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Abstract: Industry 4.0 is an industrial paradigm that is causing changes in form and substance in factories, companies and businesses around the world, and is impacting work and education in general. In fact, the disruptive technologies that frame the fourth industrial revolution have the potential to improve and optimize manufacturing processes and the entire value chain, which can lead to an exponential evolution in the production and distribution of goods and services. All these changes imply that the fields of engineering knowledge must be oriented towards the concept of Industry 4.0, for example Mechanical Engineering. The development of various physical assets that are used by cyber-physical systems and digital twins is based on Mechanics. However, the specialized literature on Industry 4.0 says little about the importance of Mechanics in the new industrial era and more importance is given to the evolution of Information and Communication Technologies and Artificial Intelligence. This article presents a frame of reference about the importance of Mechanical Engineering in Industry 4.0 and proposes an extension to the concept of Mechanics 4.0, recently defined as the relationship between Mechanics and Artificial Intelligence. For the analysis of Mechanical Engineering in Industry 4.0, the criteria of the four driving forces that defined Mechanics in the third industrial revolution was used. An analysis of Mechanical Engineering Education in Industry 4.0 is presented, and the concept of Mechanical Engineering 4.0 Education is improved. Finally, the importance of making changes in the educational models of engineering education is described.

Keywords: Industry 4.0; mechanical engineering; engineering education; Mechanics 4.0

1. Introduction

Industry 4.0 is a new industrial scenario where companies, industries and businesses benefit from the implementation of new technologies in their production processes and business operations. Currently, industries are orienting their traditional operating framework to a technology-centric operating framework, this due to the technological disruptions that are modifying production systems [1]. Today's technologies and the adoption of globalized production processes are transforming companies, in such a way that product requirements have diversified, making the analysis of product is a priority in Industry 4.0. [2]. The changes provoked by the fourth industrial revolution in companies are not simple improvements due to the use of a new technology, but transformations of substance and form, and are radically innovating processes in companies, businesses, organizations and administration.

The needs and requirements of customers have become more personalized, which implies that a new era is being generated in productive organizations and in the control of value chains throughout the process, that is, throughout the product life cycle [3]. The fourth industrial revolution is also causing changes among suppliers and consumers and is consolidating a massive personalization that represents one of the strategies of the digitalization of companies, companies and businesses in the context of Industry 4.0. The changes and transformations that take place in the fourth industrial revolution drive and promote deep digitalization, that is to say, digitalization on the whole value chain improve and optimize production processes. In addition, the introduction of various disruptive technologies in production systems, such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data, cloud computing and collaborative robotics, among others, have accelerated the process of change from the classic or traditional factory to the Smart Factory [4]. Disruptive technologies not only cause industrial revolutions, but also cause changes and impacts of great relevance in the social and economic sphere in modern societies [5], which are identified by their enormous differentiation and specialization. Industry 4.0 applications cover a wide range of industrial and non-industrial fields, such as textile manufacturing [6], medicine [7], aeronautic industry [8], automotive [9], agriculture [10], petrochemical industry [11], construction [12] and food industry [13], among others.

On the other hand, disruptive technologies are the result of research and technological advances that are developed in various fields of knowledge, such as electronics, nanotechnology, computing and mechanics, among others. In this context, Mechanical Engineering has contributed over time and today, with the development of technology and products, which makes it essential in Industry 4.0. Like any field of knowledge, Mechanical Engineering transforms, improves and adapts to new knowledge, and history has shown that it has been a factor of change and transformation in every known industrial revolution [14]. The essentiality of Mechanical Engineering in Industry 4.0 lies in the fact that it is the design platform for the development of various physical assets, such as robots, belts, actuators, mechanisms, devices and machinery, among others, which represent the basis of production systems in factories and in various companies. Mechanical Engineering synergizes with computing, electronics, and control to develop various mechatronic systems and products that are essential in Industry 4.0 applications. [15].

