humans from production systems due to high automation and AI. This distortion of I4.0 in the activities of professionals causes education to seek mainly skills and abilities, and specialized development in engineers, for example, in the mastery and applications of AI and in the handling of large amounts of data (Big Data). In this sense some of the skills required today to face I4.0 are advanced analytics, digital security and IoT. It should be noted that in order to align with the challenges of I4.0, education is moving towards the digitization of its processes [18].

I4.0 seeks to ensure that intelligent production processes generate customized results through more efficient, sustainable and environmentally friendly production strategies. However, in order to achieve the proposed objectives (producing efficiently and under sustainable criteria), entrepreneurs must face certain challenges, such as the lack of personnel with the necessary knowledge and skills to enable them to develop, implement and manage high-tech systems. Therefore, the implementation of I4.0 requires the labor market to change and to promote the training of professionals with the necessary knowledge and skills so that companies can achieve their objectives within this new industrial paradigm [19].

In this context, engineering education must seek approaches, methods or educational models that allow it to train the engineers of the present and future to meet the challenges imposed by the I4.0 and the fifth industrial revolution, without forgetting that in many countries the transition from manufacturing 3.0 (I3.0) to I4.0 is taking place. Competency-Based Education (CBE) may be an ideal educational approach for training engineers in the context of I4.0, as it fosters comprehensive training, flexibility and self-management, promotes active learning, develops technical and social skills, and encourages engineers to solve problems in complex situations [20], among other relevant features of this approach. Competency is considered substantially important and is given high consideration because of its ability to provide competitive advantage to organizations. One of the challenges that professionals and operators face in the workplace is to a constantly changing environment, whether brought about by management or by industrial change in technology or ideology. These changes have a significant impact on the skill and competency needs of workers [21].

On the other hand, the specific competencies associated with the job are essential to find those professionals required by companies, so a meticulous identification and description of them helps employers not only to obtain employees in line with their requirements, but also provides information to determine the measures to be adopted in the company. Specific competencies are the guidelines for universities to develop their curricula. I4.0 and cutting-edge technologies have caused progressive companies to seek professionals trained in information technologies and digital systems [22].

CBE is both goal-oriented and outcome-oriented. Competency-based education focuses on standards or norms that involve all the processes involved in the models and modalities that adopt it, namely: standardization, assessment, certification, recognition, training and validation. In this arrangement, competency standards can motivate the learning of individuals and groups, but also limit and even discourage it [23].

The I4.0 promotes changes in engineering education, but with more emphasis on Mechatronics Engineering, so it is necessary that education in mechatronics and, in general, mechatronics as an area of knowledge, must be reinvented. There is no single path that indicates how mechatronics should be reinvented, but it is possible to know important aspects of its evolution. In this sense, today's mechatronic systems have very advanced capabilities that are mainly based on the evolution of mechatronic enabling technologies and of the mechatronic design methodology itself. It is possible to observe the improvement in intelligence of mechatronic systems and, above all, the increase in their complexity. The changes that are occurring in the technologies and in the mechatronic design methodology itself drive the new processes, products and systems that are generated under the vision of mechatronics to possess new properties and capabilities, which drive the generation of new systems that support productive systems [24]. These devices or products evolved from simple monitoring to self-optimization of their performance.

Mechatronics Education is essential in I4.0, so it is necessary to apply or propose appropriate educational models or approaches for the training of engineers that allow their incorporation into the working world whose dynamics is being affected by the integration of various disruptive technologies. In this sense, this article proposes a general conceptualization of the technologies and processes of I3.0, I4.0 and I5.0, mainly related to CPS, DT and technological conditioning (Retrofitting), with the objective of proposing a series of technical considerations through which it is possible to build specific competences for mechatronic engineers. The importance of CBE and active methodologies in the training of the engineer in the vision of I4.0 and I5.0 is discussed.

Although all the competencies (basic, generic, specific) are important in the training of the mechatronic engineer, this article only focuses on proposing some technical considerations that help to shape the specific competencies. It does not propose an in-depth study or the methodological construction of these competencies, because in reality these are shaped taking into account the local, regional or national needs of companies and industries.

2. Materials and Methods

This section presents the methodology used in this research work. The type of research was descriptive-qualitative, because the generalities of I4.0 and I5.0, and their relationships with engineering education, especially with Mechatronics Engineering and CBE, were analyzed. This part of the paper consists of two general blocks: (1) The first block is related to the industrial aspects of I4.0 and I5.0 and (2) The second block is associated with the aspects of engineering education. The first block describes some aspects related to industrial revolutions, I4.0 and I5.0 and the technologies that support them, as well as the definitions of CPS, DT, AI and simulation. Block 2 describes some important aspects of engineering education and Mechatronics Engineering education in the vision of I4.0, CBE and active methodologies. With the analysis of both blocks, 15 guides for the conformation of specific competences in Mechatronics Engineering are proposed.

2.1. Industries 4.0 and 5.0

This section presents various concepts and definitions that shape I4.0 and I5.0, as well as the transition process between I3.0 and I4.0. Some disruptive technologies, CPS and DT, are described, and the concept of technology overhaul is discussed. The understanding and analysis of these technologies will allow to know those technical characteristics important for the shaping of specific competences in mechatronic engineering.

2.1.1. General Aspects of Industrial Revolutions

Throughout history, each industrial revolution has changed the way of life of the human race; in fact, the industrial paradigms that are currently being presented provoke a broad reflection on what human beings can do in terms of technology and on the capacity and enormous importance of people's creativity [25]. An industrial revolution or industrial paradigm is generally conceived by human beings as a single occurrence or an isolated event, but in reality paradigms in a given time bring about changes and innovations that give impetus to companies and improve world economies. History has shown that the changes brought about by industrial paradigms are progressive, i.e., they are modernizations of previous ones [26].

Each industrial revolution has one or more core technologies and processes that distinguish them. The rise of the textile industry was the main feature of the first industrial revolution (IR1.0); the introduction of electricity, production lines for mass production and internal combustion systems were the core technologies of the second industrial revolution (IR2.0) and the introduction of automation and computers were the focus of the third industrial revolution (IR3.0) [27]. The last two technological paradigms appeared just 12 years ago and their core technologies are CPS and DTs, for the case of I4.0 (fourth industrial revolution) and human-machine collaboration systems and personalization, for the case of IR5.0 (fifth industrial revolution). Figure 1 shows each known industrial revolution and its core technologies [28].

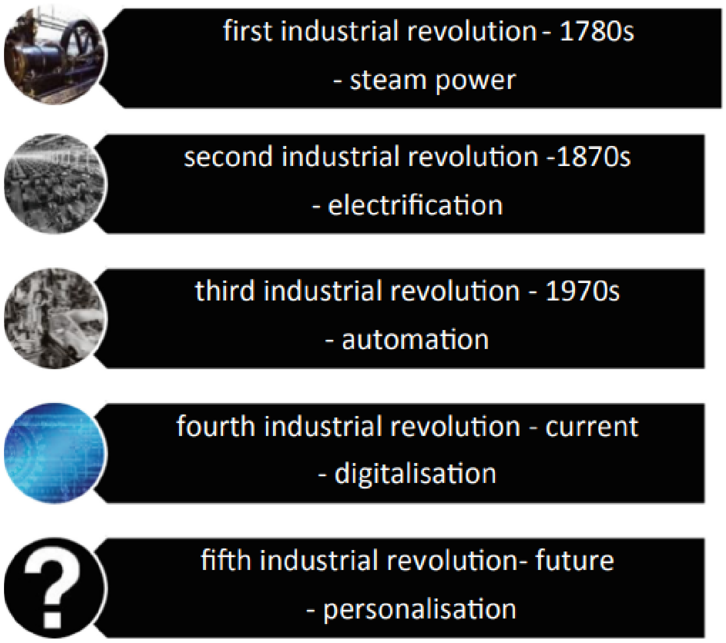

Figure 1. Industrial revolutions and their core technologies [28].

Steam engine, electrification, automation, digitization and customization describe one of several characterizations of industrial revolutions (see Figure 1). Another such characterization up to I4.0 is the following [29]:

IR1.0: Steam systems marked the beginning of IR1.0 in human history.

- IR2.0: Assembly lines for mass production of cars involved the systematization of manufacturing processes.
- IR3.0: The introduction of the computer increased production volumes and reduced the importance of human labor.

- I4.0: The CPS are identified as the central part of the I4.0 technologies, since developments in computing and in the conformation of high-powered information systems allow productive systems to operate in an interconnected way.

According to Ratanlal [30] IR5.0 should perfectly be the elaboration of the modern manufacturing framework to enable man and artifact to perform tasks hand in hand, combining the specific and cognitive knowledge of workers and the precise and specialized knowledge of robots to introduce an ultramodern way of life in care.

2.1.2. Industry 4.0 and Industry 5.0 Definitions

In order to know the field of action of the mechatronic engineer, it is necessary and important to know the definitions and general aspects of I4.0 and I5.0.

According to Dilmé [31], in some studies conducted by universities and companies, they found that 90% of the data in the world today has been created only in the last two years, 30% of companies started to monetize their data assets in 2017, and according to S&P 500, the average lifespan of an industry has shrunk by 50 years in the past century, from 67 years in 1920 to 15 years today; 86% of CEOs consider digital their first priority and 76% of millennials believe innovations are their most valuable trait. These studies show the changes that are occurring at an accelerated rate in industries and that have to do mainly with the changing demands of consumers and that are related to the applications of novel (disruptive) technologies in production processes.

I4.0 will bring about major changes in companies, from technical to organizational issues [32]. It is possible to exemplify some visions of the changes that I4.0 will bring about:

- New level of social-technical interaction: It is possible to plan high value-added processes between organizations using autonomous and self-organized production resources.
- Intelligent products: The operating parameters of the production lines and of the generated products are known data and the information of both is exchanged. The production of the products can be optimized if it is possible to form them into technological groups.
- Individualized production: Flexibility in production systems allows the specifications or characteristics required by customers and the products themselves to be taken into account during the design of the product life cycle.
- Autonomous control: Operators will be able to take control and reconfigure intelligent technology assets taking into consideration the highly sensitive objectives of today's environment.
- Product design controls product-related data: Product information is key and crucial for product life cycle management and development.

On the other hand, the World Economic Forum applied a survey to 371 companies of high global relevance, to find out which were the main technological resources that are driving innovations in current jobs, in competencies and that will be determinant in future jobs [33]. The results obtained from this survey were as follows:

1. Systems that increase computational capacity and the use of large amounts of data (Big Data).
2. The Internet that allows connection between mobile devices and cloud computing.
3. New energy supplies and technologies.
4. The IoT that makes possible the connection through sensing elements, communications and better processing of information and energy in industrial equipment and domestic systems.
5. Open collaboration, collaborative economy and peer-to-peer (P2P) networking.
6. Collaborative and advanced robotics, as well as independent (autonomous) transportation.
7. AI and machine learning.
8. Modern advanced manufacturing and additive manufacturing.
9. Novel and advanced materials, biotechnology and genomic technology.

The technological resources mentioned above can be applied to various processes in companies and factories with the aim of improving efficiency and optimizing production systems by injecting added value. I4.0 was conceived with the purpose of being able to systematize and understand the changes in industries in recent years arising from innovations and improvements made by companies, the incursion of novel technologies and the implications of digitalization in industries. I4.0 describes a set of methods that are used to move from manufacturing conducted primarily by machines to digital manufacturing [34]. I4.0 can be understood as the integration of novel and disruptive technologies whose main objective is process optimization. I4.0 is a trending concept, promising remarkable results for industries while profoundly changing organizations in many terms. The changes start in the way business models are established throughout the entire production process up to the end point when the customer receives the product [35]. One of the goals of every company is to decrease the costs of parts or processes and to have processes that are more flexible and capable of manufacturing small but complex batches of products to meet the demands of highly specialized and differentiated markets. In this sense, I4.0 focuses on improving competitiveness by reducing costs and increasing flexibility in decentralized production systems to offer customized products, which is an advantage to satisfy customer markets [36].

The I4.0 promotes the use of a wide variety of technologies to encourage companies to implement changes in their production processes, including AI, Big Data, additive manufacturing, among others [37], which make it possible to form CPS since it is possible to create significant information flows in real time. In addition, the I4.0 makes it possible for industries framed in the vision of the I3.0 to be highly interconnected and to seek the computerization of their processes. I4.0 seeks to achieve several objectives, including ICT-driven production customization, autonomous flexibility of production lines, systematic monitoring and communication of components, products and machines, and promoting methods where human-machine operations need to be implemented, as well as promoting the application of optimization methods in production lines using the IoT and offering industrial models in which there is high interaction in high-value production chains [38].

The I4.0 paradigm seeks to link physical and digital systems in new interaction models. There is a consensus among the visions of scholars and industries related to the projections of production for the future based on I4.0. These visions agree that there will be [39]: (1) Smart industry, (2) Products or items with certain degrees of intelligence, (3) New models for doing business, and (4) Buyers and customers.

In 2011, the concept of I4.0 was first proposed in Germany and was considered as a new initiative or strategic projection with the objective of being the first country to push its manufacturing industry to modern development [40]. A formal definition of I4.0 is as follows [41]:

I4.0 is the technical integration of CPS in manufacturing and logistics and the use of IoT and services, for applications in industrial processes. This integration will have implications for value creation, business models, downstream services and work organization.

I4.0 is defined according to Rodriguez and Bribiesca [42] *as the digital transformation driven by connected technologies to build a cyber-physical organization.*

The common term between the two definitions described above is the cyber-physical entity or CPS, so it can be said that CPS is the core of I4.0. I4.0 can be considered as an industrial paradigm that promotes high automation for process optimization. Somehow this industrial paradigm displaces the human being from the center of production. However, it is well known that AI applied to industry makes it possible for humans and devices or machines to interrelate with each other. Many machines, such as robots, can now learn many operations performed by operators. It is from these collaborative practices between cybernetic machines and humans that the term Industry 5.0 (I5.0) is conceived.

I5.0 promotes the use of robotic systems to collaborate with operators, particularly in mitigating risks in companies. These systems may be able to understand and in some way sense the operators, as well as understand the tasks they perform. The aim is for robotic systems to be able to observe, sense and learn the tasks that workers perform so that they can help them perform them. I5.0 promotes the integration of AI into the lives of human beings with the main purpose of improving their capabilities [43]. In most applications, I5.0 has shown an important connection between intelligent systems and humans through precise manufacturing automation with critical thinking skills [44]. In addition, I5.0 will put workers on another level by moving from manual work to cognitive work, which will involve adding more value to work activities in modern industries. I5.0 will be based on decision making, human creativity, innovations and critical thinking, which will generate more personalized products, articles and services with higher added value, while robotic systems will perform repetitive, high-risk and labor-intensive tasks [45].

I5.0 promotes integration and greater collaboration between operators and intelligent machines through the application of highly specialized and precision automation techniques accompanied by the power of human critical thinking. The idea of I5.0 is to empower organizations to reach high levels of competitiveness with the help of novel and efficient tools, and that companies can use industrial recycling seeking to have rapid change capabilities without economic or capital investment [46].

Another contribution of I5.0 is the mass customization of products, where users have the facility to prefer products made to their liking or to their specific needs. I5.0 will lead to a significant increase in the efficiency of production and will make possible a great versatility between humans and machines, which will allow for task responsibility and constant supervision [47].

There are several proposed definitions of I5.0, two of which are described below:

Definition 1. *I5.0 is considered as an initial evolution of human-operated industry based on the principles of the 6Rs (Recognize, Reconsider, Realize, Reduce, Reuse and Recycle) of industrial upcycling. The 6Rs represent a technique of waste prevention and logistic efficiency design to value standard of living, innovative creations and to produce customized items developed with improved quality* [48].

Definition 2. *The I5.0 brings together the most elementary and strongest concepts of the so-called SCP and the power of the intelligent mind of human beings for the conformation of productive systems that operate synergistically* [49]. *Because I4.0 weakens the direct work of operators, government officials promote a design of products and systems that is innovative, ethical and where man must be the center of the proposals.*

I5.0 not only refers to the integral cooperation between cybernetic machines and human beings, but also involves aspects of sustainability and social considerations. The I5.0 paradigm promotes the recognition that companies have the power to achieve more far-reaching social goals beyond the benefits of work and economic growth, and that they can be resilient and prosperous providers, that make it possible for production systems to respect the limits of the planet and that put workers at the center of production [50].

2.1.3. Base Technologies of I4.0. and I5.0

Knowledge of the technologies that support both I4.0 and I5.0 is fundamental for the design of specific competencies in Mechatronics Engineering. I4.0 is supported by nine technological pillars, which are shown in Figure 2 [51].

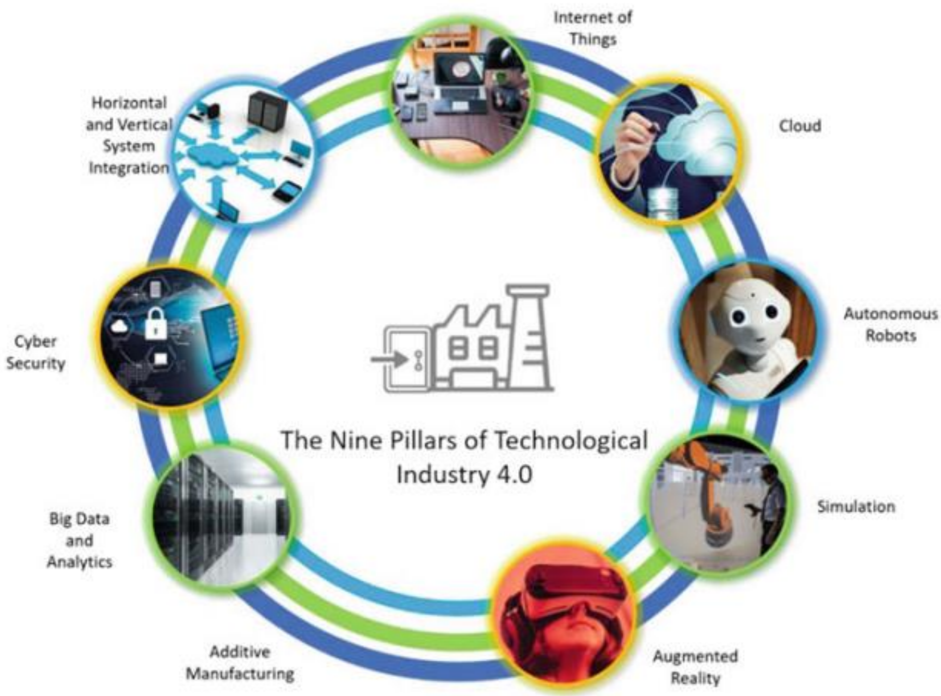

Figure 2. Technologies supporting I4.0 [51].

Each of the technologies shown in the figure above are described briefly below [51]:

- Autonomous robots: These systems have been improving over time and when incorporated into production lines they make them more flexible and more autonomous, allowing close collaboration between humans and other robotic systems.
- Simulation: This technology allows the creation of DTs that are used to optimize processes, and is also applied for virtual product design, for material selection and to mimic the behavior of production lines where machines, products and humans coexist. It is possible to virtually build complete production systems with the help of simulation.
- Horizontal and vertical systems integration: This technology seeks to computerize supply chains by forming networks that are capable of integrating information and data between external and internal systems (cross-functional type).
- Industrial IoT: This technology allows the integration of mobile devices with IT systems with the objective of sharing data and information in real time.
- Cybersecurity: This technology is necessary in I4.0 in order to protect the sensitive information of industries and so that productive systems can be guaranteed the exchange of reliable information.
- Cloud: Many of the services of different IT sites that rely on the storage and exchange of information and data will be managed in the cloud.
- Additive Manufacturing (AM): This technology is used for the design and manufacture of parts and products that can be customized to customers' needs. Because AM produces lightweight designs and small batches of products, product warehousing is reduced as well as logistics costs.
- Augmented Reality (AR): AR can be used for virtual training of companies' human resources, for equipment maintenance and to perform better work techniques and procedures on production lines.

I4.0 can be implemented by companies seeking to be competitive. However, to achieve this they must know what I4.0 is, the pillars on which it rests and their interrelationships. Figure 3 shows a proposed conceptual map based on three major sets of connections (inherent connections, cybersecurity connections, and interpillar connections) [52].

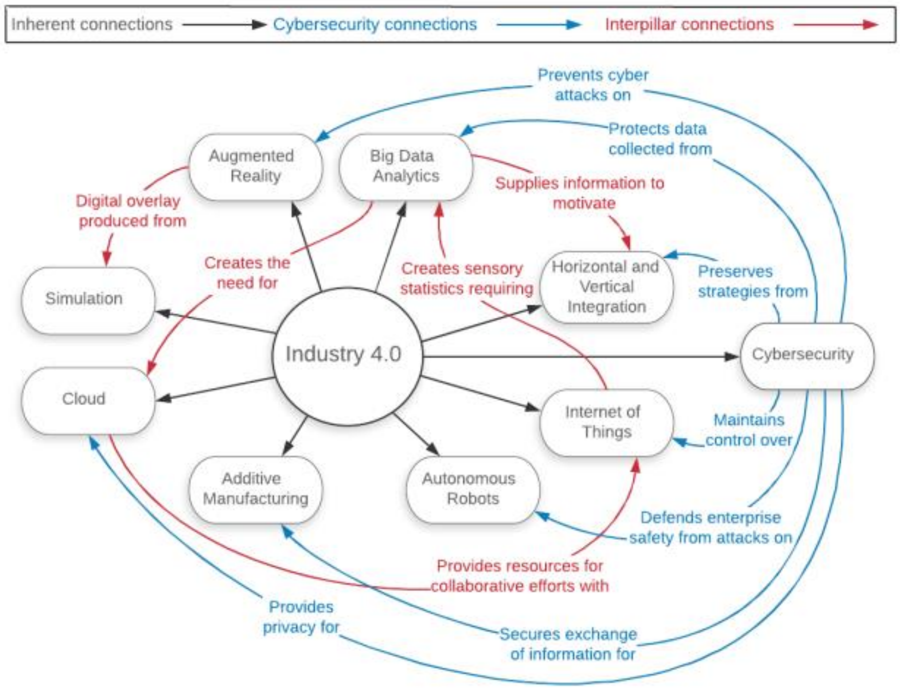

Figure 3. The relationships between the three pillars of connections of I4.0 technologies [52].

The map shown in Figure 3 does not represent fixed relationships between technologies and more sets of connections can be considered, as the rapid pace of technology innovation may pose different connections. On the other hand, Figure 4 shows a proposal of the technologies that integrate I5.0 [53].

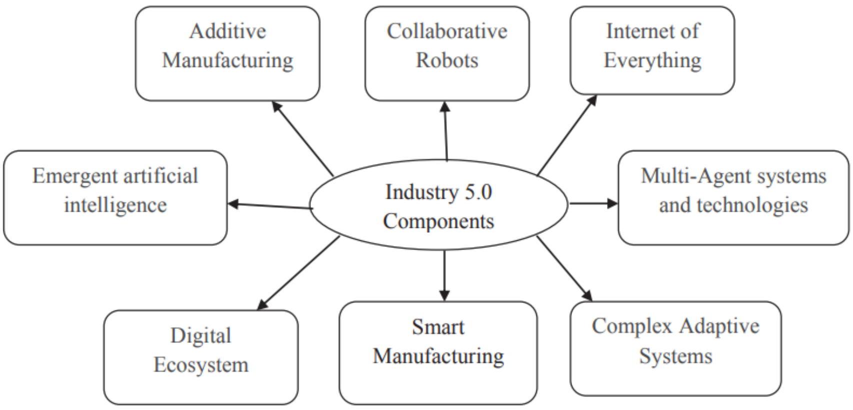

Figure 4. Technologies supporting I5.0 [53].

The I5.0 associates aspects of environmental care and social aspects, as well as the interaction between men and machines, in fact, from this interaction is generated the concept of Operator 4.0, which seeks the conformation of new manufacturing systems called Human-Cyber-Physical Production Systems (H-CPPS) whose objective is to generate the necessary conditions for workers to improve and expand their capabilities [54]. The development of trust-based relationships between operators and devices or machines is a goal of the Operator 4.0 idea. Such relationships would enable smart industries to maximize their strengths in their context by including machinery endowed with intelligence. At the same time, these human-machine interactions would enable empowering and augmenting the skills and capabilities of workers to achieve more far-reaching goals and opportunities that are generated by the implementation of I4.0 [55].

Figure 5 presents the technological resources associated with the Operator 4.0 idea [44].

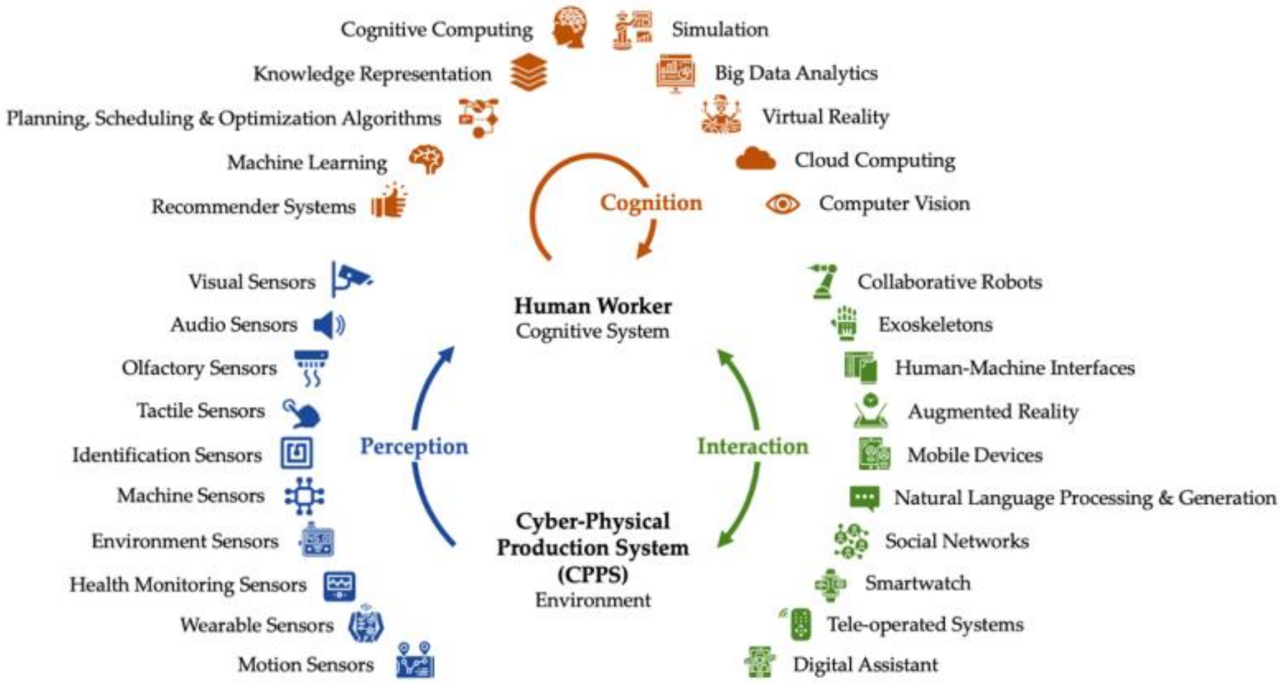

Figure 5. Human-machine interactions (symbiosis) of I5.0: Technologies increase people's capabilities and skills due to a cognitive-type process [44].