Recently, the concept of Mechanics 4.0 [16] has been proposed, which description is more oriented towards the applications of the methods and algorithms of Artificial Intelligence to the analysis, modeling, calculation and simulation of various industrial problems where physical systems are involved. Although Artificial Intelligence is a powerful tool for Mechanical Engineering, it is still a disruptive technology, so the concept of Mechanics 4.0 must be extended to cover more fields of study and applications. For example, Mechanical Engineering is related to other related fields of knowledge, such as materials, design engineering, manufacturing, and maintenance, among others, and each of these fields has been integrated into Industry 4.0, giving rise to concepts such as Materials 4.0 [17], Design Engineering 4.0 [18], Maintenance 4.0 [19] and Manufacturing 4.0 [20], among others. In this way, Mechanical Engineering and its related fields or specialized fields, together with disruptive technologies, enhances their applications in Industry 4.0, for example, it has been applied in the development of digital twins for the monitoring of wind turbines [21], in intelligent reconditioning that seeks to modernize old machinery towards the Industry 4.0 approach [22] and to evaluate the behaviors of an electromechanical cooling pump in a cyber-physical system [23], among other applications.

On the other hand, the scope of Industry 4.0 has extended to education in general, mainly to Engineering Education. The fourth industrial revolution requires the design of new competencies for engineers that allow them to solve the technologically specialized problems they will face. In this context, Engineering Education must apply modern educational models and introduce disruptive technologies into the teaching and learning processes, and in this way, engineers can be trained with the appropriate skills to face the challenges brought by Industry 4.0 and 5.0 [24]. Like other fields of study, Mechanical Engineering Education must be transformed towards the vision of Industry 4.0, otherwise graduates will not have the knowledge and skills necessary to face the various problems that involve knowledge of Mechanical Engineering in specialized systems and products conceived under the modern approach of the fourth industrial revolution. In this sense, engineers trained in Mechanics must be highly qualified and with a clear vision of technological innovation [25].

This article presents an overview of the conceptualizations and applications of Mechanical Engineering and its related fields in Industry 4.0 and its importance in previous industrial revolutions, with the purpose of placing Mechanics as an important ally of the fourth industrial revolution, due to the fact that most of the specialized literature pays little attention and highlights more to Artificial Intelligence and Information and Communication Technologies in the explanation of Industry 4.0. An extension of the concept of Mechanics 4.0 [16] is presented beyond the connection of Mechanics with Artificial Intelligence. Finally, some applications of Mechanics in products and processes envisioned by Industry 4.0 are described and the new educational approaches and digital disruptive tools that exist today for the new training of the mechanical engineer are discussed.

2. Materials and Methods

This section describes the methodology used in this article. For the development of this study, the descriptive-qualitative type of research was considered because the generalities of Mechanical Engineering in the context of Industry 4.0 were analyzed and some considerations about Mechanical Engineering Education were discussed. This work is composed of three blocks: the first describes the industrial revolutions, the concept of Industry 4.0 and disruptive technologies, as well as the importance of Mechanical Engineering in the vision of Industry 4.0. The second block describes Mechanical Engineering 4.0 and the specialized fields of knowledge that are being developed under the Industry 4.0 approach, such as Materials 4.0, Product Engineering 4.0 and Maintenance 4.0, among others, and some application examples, in particular in the development of digital twins and in the intelligent refurbishment process. The third block describes some considerations about Engineering Education that must be taken into account for the new training of the Mechanical Engineer who will face the challenges of Industry 4.0.

2.1. Industrial revolutions and Industry 4.0

This section presents an overview of the industrial revolutions that have risen due to the scientific and technological development of human history, with the goal of understanding their historical context, their core technologies and future technological revolutions. Some important concepts and definitions related to Industry 4.0 and its disruptive technologies that have impacted current production processes and are causing a radical transformation of great proportions in industries, business, education and society in general are described.

2.1.1. The Industrial Revolutions

In general terms, an industrial revolution can be considered as an event or event of a global nature that brings changes of form and substance in the industrial world and in societies due to the insertion and domination in a given time, of the contemporary disruptive technologies in the means of production and in human daily activities. In fact, industrial revolutions have been considered as disruptive events or breaking points throughout history [26]. Although ordinary people consider a revolution or industrial paradigm as a unique and isolated event, in reality this is not the case, because as history has shown, great industrial transformations, such as the first industrial revolution, induce profound changes and innovations in companies, bring important improvements in the economies of countries and cause transformations in societies [27]. A characteristic of industrial revolutions is that they are cumulative and progressive, that is, they are usually modernizations of all previous revolutions [28]. For an industrial revolution to occur or emerge, there must be a set of improved or entirely new industrial disruptive technologies at the right time [29].