2.1.4. Technological Transitions: Technical Aspects

The knowledge of the information of industrial processes related to the technological transitions between one revolution and another is fundamental to be able to design specific competencies for Mechatronic Engineering. This information allows determining which knowledge should be taken into account and which should not, since the industrial world is actually undergoing an industrial transition that implies gradual and/or disruptive changes in production systems.

Transitions between industrial revolutions are often complex and pose significant economic challenges, especially for companies, as they must adapt to change in order to be competitive. For several companies in the world, especially those whose production systems are framed in the I3.0 and that do not have sufficient capital, the technological transition (from I3.0 to I4.0) has become a serious problem, as they face the challenge of deciding whether a technological upgrade (an almost total change in production systems) that involves a considerable economic investment or a technology reconversion that involves a substantial improvement to the production systems they already have and, therefore, less economic investment, is relevant [20]. The Industry 3.5 (I3.5) concept is associated with the representation of the technological transition from I3.0 to I4.0, and can be considered a hybrid strategy, not only for a technological transition in production systems, but also for managing any disruptive impact, such as total resource management for sustainability [56]. The concept of I3.5 becomes an overall strategic framework that concatenates high-tech applications, IoT, big data analytics, resource allocation, improvement and optimization, seeking to develop a basis for smart production [57].

One of the main objectives of I4.0 is to promote the development of productive systems endowed with intelligence where devices or machines have special characteristics, such as adaptability, a high degree of flexibility, learning by themselves (self-learning) and being able to be self-adaptable [57]. However, I3.5 is only interested in ensuring that the benefits and improvements made to production systems are short term, and for this purpose it must use various tools, including those used for analysis and those applied to process optimization. These tools are applied to the development of company operating plans and supply chain management, plant and quality controls, so that highly automated operating systems conceived under the I3.5 approach can perform various tasks, including decision making. An expected result with the incursion and improvement of IoT, DT, CPS, data processing and physical assets (infrastructure), is the effective and efficient communication between the different and diverse devices, machines and production lines conceived under the I3.5 approach, so that a conception towards the intelligent industry of the I4.0 can be derived from this communication. Table 1 shows a comparison between I3.0, I3.5 and I4.0 [58].

Table 1. Comparison between I3.0, I3.5 and I4.0 [58].

Features	Industry 3.0	Industry 3.5	Industry 4.0
Core Concept	Highly automated system	Decision making ability with the improvement of existing environments	Smart factory with CPS and IoT
Production Strategy	Mass Production	Flexible Manufacturing (diverse products with small lot size)	Mass Customization
Quality Control	Statistical Process Control	Advances Process Control	Self-aware; Self-prediction
Resources Management	Materials Management; Human Resource Management, etc.	Total resource Management	Self-configure; Self-optimize
Development Priorities	Investment of hardware	Integration of ability of data analysis and experience of management	Construction of CPS and IoT

Another challenge faced by I3.5 is the decision making of companies to decide how to introduce disruptive technologies to their production processes, especially those companies that have difficulties investing in new equipment. Technological reconversion or also called technological upgrading may be an option. However, it is not an easy task to upgrade a conventional system or machine to align with the demands and requirements of I4.0, because components and systems, such as actuators, sensing systems and computer systems generally have communication protocols that prevent, among other things, multidirectional interconnection both internally and externally. In other words, although an I3.0 CNC machine is a CPS, its transformation into a CPS developed under the I4.0 approach is complicated due to its technological limitations. In this sense, the retrofitting of machinery and systems can be a suitable method for technological reconversion.

Retrofitting can be classified into: (1) Traditional retrofitting and (2) Intelligent retrofitting. The first one refers to the replacement of parts or subsystems to achieve the optimization of some process variables such as, for example, the reduction in maintenance time, the speed of machines and processes, as well as the accuracy of various tasks, among others; while the second one focuses on the low-cost adaptation of subsystems, machines or equipment that already exist in the companies [59]. In fact, Intelligent Retrofitting studies and analyzes production lines and machinery whose design was not conceived to operate in I4.0, so its priority objective is to achieve the transfer of the most important aspects of the I4.0 paradigm to the machinery and production systems of companies in a shorter time and at a low cost. This type of reconditioning can be supported with the help of the Lean philosophy [60]. I4.0 requires both reconditioning of machines or production systems to achieve its purposes.

Technological reconditioning does not have a single methodology, so there are several proposals for machines or CPS, as well as for processes. Figure 6 shows a proposal for the reconditioning of a process for its operation under the I4.0 philosophy.

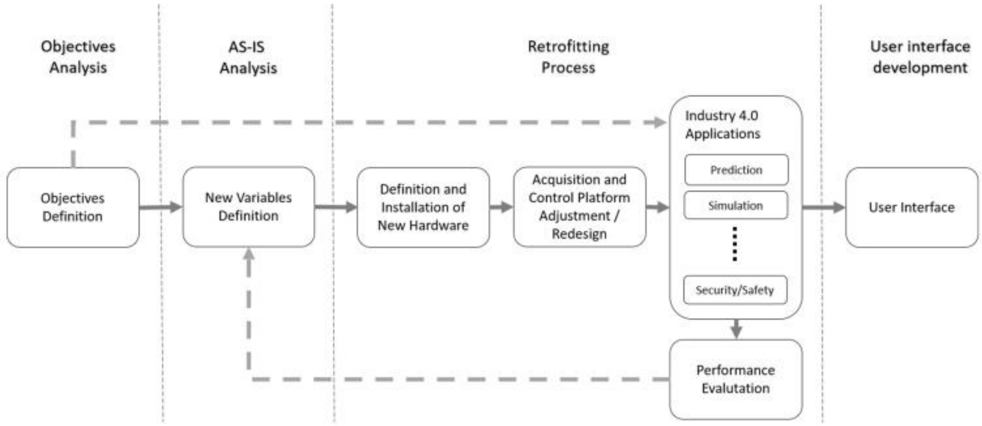

Figure 6. Approach adopted for the retrofitting process [61].

2.1.5. The Importance of CPS

History shows that in general there is one or several technologies on which each industrial revolution is based. It is crucial for the formation of specific competences in Mechatronics Engineering to know the generalities of the CPS since they represent the technological basis of the I4.0.

Cyber-physical systems (CPS) are very complex systems that are integrated with collaboration of communication, computation, and control together termed as 3C technology [62]. Cyber–physical systems (CPS) are composed of physical and computer-based (i.e., cyber) parts, which are highly interconnected [63].

I4.0 has CPS as its technological backbone. In fact, there are a large number of researchers who claim that CPS is the critical element [64] and the core [65] of I4.0. The idea of CPS was initially described and coined by the National Science Foundation (NSF) in the USA in 2006 [66]. CPSs are described as any entity composed of physical and cyber elements that interact autonomously with each other, with or without human supervision [67]. There is a range of cyber-physical entities that can be currently observed in industrial activities, e.g., robots, coordinate measuring machines, manufacturing cells, CIM (Computer Integrated Manufacturing) systems, machining centers, data acquisition systems, and SCADA (Supervisory Control and Data Acquisition) systems, among others. Figure 7 shows a CPS represented by the iCIM 3000 (FESTO DIDACTIC, Denkendorf, Germany) didactic manufacturing cell conceived under the I3.0 philosophy and located in the facilities of Universidad la Salle Noroeste, Mexico.

Figure 7. Traditional CPS: iCIM3000 didactic cubicle.

CPSs are characterized by high computational integration, physical assets that perform a large number of tasks and operational networks. It can be stated that the most important particularity of the CPS is the high integration between different hardware components and software systems. In such integration, actions and operations of computation, effective control and efficient communications coexist, which are taken into account at the same time and together with physical assets for the design of production systems [68]. CPS represent a generation of new digital systems that are based on complex interdependencies and relationships, as well as high integration between physical assets and the digital world [69]. The CPS is an intelligent computer system that uses controlled mechanisms and different algorithms to connect software and hardware parts so that it can function and display a variety of forms and approaches.

The CPS is an intelligent computer system that uses controlled mechanisms and different algorithms to connect software and hardware parts so that it can function and display a variety of forms and approaches [69]. The general structure of a CPS is made up of two major groups of elements or subsystems. The first of these corresponds to the physical assets and the conditions imposed by the environment surrounding them, while the second subsystem relates to the computer control system whose function is to analyze and control the state variables of the processes by sending information via sensors to the physical assets so that they adjust if the parameters of the environment change. There is no person who is able to observe with his sensory system the environment around him and who can develop a mental map model of the tasks that are being presented and at the same time is able to provide an intelligent buffer between the system of physical assets and the cyber-physical world [70].

A CPS is integrated by two layers: (1) The cyber layer is composed of many intelligent monitoring nodes (including people, servers, information sites or various mobile devices) and their communication links and (2) The physical layer that integrates various interrelated physical entities. Under the interaction both layers, the system realizes information interaction and decision making by 3C (Computation, Communication and Control) technology [71]. The design of CPSs is a challenge nowadays and engineers must take into account variables such as: security, scalability, interoperability and robustness, among others, to develop reliable and trustworthy CPSs. CPSs are interrelated between computational processes and physical processes, and can have the potential and ability to perceive the environment and have autonomous control, as well as make important decisions. Therefore, the deep integration of discrete computation of discrete computation and continuous physical process is one of its typical characteristics of CPSs [72], i.e., they integrate a series of dynamic models and with hybrid characteristics.

The study of CPS requires knowledge of various models, such as computational, physical and network models. The former can be considered as analytical discrete transition models that number states (e.g., data flow models, event models and state machines, among others), while the latter can be represented by differential equations (continuous-time models) and their solution methods [73]. CPSs are associated with various highly integrated systems such as equipment, various devices, offices and buildings, transportation systems and production lines, among others, however, CPSs also integrate various logistics, process management and coordination processes and operations.

CPSs collect, manage and analyze data through the support of various signaling elements, while actuators are used to react to production or organizational changes and communicate with the other components. CPSs can be implemented to manage different issues such as production, logistics, quality, planning and scheduling activities within the factory [74]. There are many different types of CPSs in everyday life: industrial control system CPSs, smart grid CPSs, medical CPSs, smart vehicle/automobile CPSs, domestic CPSs, aerospace CPSs, and defense CPSs, among others [75].

The development and operation of a CPS requires consolidating and integrating various systems and actors, such as mathematical and computational models, analytical methods and techniques, as well as a great diversity of tools. In order to increase the probability of operation of a CPS (reliability), it is necessary to consider two aspects: (1) To have the ability to consider the consequences and implications of the evolution of the elements that make up the system and (2) To have the ability to look for and point out those changes that, although considered as optimal, may jeopardize the reliability and overall reliability. In this sense, for the conception, design and operation of a CPS it is necessary to take into account several descriptive type models (generated during the process in which the CPS sub-systems are designed) and inductive type models (obtained from the databases that are generated when the system is in operation) or combinations of such models. By considering a combination of the aforementioned models, there can be a huge potential for the conception, design and operation of a DT that learns and optimizes processes and that can be integrated to a CPS so that it can make various decisions either when it is operating online or offline [76].

CPSs are capable of performing a variety of tasks [77]:

- Capture data from sensors and store it on local servers or in cloud architectures;
- Drive physical processes by means of actuators;
- Connect and operate with other CPS;
- Interacting with machines and humans;
- Provide real-time response to stimuli generated by both the surrounding environment and the CPS itself.

Some key features of CPSs include [78]:

- They are considered as a system of systems: This means that CPSs are made up of various subsystems that operate and interact with each other in many ways and in complex ways.
- CPS requires new and novel relationships between computing, control and communication systems to be considered; that is, a robust and integrated design needs to be considered in order to develop tasks and operations that work on their own and with a high level of automation.
- CPS requires that there is a strong relationship or articulation between physical assets and cyber systems that must be considered depending on the specific application.

It is possible to describe the main elements that make up the CPS [79–81]:

1. Supporting technologies: IoT is a necessary technology as it provides and enables machine-to-human and machine-to-machine communications, ubiquitous computing, embedded systems, fuzzy systems and cloud computing, among others.
2. Physical assets: actuators, sensors, numerical control machines, control systems, robotic systems, mechanical production systems, server technology, intelligent devices or machines, data handling and processing systems, interfaces and data transmission systems, among others.
3. Elements of the information environment: PLCs (Programmable Logic Controller), software for cloud implementation, SCADA systems and other systems such as: component and data lifecycle management and administration, and planning systems, among others.

Figure 8 shows a structure of a CPS in terms of the organization and behavior of the subsystems that comprise it.

The construction of its architecture is the first step in the research and development of a CPS. There are several architectures to represent a CPS, such as the 3C and the 5C type. A 5C architecture is shown in Figure 9 [83].

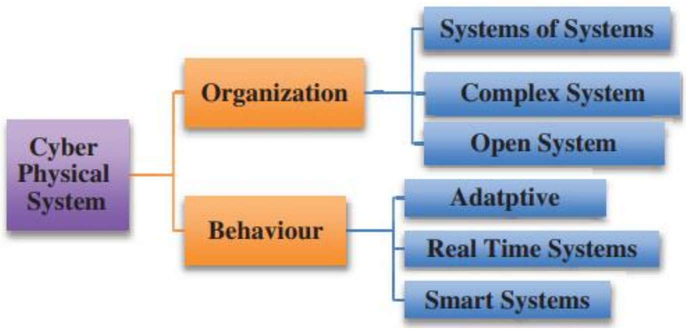

Figure 8. Configuration of a CPS [82].

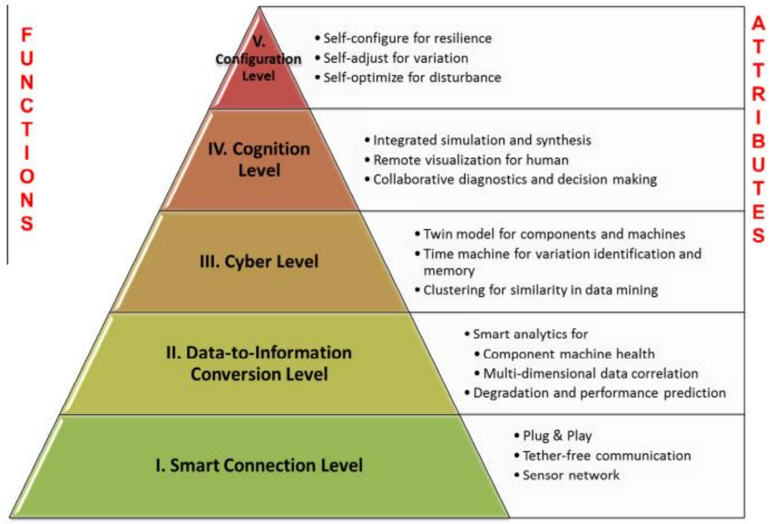

Figure 9. 5C architecture for the implementation of a CPS [83].

The 5-tier structure of a CPS proposed in Figure 9 (the 5C architecture) allows a step-by-step design, operation and implementation of a CPS. The five levels are explained below [83,84]:

- Level I: At this level, physical asset data is generated, collected and sent to the next level where the data will be further converted. The data must be obtained as accurately and reliably as possible.
- Level II: Collection of data sent from Level 1 and selection and conversion of important and significant information for subsequent application at Level III in tasks such as prevention, analysis and management.
- Level III: At this level the information for the design of the system configuration is centralized. It concentrates the information of each physical asset connected to the network.
- Level IV: Once the information from other physical assets has been collected through the network layer, the system is supervised taking into consideration historical information and various predictive models to determine any machinery failure.
- Level V: At this level the company's managers make decisions by reviewing the supervision, monitoring and control systems, taking into account feedback and interactions from the digital space to the physical assets.

One class of CPS are Cyber-Physical Production Systems (CPPS); the architecture of one of these systems is shown in Figure 10, which, among other functions, is used to diagnose and anticipate the quality of molten metals, as well as to have a control of manufacturing operations which are developed in novel technologies such as computational simulation, large database management, AI and IoT, among others [85]. The extended explanation of the CPS shown in Figure 10 can be found in [85].

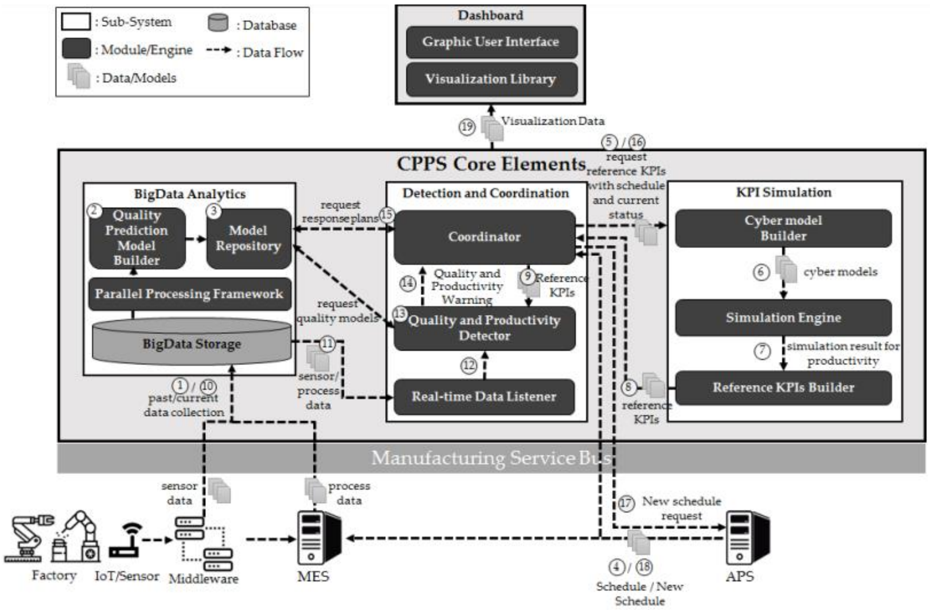

Figure 10. CPPS architecture [85].

I4.0 is not only applied in traditional manufacturing systems, but its approach is more general, for example, there is the concept of pharma industry 4.0 or Pharma 4.0 which means the digitization of the pharmaceutical industry [86]. In this sense the technology of CPSs and DTs are applied in the pharmaceutical industry. Figure 11 shows a CPS used in the production of the pharmaceutical industry [87].

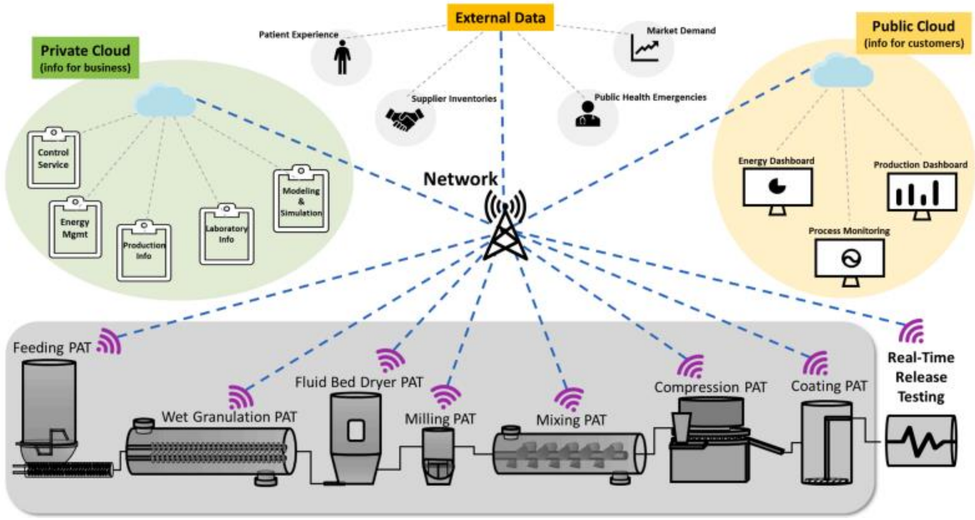

Figure 11. SCP for pharmaceutical manufacturing in I4.0. [87].

The CPS shown in the figure above is made up of three major components:

1. A public cloud that performs an integration of application services (used by customers).
2. A private cloud that is responsible for information management, which is used to perform tasks of the main or upper layer that integrates SCADA systems, manufacturing, simulation, information and data from laboratories, process control, modeling and analysis, among other technologies. The first and second layers are related to the digitization of system states, which allows various on-the-fly predictions and process optimization studies to be carried out.

3. The manufacturing plant is integrated by various physical assets, process analytical technology (PAT) and RTRt (real-time release testing). The control and management of the production line is governed by the PAT while production quality, which is derived by taking and utilizing information from the manufacturing process, is performed by the RTRt system. Many of the operations such as blending, tablet coating, wet granulation, among others, are connected to the company's network systems and cloud systems through cyberspace [87].

There are various applications of the Pharma 4.0 concept, for example, Ouranidis et al. [88] conducted an inquiry on mRNA therapeutics for the treatment of SARS-CoV-2 and studied the laboratory production of therapeutic mRNA. The proposed process flow design releases a continuous and highly automated production that satisfies GMP (Good Manufacturing Practice) standards, in line with the standardization principles of the pharmaceutical industry 4.0. In another work [89] digital design tools focused on pharmaceutical 4.0 systems, i.e., convergent mass and energy balance simulations, Monte-Carlo machine learning iterations and spatial layout analysis were used, to design the related and integrated bioprocesses in scalable devices, compatible with the continuous operation of mRNA drugs. Similarly, in the work [90] an elastic tensor analysis was performed to quantify the stability of the API (Active Pharmaceutical Ingredient) during the process. In the same way the authors structured a thermodynamic model, represented by the anisotropic minimization of the Gibbs energy, of the stabilizer coated nanoparticles, to predict the system solubility of the material quantified by the application of PC-SAFT (equation of state that is based on statistical associating fluid theory) modeling. The comprehensive fusion of elastic tensor and PC-SAFT analysis in the systems-based Pharma 4.0 algorithm provided an integrated, validated, multi-level method capable of predicting critical material quality attributes and corresponding key process parameters.

Finally, CPS have a relationship with the so-called "embedded systems". These systems are integrated by complex electronics that admit information and send actions to physical assets and software elements using lists of instructions [91]. CPSs integrate digital systems, such as the following: SCADA system, Machine-to-Machine (M2M) systems and industrial automatic control systems [92,93]. CPSs focus on research and development in the area of embedded systems and the study of sensorics [94], in fact, in [95] defined a CPS as "the integration of embedded systems with global networks such as the Internet". A typical architecture of an embedded system is shown in Figure 12.

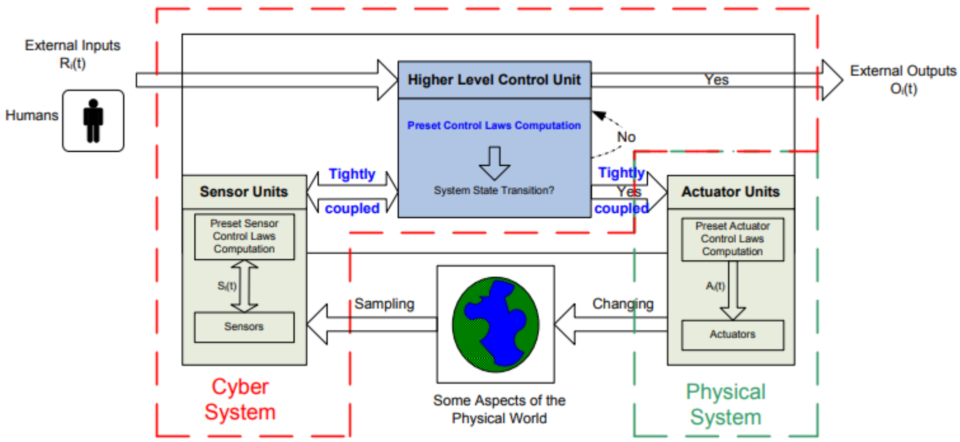

Figure 12. Typical architecture of an embedded system [96].

As can be seen in the figure above, sensors and actuators are tightly coupled and related to a control system that has a higher level. At each operating level of the system, variables are being monitored and synchronization is being measured so that the control loops and cycles operate correctly in functional and temporal terms.

2.1.6. Digital Twins

Another technology of utmost importance in the operation of I4.0 and I5.0 are the DTs. Knowledge of this technology is crucial for the education of the mechatronic engineer, since its design and operation are based on various fields of knowledge, mathematical models of various physical phenomena and computational models that include some AI tools.

DTs are equally important as CPSs in the I4.0 vision. A digital twin (DT) is a structure of interconnected digital replicas of physical entities [97]. A DT is *a formalized digital model that represents a system, entity, asset or process that collects attributes and properties of assets to establish a bidirectional communication, to form a storage process of the attributes and to perform certain information processing within a specific environment that is influenced by cyberspace* [98]. It can be said that DTs are functional connections between physical assets and the digital world and they use signaling systems (sensors) to collect data and information instantly from the physical asset. The information obtained is applied to generate a computational or digital duplicate of part or the entire asset, which facilitates the understanding of its operation. In this way, it is possible to carry out various analyses of its behavior, to have control over it and to implement different methods to optimize its functions, such as performance [99].

Semeraro et al. [100] conducted an extensive literature search related to DTs and concluded that: a DT can be considered as a set that collects several adaptive models that reproduce the behavior of a physical asset, process or system, in a digital or virtual system which is able to obtain data instantaneously in order to update or reconfigure itself throughout its life cycle. The DT virtually models the physical asset and is used for various applications such as, for example, detecting and fixing faults in the operation, obtaining instantaneous information to optimize processes and to analyze and evaluate events that occur unexpectedly during the operation of the physical asset. Between the DT and its physical replica there must be communication, i.e., [101].

- Between the physical asset and its digital replica.
- Between the digital replica and other different DTs that are located in the environment.
- Between the DT and the domain experts, who interact and operate digital replication, through a set of usable and accessible interfaces.

Originating from industrial design, the DT concept leverages object-specific data to simulate replicas in the virtual world for predictive analysis of security risks and testing of different optimization solutions [102]. DT has three constituent parts [103]:

1. An asset or a set of physical assets (a machine, some process or production system).
2. A digital model with which simulation processes can be performed in terms of the data present and which is integrated by: (a) Various types of algorithms that represent the model to be simulated, machine learning algorithms and data and information extraction procedures to extract special models from the collected data and implement them in the corresponding software and (b) Connectivity components and systems, such as IoT.
3. A collection of historical data or data being obtained instantaneously from the operation of physical assets. The data are the key elements in DT and are used to know whether the objectives of digital replication can be achieved.

The Figure 13 shows a graphical representation associated with a DT.

Tao et al. [105,106] proposed a complete framework of a DT composed of five parts: digital space, virtual space, connection, data, and service. The connection between the five is shown in Figure 14. The DT contains information of the static type (geometric dimensions, bill of materials, processes, and order data) and information that evolves over time (dynamic).

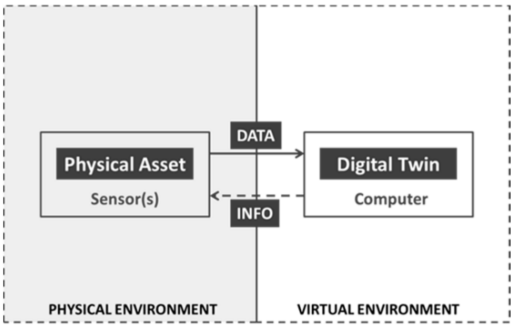

Figure 13. Conceptual representation of a DT and its association with a physical asset [104].