Four industrial revolutions have been documented throughout history, and there are currently two transitions. In addition, in the specialized literature there is talk of two futuristic revolutions.

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Figure 1 shows the timeline of the industrial revolutions in terms of their basic technologies and the dates of their appearance [30].

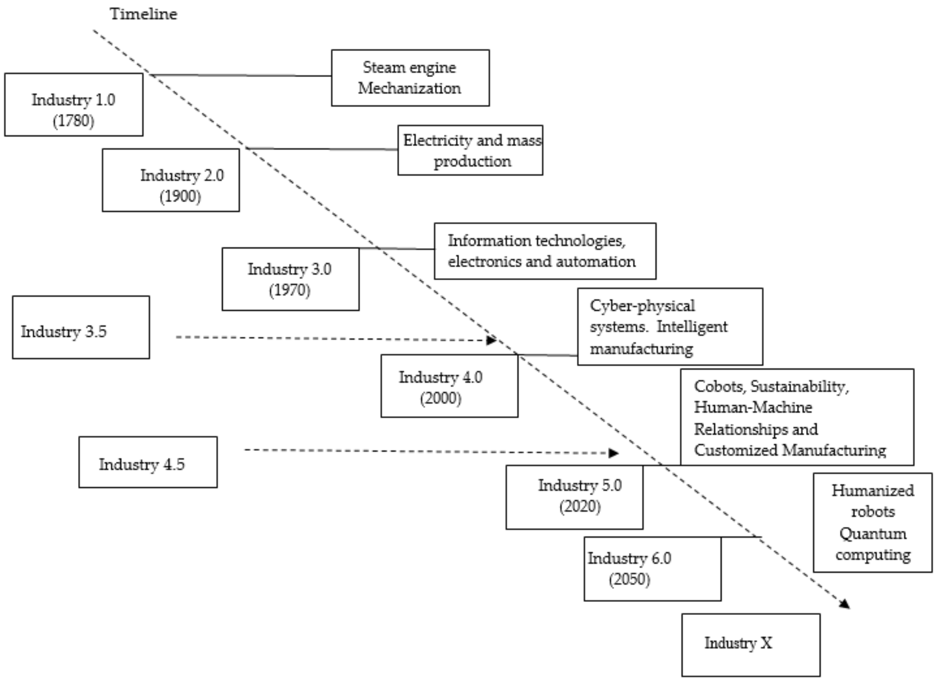

Figure 1. Timeline of Industrial Revolutions and Their Transitions [30].

Each industrial revolution has one or more basic technologies associated with it (see Figure 1). The explanatory extension of the first four industrial revolutions can be found in [31–33]. The two transitions between revolutions will be explained below: 1) Industry 3.5 is characterized by being a transition between Industries 3.0 and 4.0, and in it the processes of modernization, updating, technological migration and technological reconditioning are carried out. Industry 3.5 actively promotes globalization and offshoring processes [34] and 2) Industry 4.5 or also called "4.0+"[35], is representative of the transition between Industry 4.0 and Industry 5.0. This transition promotes and embraces digital solutions and personalization in manufacturing processes. On the other hand, the Fifth Industrial Revolution or Industry 5.0 is conceived by some authors as necessary, since Industry 4.0 has not fully matured, is characterized by promoting and establishing personalized manufacturing, introduces cobot technologies, motivates human-machine relationships and takes sustainability into account [36]. Another technological paradigm planned for the year 2050 is the Sixth Industrial Revolution or Industry 6.0. which will seek to expand the applications of Artificial Intelligence on a large scale aided by quantum computing [37]. The basic technologies of Industry 6.0, according to the specialized literature, will be: the humanized robot, Augmented Reality/Virtual Reality AR/VR, quantum computing, IoT and Big Data [38].