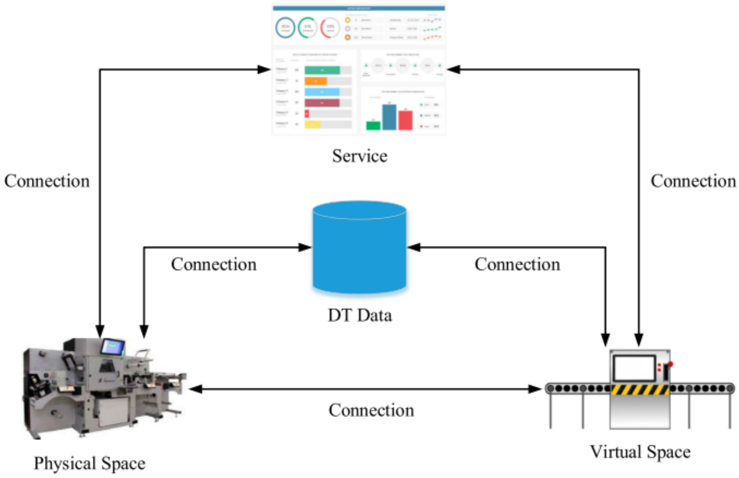

Figure 14. Five elements of a DT [105,106].

On the other hand, according to Malakuti [107], industries for many years have used digital representations to model the information of an asset or system (e.g., a device, a production cell, a plant) throughout its life cycle, but often do not study them from the view of DTs. Today, DTs are beyond information models and relate mainly to improvements in digital technologies, architecture development and standardization, interactions, new use cases and business models that enable DTs. Some important elements that integrate a DT are shown in Figure 15.

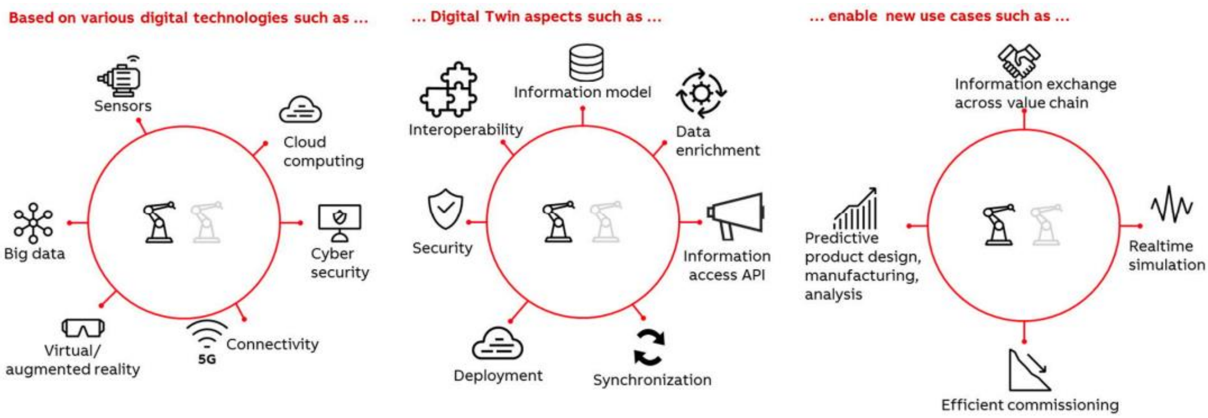

Figure 15. Overview of some concepts associated with a DT [107].

There are other concepts similar to DT, so it is necessary to know the differences between them:

1. Digital Model: this model only allows data to be exchanged manually, and no online status update or synchronization between the two objects is possible. This is the typical concept associated with the design phase.
2. Model called Digital Shadow: In this model, the data flow is automated and only occurs in one direction, namely from the physical to the virtual entity, so there is no feedback to the real system from its virtual replica. This model is adopted at most in the service and maintenance phase, and is used to track and predict the behavior of a product in its use phase.
3. The DT: This model is characterized by a complete, automated, bi-directional data flow between physical assets and cyberspace. This vision is best suited for manufacturing applications, such as product quality prediction, production planning or human-robot collaboration.

The differentiation described above between the models is a function of the degree of integration between the physical asset and its digital replica, and the nature and frequency of data and information exchange between the two entities [106]. A DT is endowed with the following capabilities that can be used as decision support [108]:

- Descriptive capabilities: These are based on data describing the current and past states of the production lines, considering the monitoring of the system's good condition and data describing the production that is generated and updated instantaneously.
- Predictive capabilities: These capabilities are developed from models that have the ability to deduce future states and conditions, and the productivity of the system based on hard data according to different circumstances. Some examples of this type of models are: (1) Those based on physics, and (2) Models that allow autonomous learning and are capable of producing predictions in short times so that it is possible to make decisions.
- Prescriptive capabilities: These capabilities serve to support various decision making processes in the physical context through the use of improved or optimized action plans transformed into production managers. The process to generate prescriptive capabilities uses various predictive and/or optimization models taking into account simulation or can also use single models. The results generated by the models must be obtained quickly so that they can be used to make decisions instantaneously or in operational terms and with the ability to react quickly to sudden and unexpected events.

Some of the requirements that apply to the design of DTs are summarized in the following points [109]:

1. Reusability: DT solutions need to be more portable and reusable to better leverage the "develop once, use many" approach.
2. Interoperability: The proposed solutions of a DT design must have the capability to interoperate with other DTs and other classes of DTs, as well as have the ability to interoperate with non-DT systems.
3. Interchangeability: The proliferation of DTs requires them to be designed in a modular way to facilitate their evaluation, easy replacement or updating.
4. Verification and validation capability: Because the DTs will be in common use and integrated into critical production systems, the capability of the DTs must be ratified and verified before they are incorporated into real applications.
5. Maintainability: An underrated feature of DTs is their maintainability, however, they are required to be able to operate and be maintained throughout their lifetime and usefulness.
6. Capability and accuracy: Capability and precision (accuracy) are two capabilities that DTs must have, as these capabilities are a consequence of the evolution of intelligent manufacturing.
7. Extensibility: It is required that the DTs can be extensible with the help of ICTs and that they are part of an ecosystem.

8. Support of a technology partnership: The design of a DT requires special and strict technology requirements, and to develop them there must be a better and greater collaboration between those actors that make applications of DTs in different areas and those existing technology partnerships.

DT is exploited by many industrial sectors such as [110]:

- Automotive industry: The concurrence of physical and virtual products has the potential to address many of the challenges that currently exist in the automotive value chain. DT in the automotive industry can enable the convergence of existing gaps between physical and virtual versions of product prototypes, the shop floor and the actual vehicle on the road.
- Aeronautics: The large number of sensors on commercial aircraft transmit asset data to improve system maintenance and operational status.
- Medical industry: Connected medical systems and tools provide assurances of product integrity and are able to measure patient outcomes.
- Manufacturing: Physical assets in digital factories can increase manufacturing uptime and throughput while potentially reducing repair and maintenance rates.
- Oil and gas: Remote platforms send system health data that limit routine inspections and maintenance.
- Rail: Vision of deployed locomotives and asset health optimizes scheduling and reduces maintenance time.
- Utilities: Digital models of power grid systems improve demand response and energy efficiency functions.

On the other hand, CPSs and DTs are similar, but not the same, in their description of cyber-physical integration, since both are composed of a physical and a digital part. Table 2 presents the differences between these technologies [111,112]. DTs, such as CPSs, achieve synergistic (cyber-physical) integration between physical assets and cyberspace, due to the fact that they support dynamic functionality of the bidirectional type between real systems and digital representations [113]. DTs are important and necessary because they enhance the capabilities of CPSs. DTs and CPSs seek to be coherent through the interrelationship between physical assets and digital entities. The central characteristic of the DT is to achieve one-to-one interactions or relationships, while the CPS works on one-to-many or many-to-many relationships. The CPS has interactions more with the digital part of the system, while the DTs have relationships and interact more with the physical assets. It is worth mentioning that communication systems, control and computation, enabled by physical assets (signaling elements and actuators), are the primary elements of the CPS. These elements make interactions and relationships between physical and digital assets easier due to information and data exchange processes, while DTs are dependent on the design of models that are generated from the data and the application of the data to perform predictive tasks and to have control over the actions or behavior of physical assets [112].

Table 2. General differences of CPS and DT ([111,112]).

Criteria	CPS	DT
Origin	Proposed by Helen Gill at NSF in 2006	Presented by Michael Grieves in 2003
Interaction type	Cyber and Physical interaction	Cyber and physical interaction
Interaction level	One-to-many components interaction	One-to-one component interaction
Core elements	Computation, communication, and control	Computation and communication
Control means	Models and actuators	Models

There is a symbiotic role between IoT and CPS towards DTs. A DT is an entity that is built in an emergent manner, but has conceptual differences in relation to CPS and IoT. Similarly, to CPSs, DTs rely on communication to generate a highly coherent and synchronized digital image/representation of physical objects or processes. However, DT, in addition, uses softwarized embedded models in this accurate image to simulate, analyze, predict, and optimize its operation in real time through feedback [114].

2.1.7. IoT, Simulation, AI and Interoperability

In this section we describe other disruptive technologies that are involved in I4.0 and I5.0, with the objective of being able to understand their important considerations that allow us to establish that essential knowledge for the formation of the mechatronic engineer.

One of the important technologies in the implementation of I4.0 is IoT, which is about connectivity with objects rather than people. In fact, IoT is a new paradigm that is rapidly gaining ground in the modern wireless telecommunications scenario. The basic idea of this concept is the ubiquitous presence around us of a variety of things or objects such as sensors, actuators, cell phones, etc. that, through unique addressing schemes, are able to interact with each other and cooperate with their neighbors to achieve common goals [115].

IoT is a technology that is focused on the connectivity of many computing devices and appliances. Many applications can be realized if the devices can be combined or integrated with AI, autonomous learning models and various data mining techniques. It can be said that IoT makes the interaction between humans and computing systems easier. The IoT is a concept that allows us to have the idea that devices and devices can have the power to perform various inspections and that they can collect or lift information flows from the environment, and then introduce it into cyberspace and have the opportunity to perform a myriad of applications with that information [116]. IoT with industrial applications can transform data into novel information, depth knowledge, and intelligent systems. IoT applications in industries enable industries to improve their efficiency and increase reliability in processes and operations, because IoT technology is directed towards various industrial communications such as M2M, large database management, and autonomous learning. According to its use and customers IoT is divided into [117]:

1. Consumer IoT: This technology considers devices and appliances that are connected to the network, such as portable phones, games, smart cars and home appliances, among others.
2. IoT for commerce: This technology takes into account devices and appliances such as GPS, medical devices and inventory control systems, among others, that are connected to the network.
3. IoT for industry: This technology operates physical assets connected to the network, such as: robots, production lines, machines and wastewater management systems, among others.

IoT can be classified in terms of its functionality (see Figure 16) and different technologies can be related to each subclass [118].

Figure 16. IoT elements [118].

IoT is a technology that facilitates communication and cooperation between CPSs. It is worth mentioning that various physical assets, such as signaling elements, actuators and portable devices, among many others, are everywhere and are applied for countless tasks, such as in transportation tasks, in medical centers, in traditional households, in companies for product manufacturing, in agricultural production and in systems in critical infrastructures, such as in refineries or nuclear power generation plants [119]. Figure 17 shows a diagram showing the connection between IoT, CPSs and DT [114].

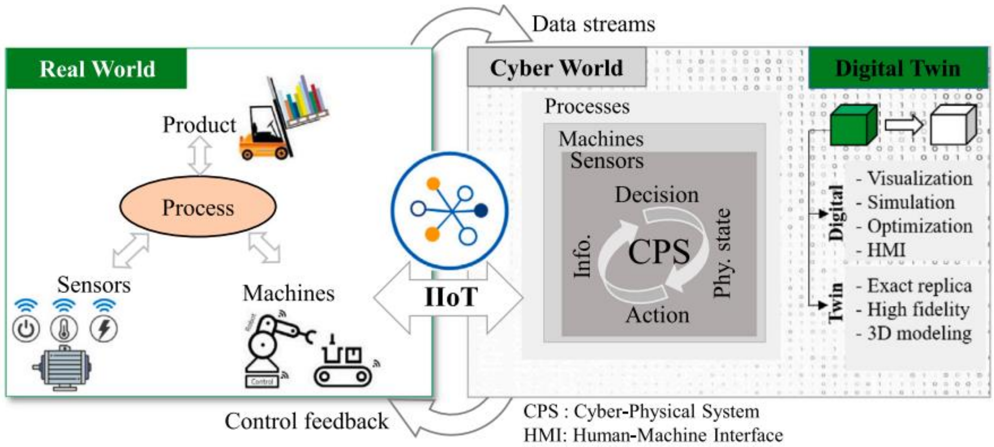

Figure 17. Functional relationships between industrial objects and processes from the real environment to cyberspace based on industrial IoT, data flows and DT [114].

On the other hand, one of the technologies on which the CPS is based is computational simulation, which is conceived as the imitation of the behavior of a system operating in the real world over time, and which takes as a reference the generation and observation of artificial histories, from which it is possible to draw inferences about the operation of the real environment [120]. Simulation technology modeling can be interpreted as a methodology that is based on models that can be physical, mathematical or other, which are related to the real or fictitious behavior of a system and which are used for various applications, among them to make predictions or to improve the operation of systems [121]. Simulation is the central basis of DTs and the support of CPSs. In fact, simulation technologies are taken into account for engineering processes and in decision making. Traditionally, simulation focuses on design phases and engineering processes. However, simulation will be more commonly used in production lines to make decisions and drive processes. For simulation to be used in industry as a useful and productive tool it must be transformed into a multipurpose or multidisciplinary simulation [122].

However, today there is no integrated simulation base or platform that has the power or capability to mimic the behavior of an entire CPS. This fact is of utmost importance due to the fact that there are several advanced tools and methods to build models and to perform the necessary testing of physical assets or data and communication networks. In order to enhance the simulation, several approaches can be used, such as co-simulation, which consists of taking two conventional simulators and combining them to perform the tasks, so that one of them is associated with the physical assets and the other one is related to the communication networks. Co-simulation is a good alternative since it can consider, on the one hand, technologies that already exist to perform simulations and, on the other hand, it can take advantage of the large number and variety of tools and methods that are ready to be used in deep and comprehensive studies [123]. Computational simulation is considered as one of the main tools used to study and evaluate the performance and efficiency of a system, and to assist humans and digital systems in decision making. Posada et al. [124] consider simulation as a base component for the successful implementation of I4.0, due to the fact that the following three dimensions can be evaluated: (1) The integration dimension: as an end-to-end digital engineering integration tool, (2) The product and production dimension: as a decision-making tool, and (3) The human factor level, as it can improve work organization and design. Simulation with mixed approaches is considered a primary technological tool of I4.0, in fact, DT is a derivative of simulation and is pointed out as one of the most hopeful modern technologies [125].

Simulation in general has diverse applications, for example, many production processes can be simulated before being taken to real operation; logistics is another important task in industries that can use simulation models for decision making. Computational simulation uses methodologies and tools of a technological nature with the purpose of performing various tasks, such as, for example, carrying out different experimentations, predictions, validations and design, among others. In the case of I4.0, simulation will face important challenges due to the fact that systems are increasing in complexity and must also integrate other tools such as big data, cloud computing and IoT, among others.

Just as CPSs are related to embedded systems, DTs are closely associated with simulation. Table 3 shows the evolution over time of modeling for simulation.

Table 3. Evolution of the simulation modeling paradigm [121].

Individual Application	Simulation Tools	Simulation-Based System Design	Digital Twin Concept
Simulation is limited to very specific topics by experts, e.g., mechanics	Simulation is a standard tool to answer specific design and engineering questions, e.g., fluid dynamics.	Simulations allow a systemic approach to multi-level and multi-disciplinary systems with enhanced range of applications, e.g., model based systems engineering.	Simulations is a core functionality of systems by means of seamless assistance along entire life cycle, e.g., supporting operation and service with direct linkage to operation data.
1960+	1985+	2000+	2015

DTs are used for various operations, such as physical asset control, and have the ability to process and manage data and information generated by various devices and appliances. A DT has the ability to operate in instantaneous time and is capable of making predictions of the possible effects of the operation. If considered a "software copy", the DT can be conceived as a simulation of the part, system or process being copied. The main tasks to be performed by a DT operating in a CPS, is to perform simulations in cyberspace and make various predictions, in this way business managers or AI methods will be able to know evaluated information and make decisions as required [126].

It is possible to consider that the most significant transformation related to the way products are manufactured is digitalization. I4.0 has as a priority to optimize I3.0. This needs the development of intelligent equipment and systems that have access to more data, thus becoming more efficient and productive by making decisions in real time [127]. The concept of AI is one of the most fundamental components of I4.0. AI is divided into two types: narrow and powerful. Narrow AI applications have been created to perform a single task in a single application area. Strong AI has human-level intelligence and problem-solving capability. In AI studies, there are complementary elements such as IoT, deep learning, autonomic learning, and neural networks [128,129]. AI has diverse applications, as shown in Figure 18.

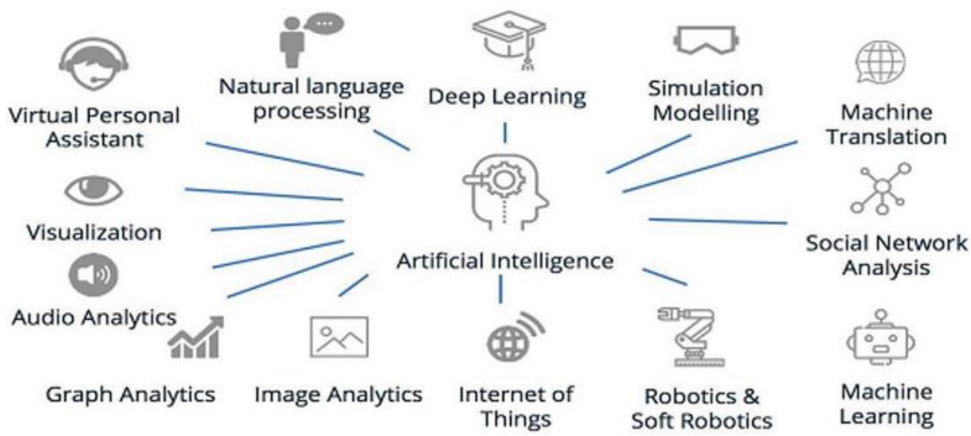

Figure 18. Applications of Artificial Intelligence [128,129].

A CPS is an intelligent system in which computer units and physical objects are highly integrated and interact in a networked environment [130]. There are various applications of AI in which other technologies are combined, such as IoT. Specifically, the automotive technology TESLA uses AI and various devices to know several variables that allow cars to drive safely, and are even able to make predictions about the physical movements of the environment. In future applications, the AI incorporated in CPSs will be used for various applications such as monitoring the health status of patients, operating robots and managing manufacturing systems, providing solutions to human problems and natural disasters, among other important tasks [131]. AI applied in DTs is considered as universally applicable theoretical and technical system with many uses, such as product design, equipment manufacturing, medical analysis, aerospace and other fields [132].

AI with applications in Industry has the following particularities [133]:

1. Infrastructures: with respect to hardware and software, there is a strong emphasis on real-time processing capabilities, ensuring reliability in industrial terms with high security and interconnectivity requirements;
2. Data: high volume and high speed data is required from various units, products, regimes, etc.
3. Algorithms: integration of knowledge of physical assets, digital and heuristic resources and high complexity derived from model management, implementation and governance is required.
4. Decision-making: in the industrial environment, tolerance to error must be very low, so a significant management of uncertainty is required. Similarly, to handle problems that require robust or large optimization, system efficiency must be taken into account.
5. Objectives: AI focuses its attention on shaping real value by taking into account various factors such as increased quality, decreased waste, multiplied operator capabilities and performances or accelerated times.

On the other hand, I4.0 can be described as a high integration of disruptive technologies whose main function is to optimize current manufacturing systems. To achieve the goal of integration, global interoperability is a property of utmost interest in I4.0. Interoperability has the capability or ability to make two or more software components or systems cooperate with each other despite their differences in interface, execution platform and language [134]. IEEE defines interoperability as the ability of two or more systems or components to exchange information and use the information that has been exchanged [135].

It is of paramount importance in the I4.0 vision that physical assets and cyberspace are linked or integrated so that effective and seamless collaboration can exist. However, connectivity and interoperability of information and communication technologies are challenging tasks for I4.0 implementation. Interoperability can be considered as an advantage in I4.0, but to make it efficient, standards or proprietary approaches must be homogenized and exchanged for open and standardized communication solutions. Then it can be deduced that the lack of standards is considered a major problem so it is necessary to direct research efforts in the definition of protocols, languages and standard type methodologies [136].

In smart manufacturing and production, interoperability takes two general forms. The first is associated with vertical type integration, e.g., interoperability between software for manufacturing and production, shop floor and design departments, processes and tasks performed by different teams, various shop floor systems, etc. [137]. The second is associated with horizontal type integration; for example, interoperability between different intelligent automation devices and appliances, cloud services, cloud platforms and enterprises [138].

The study of the concept of interoperability in I4.0 is very important, and several authors have researched on the subject. Yang [139] presents a concentrate of studies of the issues related to this concept. The studies agree that the architecture or structure of interoperability in I4.0 has four levels: (1) Operational (organizational), (2) Systematic (applicable), (3) Technical and (4) Semantic interoperability. The first of these relates to the general structures of concepts, standards, languages and relationships within CPS and I4.0. The second level identifies the guidelines and principles of methodologies, standards, domains and models. The third level articulates the tools and platforms for technical development, IT systems, ICT environment and related software. Finally, the fourth level ensures the exchange of information between different groups of people, malicious packages of applications and various levels of institutions [139]. Figure 19 shows a framework of I4.0 interoperability.

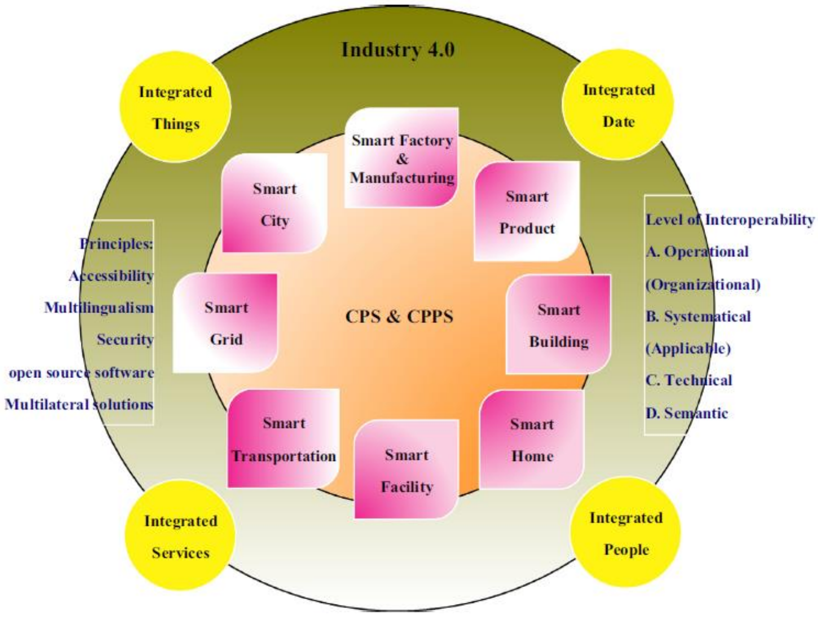

Figure 19. Interoperability framework for I4.0 [139].

2.2. *Engineering Education in the Vision of the I4.0*

In this section, some relationships between I4.0 and engineering education are presented. Then, mechatronic engineering and the basic concepts of Competency Based Education (CBE) are described, as well as active methodologies. Finally, 15 technical guides are presented, which will allow designing and building specific competencies for mechatronic engineers.

2.2.1. Engineering Education (IE), I4.0 and Mechatronics

It is important to know those relationships that exist between IE, I4.0 and mechatronics, as they are essential for the analysis and shaping of specific competencies of the mechatronic engineer.

The influence that I4.0 has on the industrial sector has been projected to the topic of engineering education. In recent years, there have been several and numerous works and researches on education topics in the vision of I4.0, ranging from qualification studies, analysis of topics that should be in the curriculum to adapt them to I4.0, in the search for an Education 4.0 similar to the philosophical framework of I4.0 to the conceptualization of practices in the laboratory [140]. While the impacts of I4.0 are still unquantifiable, the innovations it will bring will be too rapid and too profound, requiring higher education to respond to the challenges and opportunities posed by I4.0. Sakhapov and Absalyamova [141], state that I4.0 has already started due to industrial changes in IoT, integration of CPS in production processes and application of neural networks. For education, and especially for engineering education, this brings important implications such as individualization and digitization of education, empowerment of projects and multidisciplinarity of engineering education, as well as interaction of educational resources.

Due to the implementation of I4.0, current and future engineers will have to face a highly differentiated and specialized society operating with a globalized vision, and with highly automated production systems, with a digitized world connected to cyberspace, where diverse and novel business models and plans, intelligent artifacts, cutting-edge procedures and techniques, and optimized processes are dynamically generated [142]. As mentioned above, the CPS represents the technological center of the I4.0, which may represent several advantages, but also a cataclysm for many professional careers, engineering and technical specializations, because these systems may involve various changes not necessarily positive in education and universities since it should be noted that companies and industries are truly in a fundamental change in production and industrial manufacturing, and not as commonly thought that the I4.0 is only a technological improvement of services to industrial processes [141]. The innovations brought about by I4.0 involve the design of fully automated production systems, displacement of operators from the center of production, fundamental changes in the value chain and business in companies and industries, minimization of social implications, innovations in intellectual assets (patents and industrial secrets) and technical specialization of modern industrial processes [143].

It can be observed that due to the incursion of the I4.0, there are innovations of great importance in economic aspects, both in the processes and in the micro and macro economy of the countries. These changes or innovations are a consequence of the incursion of new knowledge generated by science and new disruptive technological resources that are producing significant social changes and are reducing the cycle and life time of professions, which motivates workers and in general the workforce to have a greater and better adaptability. Therefore, universities play a role of utmost importance as they must better prepare their engineers to meet the new requirements of I4.0 [144]. As previously mentioned, the I4.0 promotes the use of novel technologies (AI, IoT, CPS and DT, among others) in industrial processes; these technologies have disruption as their main characteristic and imply that students in study centers must be prepared, qualified, highly competent and master multiple technical skills such as: having leadership, possessing strategic thinking, mastering computer skills and capabilities to design cyber security systems, among others, to be able to operate in the vision of the I4.0 [145].

The I4.0 vision needs preparation and high training of engineering students so that they have the ability to solve problems and to face the challenges and challenges of I4.0. One of the key technologies, as mentioned above, is CPS, so engineers must be able to be trained under an inter- and multidisciplinary approach to master this technology so that, as a result, I4.0 can be implemented quickly and efficiently. [146].

Although all engineering education is influenced by the inertia of I4.0 implementation, Mechatronics Engineering stands out for being of an integrative nature (a process on which I. 4.0 itself is based). Mechatronics was conceived in IR3.0 and consequently, together with computing, informatics and robotics, brought a significant technological impact to the industrial world for a period of at least 50 years [20]. Today, the training of the mechatronics engineer faces the major challenges of transforming CIM systems (core of manufacturing 3.0) into modern CPSs that integrate several DTs and that are the basis of I4.0. While Mechatronic Engineering was first conceived as a synergistic integration of mechanical engineering with electronics and intelligent computer control in the design and manufacturing of industrial products and processes [147], over time there have been many changes in the functionality of the systems, due to the evolution of ICT, which has involved the development of much more complex and computationally intensive computing systems. Mechatronics is being strongly influenced by new technological developments related to CPS, DT, cloud computing and IoT. These technological developments have meant that there are better opportunities to make the changes and innovations, particularly in terms of supplying smart components and subsystems and configuring them. For mechatronics to be incorporated into I4.0 it must evolve in such a way that traditional mechatronic devices and systems must be transformed to provide the intelligent components and objects with which the new industrial revolution is being built [148]. This implies that Mechatronics Engineering Education must also be transformed to be able to integrate various disruptive technologies already present and ICT in modern industrial processes. Such transformation must be able to integrate new conceptual approaches, seeking as far as possible to preserve the basic theory of systems integration as a support for mechatronic engineering.

Undoubtedly, mechatronics from the 1960s to the present day has and continues to provide the tools for technological integration that enable the design and manufacture of complex production systems that require a convergence of technologies and knowledge. However, mechatronic systems have transitioned over time towards CPS and IoT. Figure 20 shows such a transition [149].

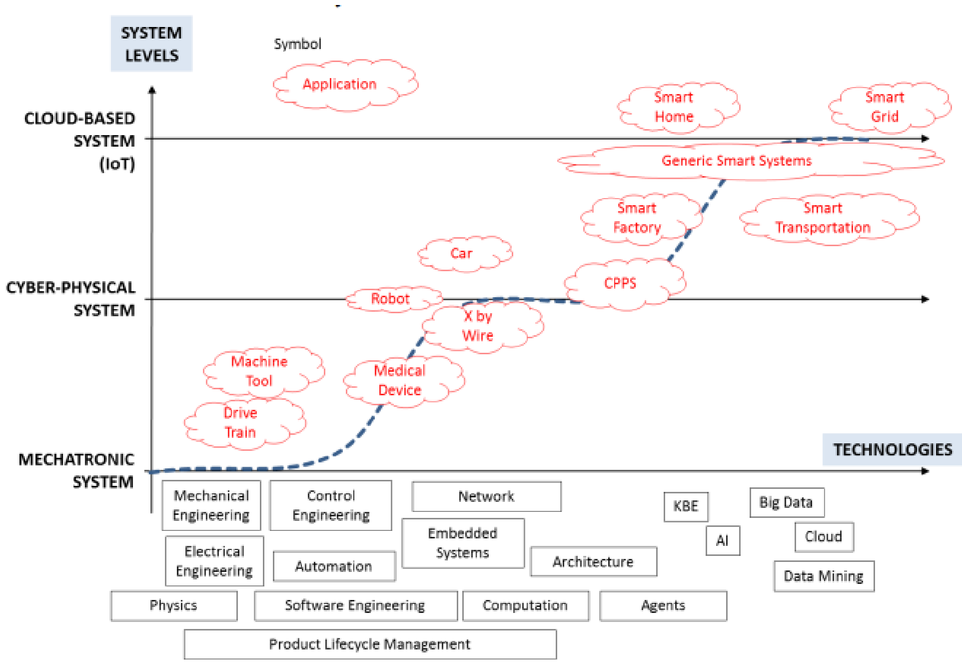

Figure 20. Evolution of mechatronic systems towards CPS and IoT [149].

The systems shown in Figure 19 are shaped or structured around a massive interconnection process of products, devices and mechatronic objects that have certain intelligence, and are associated with a large amount and variety of information in terms of parameters of the physical environment. The information collected has several uses: (1) To verify how the entities behave in time and space, (2) To inspect and control the relationships and interactions within the physical and computing environments, (3) To enable the analysis of the processed data and allow its visualization, to have a good support to enable the operation of the system and the interaction with the consumer or user [150]. Mechatronics can be considered as an evolution of electromechanical products and CPSs come from an evolution of cyber-systems. Thus CPSs have their origin in an information technology (IT) domain and in software development. This helps to explain why there is a strong software and communications dimension to CPS. The design methodology of CPS is strongly linked to systems engineering approaches [151].

The pressing industrial needs have led mechatronics to be considered as one of the best practical applications of engineering graduates. Since its origin, mechatronics was conceived as a field of knowledge that integrates diverse technological systems to achieve a greater optimized functionality of the systems it develops. It seeks a synergy between physical assets (mechanical, computational and electronic components) to optimize the operation of the system from its conception and throughout its life cycle, this advantage enables engineers to make complex decisions. Consequently, it can be stated that integration is the key concept in any mechatronic design and that the complexity of the design has shifted or transferred from mechanics to electronics and computation.

It is possible to consider mechatronics as part of evolutionary design which implies that there is a vertical and horizontal integration of various disciplines related to engineering and between design tasks and manufacturing activities. Some authors have proposed that mechatronics be considered as the new modern mechanics [152]. Mechatronics has gradually transformed due to the incursion of new technologies and cutting-edge knowledge. Today the new industrial revolution imposes new challenges to mechatronics engineers.

Faced with the constant challenges of I4.0, mechatronics and its teaching must be reinvented. In this sense, mechatronic engineers who develop products, processes and systems of any type and variety, must be able to know, master and apply a collection of principles to be successful in the implementation of I4.0. Some of these principles are (1) software, (2) hardware, (3) technology, (4) ubiquity, (5) connectivity, among others [153]. Mechatronics education should consider as essential and necessary the principles of mechatronics design and the application of novel technologies that cause disruptive changes. However, it is also necessary to take into account educational, economic and social aspects that directly impact I4.0. In this sense, education in Mechatronics Engineering, placed in the vision of I4.0, has several problems to be considered, for example:

- The speed of transition and adaptation of disruptive technologies is slower in universities than in companies, since the former have to go through cycles or generations to make changes in their curricula, while the latter need to adapt as quickly as possible.
- Educational models in educational institutions in general are different, which prevents the design of a single educational model for Mechatronics Engineering education.
- Another aspect to consider is that it is often planned, both entrepreneurially and in universities, in terms of the theoretical needs of the already established I4.0, when in reality a technological transition characterized by I3.5 is taking place.
- There are countries that are leaders in the implementation of I4.0, but the vast majority of the remaining countries are at some stage of technological transition and some even have manufacturing systems with technologies that are tending to obsolescence.
- The implementation of I4.0 among companies also varies in terms of technological strategy, as those with high economic capacity can replace their production systems quickly. Other companies with less economic capacity will opt for reconditioning methods to improve their production systems and adapt them to the value chains imposed by I4.0.
- Mechatronics education does not follow a universal model, as each country and each region defines the specific knowledge and skills required, according to: the regional industrial environment (type of companies and their needs), the regional educational environment (type of universities and teaching capabilities) and national educational policies.

It is possible to look at the world of education in the era of I4.0 from two different perspectives [154]: As an opportunity (the birth of a new business unit in the community that is able to penetrate the unlimited space by using information technology and vice versa) and as a threat (one of the threats is the result of automation of the many human jobs performed by machines, systems and robots that implies a displacement of operators and a loss of new businesses).

2.2.2. Educational Models in Mechatronics Engineering Education

This section describes some important aspects related to CBE and active methodologies. These educational models and approaches are being used today for the training of mechatronic engineers and in general for engineering education.

Engineering education has been characterized by having a teacher-centered pedagogical model. However, nowadays learner-centered and CBE models and approaches have been positioning themselves in universities around the world [155–157]. It is possible to describe CBE as an educational approach that is concerned with goals and outcomes. Adult-based learning theory is integrated into CBE and describes that it increases the likelihood that adult learners will be more interested, engaged, and work harder when it comes to meeting stated goals or very specific outcomes. This idea implies that the purposes of CBE in terms of teaching and learning methods are directed toward shaping skills that are already stated and described (usually by companies) and these are measured or graded by observing how learners perform those skills [158]. The competency-based approach can be an ideal way to train new engineers, especially mechatronic engineers for I4.0, as it fosters comprehensive training, flexibility and self-management, promotes active learning, develops technical and social skills, and encourages engineers to solve problems in complex situations, among other relevant features [20].

CBE is conceived as an educational approach that is outcome-based and integrates mechanisms for the delivery of instruction and assessment methods designed to assess and evaluate student learning through the putting into practice of acquired knowledge, applications of that knowledge, and soft skills [159]. The new challenges demanded by I4.0 thus require a competent engineer, i.e., he or she must be able to have knowledge of the subject matter and a set of skills that put the acquired knowledge into practice, as well as certain attitudinal skills. The definition of competencies for I4.0 requires a universal understanding of what they are, namely the characteristics in terms of knowledge, skills and attitudes which enable the tasks entrusted to be performed to a satisfactory level [160]. There are many definitions of what a competency is. One of them is presented below [161]:

A student's competency contains three elements: knowledge, skills, and attitudes/values. These components are integrated to perform a specific activity, with measurable results, which clearly indicate what the student is capable of doing. A competency comprises a set of resources and talents that an individual has to perform a specific task.

It is possible to affirm that the design of the competencies required in I4.0 must take into account the combination of those learned knowledge, the skills that make it possible to put the knowledge into practice, and the attitudes necessary and recognized for companies to function adequately in I4.0. According to Armstrong and Taylor [162], competency is associated with a distinctive characteristic or trait that remains hidden (underlying) of an individual that results in or provides superior and effective performance. There are several ways to classify competencies. Martens [163] classifies them in the work context as follows:

- Generic competencies: these are related to work behaviors and attitudes specific to different areas of production, for example, the ability to work in teams, negotiation skills, planning, etc.
- Specific competencies: these are related to the technical aspects directly associated with the occupation and are not easily transferable to other work contexts (operation of specialized machinery and formulation of infrastructure projects, among others).

In education, there are also several classifications of competencies. Galdeano and Valiente [164], consider that competencies can be classified as follows:

1. Core competencies: these are the intellectual capacities necessary to support and promote the learning and knowledge of a specific profession; some examples of these are: cognitive, technical and methodological competencies; most of these competencies were developed in previous educational systems or levels.
2. Generic (transversal) competencies: This type of competencies are described as those attributes or characteristics that an alumnus or university graduate should possess with total independence of his or her career or profession, and are not designed with purely technical considerations, but should take into account the human aspects. These competencies collect generic considerations of all those abilities, skills, knowledge, potentialities and capacities that any university graduate should possess during his or her education and before finding a job.
3. Specific competencies: These types of competencies are described as those attributes or characteristics that students should have before graduation and should be built according to the experiences and practices of the students or graduates themselves. With the specific professional competencies, the aim is to start with the typical functions or role of the professional in society and the typical situations of the professional field in which graduates are generally incorporated, and then identify the professional competencies in terms of the actions, context or conditions for carrying them out and the quality criteria for their execution.

On the other hand, the transition from teacher-centered pedagogy to student-centered learning requires the adaptation of new active teaching strategies that allow [165]:

- To give students a greater role in their education.
- Encourage collaborative work.
- Organize teaching according to the competencies to be acquired.
- Stimulate the acquisition of autonomous and lifelong learning.

In this sense, the use of active methods related to the teaching and learning processes can support and promote those pedagogies that consider the student as the center of the educational process, since they favor in an active way, and from diverse experiences and real contexts, the construction and use of knowledge. These methods displace teachers from the center of knowledge and place them as facilitators of educational processes, whose main function is to stimulate students to reflect on the different contexts and to problematize situations within the environments in which they develop and where they construct and are the protagonists of their learning [166]. Some authors have discussed learning methodologies in depth [167,168] and agree that changes are required in the strategies employed by universities to design the expected profile of an engineer in the I4.0 era.

The methodologies considered active (strategies, techniques and methods) are used by teachers with the aim of transforming the processes and activities related to teaching into tasks in which students participate actively and where they are able to direct their own significant learning [169]. Currently, there are several classifications of learning methods where active methodologies occupy an essential place. Some of the active methodologies that exist and are regularly applied are listed below [170]: Cooperative Learning, Project-Based Learning, Learning Contract, Problem-Based Learning, Exposition/Lecture, Case Study, and Simulation and Game, among others.

According to Jimenez et al. [171], one of the active methodologies that adapts naturally to engineering education is Project Based Learning (PBL), since it is based on the construction of meanings and problem solving, where students abstract knowledge and extrapolate it to other fields in a dynamic way, that is, students learn while they create. Some important characteristics of PBL are presented below [172]: it fosters relationships between the academic world, the context of realities and competencies for work; it promotes that students are able to self-evaluate and reflect on things, and that they accept feedback and allow being evaluated by knowledgeable people; it encourages students to accept being evaluated on the basis of evidence of their learning; it helps to design and develop specific competencies and specific objectives according to current needs.

PBL is an active methodology that is applied in various universities, particularly in engineering programs, e.g., Lin et al. [173] investigated the effects of infusing an engineering design process using PBL in science, technology, engineering and mathematics (STEM) projects to develop and evaluate the cognitive structures of technology teachers in training for engineering design thinking. In [174], PBL is used for mechanical vibration control studies using Matlab 9.4/Simulink Software. In applications for the teaching of mechatronics, the APB has been applied in the field of Renewable Energies in the solution of projects that integrate various fields of knowledge [175]. In [176] the PBL is applied to the teaching of mechatronics in the subject of robotics.

PBL has been applied to support theoretical concepts in engineering curricula and to provide a learning experience that develops practical skills and competencies for I4.0 [177]. There are other concepts that attempt to relate I4.0 to education. Abele [178] defines the concept of a Learning Factory 4.0 *as a learning environment that includes four distinctive features: (a) authentic processes, which include multiple stations and comprise technical and organizational aspects, (b) an environment that is changeable and resembles a real value chain, (c) a physical product that is manufactured, and (d) a didactic concept that comprises formal, informal and non-formal learning, enabled by the actions of the learners in an in situ learning approach*.

The interconnectedness of a Learning Factory 4.0 (which is the fundamental idea of I4.0) is based on cyber-physical production systems (CPPS). Learning Factories 4.0 are intended to prepare learners for the challenges of I4.0. The implementation of these

Learning Factories 4.0 interconnected with technical vocational training centers can promote the development of technical skills related to the subject as well as multidisciplinary digital skills [179].

2.2.3. Technical Considerations for the Design of the Specific Competencies of the Mechatronic Engineer under the I4.0 Vision

Once known, in the previous sections, the generalities of I3.5, I4.0 and I5.0 and their methods and technologies, as well as the general aspects of CBE, active methodologies and mechatronic engineering, it is possible to propose technical considerations that make it possible to design specific competencies for the training of the mechatronic engineer.

Specific competencies are related to the technical aspects and considerations of a career or profession [180]. To approach the study of this type of competencies in faculties or schools, the starting point is the profile of the graduate that the study programs have in order to contrast it with the expectations in the professional field both regionally and nationally, as well as internationally, find similarities and differences, and arrive at the selection of the elements that could be recommended for the profession. The specific competencies are divided into two major classes: (1) The class associated with the training of disciplines that graduates must acquire, called academic disciplinary competencies and (2) Those competencies related to professional training that future graduates must possess: professional competencies [164]. Although the specific competencies are not universal, they can be designed based on the analysis of the key technological concepts of I4.0, such as IoT, simulation, CPS, DT, AI and technological reconditioning (retrofitting), among others. For the case of mechatronic engineers, the development of specific competencies can be carried out under the following technical considerations:

1. Similarly to mechatronics, I4.0 is considered as a paradigm that integrates various technologies whose purpose is to improve and optimize production systems under the operation of CPS. It can be stated that synergic integration represents a characteristic feature of I4.0. In this sense, the Mechatronic Engineer must be able to integrate disruptive technologies since these are the basis of I4.0. The most important feature of a CPS is the high integration, mainly of software and hardware resources, with the aim of carrying out various tasks of calculation, control, computation and communication, taking into consideration for the design of the same to the technological assets and their theories [68].
2. Mechatronics is rather an evolution of electromechanical systems and CPS (which represent the heart of I4.0) coming from an evolution of cyber-systems [151] or IT and software development. In this vision, the Mechatronic Engineer must further improve his knowledge and expertise in electromechanical technologies and gradually venture more into IT with the purpose of realizing technological integrations and more specialized applications, including Big Data, Cloud Computing and IoT, among others.
3. One of the computing disciplines that the Mechatronics Engineer must address in greater depth, both in his training and applications, is AI, since a large part of I4.0 is based on the development and operation of intelligent systems and the DTs that make up the CPS.
4. If one starts from the premise that I4.0 is actually a large-scale optimization of I3.0 [20], this concept should be considered necessary in the training and applications of the mechatronic engineer. It is worth mentioning that the applications of analytical methods such as: stochastic optimization and mathematical optimization, among others, are already well known, especially in the analysis and studies of large databases, and that they are applied to have an optimized planning and to have instantaneous time control of operations and processes. Optimization models considered as large-scale have various applications, such as in design, manufacturing and intelligent production [181]. All these optimization techniques should be valued and learned by mechatronic engineers.

5. Another key computational tool that should be considered by Mechatronics Engineering is computational simulation, since it is the basis of the DTs and the support of the CPS. However, for this tool to be applied efficiently in I4.0, it must move from applications in engineering and decision-making processes and from the phases and steps of design and engineering, towards simulation that takes into account various areas of knowledge (multidisciplinary) [125]. That is, to a simulation that integrates different models and methods from different areas to provide more robust solutions. Multidisciplinary simulation requires the use of large databases and high information processing, which implies knowing and mastering technologies that handle large amounts of data and cloud technologies.
6. IoT is a necessary tool that the mechatronic engineer must know and apply, since it allows connecting various digital devices and appliances and promotes interactions between humans and computers. This tool applied in conjunction with other disruptive technologies, such as data mining, autonomous learning and AI, can be used for specialized applications [116]. IoT facilitates communication and cooperation between CPSs. This technology is already essential in the operation of today's factories so the mechatronic engineer must be familiar with its management and operation.
7. Mechatronics engineers must transition from traditional design and manufacturing methodologies to digital design and manufacturing conceived within the I4.0 vision. Digital design and manufacturing technologies provide great support for product conception throughout the product lifecycle, which includes product sales and services [182]. Custom design and manufacturing using 3D printing are technologies that improve designs and accelerate production. The world's leading companies in design and manufacturing are already implementing digitalization as the basis of competitiveness, so it is already a pressing need for the Mechatronic Engineer to master the new methodologies.
8. Although design and manufacturing methodologies are very important in the training and applications of mechatronic engineers in the I4.0 vision, they must be complemented by introducing Reverse Engineering methods [20,171]. Technological reconditioning and to a large extent the maintenance of equipment, machines and production systems, and directly or indirectly use some method of reverse engineering to solve various problems. The information and information models generated by the application of reverse engineering can be used for the design of DT in the maintenance of production systems. Reverse engineering is a method of analysis that companies are requiring since it is not only used for technological reconditioning, but it is also applied for the improvement of products and processes.
9. Although industrial automation has been a field of action for mechatronic engineers in companies for decades, today, in order to meet the challenges of the I4.0, it is necessary to integrate new technologies and new equipment to industrial production systems with which optimization and systematic continuous improvement processes can be carried out. Similarly, it is required to know and apply different automation architectures that allow greater flexibility and modularity, and that can interoperate between different manufacturers to enable automated, optimized and efficient production systems, as well as to design viable individualized and low-cost solutions in production systems. This implies that mechatronic engineers must know the forms and operation of modern technologies so that they can automate processes in the vision of I4.0.
10. Mechatronic engineers must have knowledge and skills on technological reconditioning methods, both traditional (which consists of the replacement of parts and components in machines, processes and systems, to optimize different variables) and intelligent (which aims to adapt existing systems, equipment and devices at a low cost) [59], since several problems that currently arise, and that will arise in the future, will be related to technological upgrading. This implies that engineers must have knowledge of CPSs conceived under the I3.0 approach and of modern disruptive

technologies so that, under some technological retrofitting methodology, a traditional CPS can be transformed at a lower cost to one that can operate under the vision and needs of I4.0.

11. In today's production systems, maintenance is one of the most important tasks due to its contribution to the organization, and nowadays it is being considered more frequently in corporate objectives [183]. With the advancement of technology in companies and industries, maintenance methods and techniques are designed and developed to be able to adapt to the demands of new producers or manufacturers. With the emergence of I4.0, novel methods and maintenance techniques have been created with the purpose of meeting the new demands; all these novel techniques are conceived under the concept of Maintenance 4.0 [184], which is described as the application of I4.0 to operations and maintenance activities. The objective is simple: to maximize production uptime by eliminating unplanned reactive maintenance [185]. The mechatronic engineer must then have knowledge and develop practical skills in maintenance 4.0 and its implications in order to meet the challenges brought by I4.0. Maintenance 4.0 involves knowledge of DT and CPS, as well as the use of various disruptive technologies such as cloud computing, big data management, and augmented reality.
12. One of the technologies that supports both I4.0 and I5.0 is robotics. Mechatronic engineers must not only be able to integrate new robots into production systems conceived under the I4.0 vision, but they must also know about collaborative robotics (the basis of I5.0 [53]), which deals with the integration of machines and humans into processes.
13. Interoperability is a concept of utmost importance in I4.0, and is understood as the ability of two or more software components to cooperate despite differences in language, interface, and execution platform [134]. In order for interoperability to take place, standardization is necessary. In this sense, mechatronic engineers must be able to know and master the concept of interoperability and its implications in the design and operation of CPSs.
14. IT security in I4.0 is of utmost importance for the protection of information in companies and industries. Traditional architectures and structures that exist today to achieve cyber security have different security mechanisms and systems that provide services such as integrity, access control and confidentiality, among others [186]. Nowadays, computer security is tested by various events and specialized cyber attacks. It is necessary to consider the various methods and techniques with which it is possible to detect intrusions and respond to hackers. These methods must be used with other techniques to prevent intrusions in order to build more robust, efficient and effective defense systems. Cybersecurity tasks should be considered necessary and important by the mechatronics engineer because design, manufacturing and production information, among others, represent the heart of any company.
15. Ergonomic design of workplaces that enable human-machine interaction, design of training methods for human-machine symbiosis, personalized manufacturing, cognitive computing, and IoT-based smart spaces are some tasks and technologies that are contextualized in I5.0. The concept of operator 4.0 relates to the design of human-cyber-physical production systems [54] that aim to boost, improve, enhance, empower and optimize the capabilities of human-machine interactions. These tasks and needs should be kept in mind by the mechatronics engineer as collaborative robotics and close interaction and collaboration between operators and machines will become more and more prevalent. In I5.0, the technologies of DT, CPS and AI that consider humans in symbiosis with machines will be listed as the core technologies.

The incorporation of disruptive technologies and new design methods to the mechatronics environment does not necessarily imply more knowledge and application burden to engineers, but rather they boost and encourage teamwork among the different engineering disciplines that are responsible for designing, managing, operating, maintaining and innovating modern productive systems characterized by CPS. The 15 technical considerations described above can be used to assist in the design of specific competencies for mechatronic engineers according to the needs of the local or national industrial sector. Some of the specific competencies that can be derived from the above considerations are listed below:

1. CPS design.
2. CPS operation.
3. DT Design.
4. CPS maintenance.
5. Conversion and reconditioning of CPS.
6. Automation of intelligent production systems.
7. Design, manufacturing and digitalized production.
8. Operation of collaborative robots.
9. Cyber-security management in the CPS.
10. Technology integration in smart factories.
11. Optimization of industrial processes.
12. Design of intelligent production systems.
13. Design of man-machine systems.
14. Analysis of large databases.
15. Interdisciplinary simulation in intelligent production systems.

3. Final Considerations

The tasks of mechatronic engineers are essential for the implementation of I4.0 and I5.0, so it is necessary that their training is transformed according to the needs and requirements of the current industrial revolutions. Due to its integration nature, mechatronics is similar to I4.0, since precisely this new business vision tries to integrate disruptive technologies to the productive processes looking for improvements and optimization. However, it should be understood that I4.0 implies a real change in industrial processes and does not consist of simple improvements generated by the incursion of technologies. This fact has important implications for the training of engineers, since it is not only a matter of training them in knowledge and in the specific or integrated applications of disruptive technologies, but also requires profound changes in production methodologies and education.

CBE and active methodologies should be promoted in universities for the training of mechatronic engineers. These educational approaches and active learning methods are the basis for the transformation from traditional (teacher-centered) education to constructivist (learner-centered) education. Just as industrial processes must be fundamentally transformed due to the incursion of disruptive technologies, engineering education must do the same, i.e., it must also be fundamentally transformed if it is to graduate competent engineers capable of meeting the challenges of the new industrial revolutions. CBE and active learning methods can be the basis of the transformation required by engineering education, mainly in mechatronics engineering.

The training of mechatronic engineers should take into account not only I4.0 and I5.0, but also I3.5, since technological transitions have implications in the shaping of specific competencies. For example, technological re-engineering is a task that will occur more frequently in companies that do not have sufficient capital to upgrade their production systems. This method of re-design, together with the methodology of reverse engineering, should be promoted and taught in universities. Currently, engineering education gives more priority to direct design methodologies (a process that starts from a need and ends in a product or service) than to reverse engineering methods, despite the fact that a high percentage of technological development is based on information from existing technologies in order to improve them. Technological reconditioning is a pressing need in I4.0.

The design of specific competencies in mechatronic engineers should consider the industrial needs of each region, state or country. However, technical considerations that take into account the main technologies, tools and processes, such as CPS and DT, can be raised to assist in the design of specific competencies. The 15 considerations proposed in this work can be expanded and do not exhaust the field of study. The proposals can be very useful for those universities that are developing or improving a career in Mechatronics Engineering, since these proposals could help and guide the development of specific competencies according to the needs of the local environment.

4. Conclusions

In this paper, 15 technical considerations have been proposed that can be used for the shaping of specific competencies for the benefit of mechatronic engineers. The conclusions of this paper are as follows:

- Engineering education, especially Mechatronics Engineering, must be fundamentally transformed in order to train the professionals who will face the challenges of I4.0 and I5.0.
- I4.0 implies profound changes in production processes, in design and manufacturing methods, in the configuration of factories and in the roles that mechatronic engineers will play. In this sense, Mechatronics Engineering as such must reinvent itself to keep pace with the technological changes in companies.
- CBE and active methodologies can be the basis for engineering education to transform itself and for universities to train the engineers required by the new industrial revolutions.
- The core training of mechatronic engineers should consider CPS, DT and AI as basic concepts that should be developed throughout their careers and that should be integrated into the curricula.
- The role of the mechatronics engineer in the I4.0 is not technical mastery of disruptive technologies, but should rather play the role of integrator and administrator of engineering groups made up of different disciplines. Companies must rethink the central role of the mechatronics engineer, since they are currently entrusted with various tasks that are not of their profile (preferably integrator and technology manager). I4.0 requires a mechatronics engineer capable of managing human resources from other fields of knowledge in order to solve specialized problems.
- Industrial maintenance, technological reconditioning and reverse engineering should be promoted as subjects of study in universities for the training of the mechatronic engineer. These skills are often learned more in companies than in universities. Technological reconditioning is a pressing need due to the fact that we are in a stage of technological transition between two industrial revolutions and that many companies do not have the capital to invest in new technologies.
- The 15 technical considerations proposed in this article can be used as a guide for the formation of specific competencies through which mechatronic engineers will acquire the knowledge and applications specifically required by the work environment in which they will work. These considerations take into account the transitions between the industrial revolutions and the most representative technologies of the I4.0, such as CPS, DT, IoT, simulation and AI. The technical considerations can be viewed as generic since they propose activities that most companies apply or will apply in one way or another in I4.0.
- For the training of the mechatronic engineer in the context of I4.0 and I5.0, all the competencies (basic, generic and specific) must be designed with the rigor indicated by the different CBE proposals and models.

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