2.1.2. Industry 4.0

The term "Industry 4.0" is related to the Fourth Industrial Revolution and was coined in Germany in the year 2011 [39] and has since triggered what is called a digital revolution around the world. This new industrial paradigm incorporates new technologies into manufacturing and business systems, and is causing disruptive changes that impact industries and society in general (e.g. in production, economy, finance, health, services, transportation, education and communications, among other areas). In fact, this modern revolution, together with its technologies and new production strategies, is changing many features and aspects of man's life and has profound repercussions on administration, production management and the aspect of work. Industry 4.0 represents an obligatory change for those companies that want to be competitive in the coming years. Companies must promote the process of digitalization both in their processes and in the environment

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that surrounds them, and they need to adopt connectivity in their production systems and businesses in order to survive or be more competitive in today's markets that have the characteristics of being changing, personalized and specialized [41]. Industry 4.0 promotes hyperautomation and hyperconnectivity in companies, which brings with it significant improvements in production processes and increased productivity. However, the displacement of workers by highly automated machines is provoking a serious discussion among specialists and concern in governments about the future of workers in factories [42].

Industry 4.0 promotes the development of smart factories that serve as key elements to improve efficiency, quality and productivity in the manufacture of products through hyperautomation and the introduction of sophisticated robots, the Industrial Internet of Things, cloud computing and the methods and algorithms of Artificial Intelligence. among other technologies [43]. Smart factories, also known as dark (without light) factories, are production systems developed with the ability to carry out manufacturing in a fully automated manner and operate with virtually few staff or fully autonomous [44]. In fact, the conception of the dark factory is aimed at displacing the human being from the center of production or has as one of its objectives to reduce or minimize their intervention through automation.

On the other hand, the basic technology that characterizes Industry 4.0 is the Cyber-Physical System (CPS) [30,32,33], which is developed with the digitalization of companies and is enhanced by the so-called emerging technologies [45]. This technology unites and relates the physical world to the virtual world through communication networks. A key feature of CPS is that they possess software that actively engages with various physical assets [46]. The operations of the elements that make up a CPS must be efficient, safe and in real time. CPS are not new technologies, as there are several production systems that use software and hardware (industrial physical assets), and are even capable of communicating with each other, such as various CNC (Computer Numerical Control) systems, Coordinate Measuring Machines and CIM (Computer Integrated Manufacturing) systems, among others. However, these systems were developed with technologies from 30 years ago, which can no longer be updated by design and have obsolete communication infrastructures, less computing power and little storage, in addition, they have problems of data and information exchange, and data transmission speeds and connectivity are limited [47]. or the retrofitting of this equipment is costly and not feasible for Industry 4.0 requirements. Currently, CPS is developed using disruptive technologies and new generation computational and communication systems that enhance applications and surpass in almost everything CIM systems and CPS developed under the vision of Industry 3.0. As the technological center of Industry 4.0, CPS have diverse applications and have developed great potential that are leaving behind the so-called Information and Communication Technology revolution that had its peak in the last century. Applications of SCPs span agriculture, aviation, transportation, mining, manufacturing, traffic, security, energy, and defense, among others [48].

2.1.3. Disruptive technologies and pillars of Industry 4.0

Industry 4.0 was generated by the development and application of new disruptive or emerging technologies that are causing accelerated transformations in production processes. The definition of disruptive technologies does not have a consensus. For example, some authors define them by their implications in the market [49] and others by their effects on customers [50]. The so-called disruptive technologies are characterized by being a kind of innovation that takes advantage of unforeseen or emerging markets, seeks to create items or products that are used to solve problems not known by buyers and have the mission of transforming the industry [51]. Disruptive technologies represent the basis of any industrial revolution and cause abrupt changes in companies, organizations, markets and businesses, and in general in the ways of life of people and societies. These technologies cannot be ignored by industries as they usually make the difference between the potential of one company and another. There is no consensus in the literature on the types and number of disruptive technologies that Industry 4.0 brings with it. In a study carried out, it was possible to identify 35 technologies that can be considered disruptive [52], which are shown in Figure 2. According to the study, of the 35 technologies considered, 13 of them are recognized as highly relevant and are the following: Robots, Nanotechnology, Drones, Biotechnology, Cyber-Physical Systems, Additive Manufacturing, Big Data, the Internet of Things, Smart Sensors, Artificial Intelligence and Simulation. To carry out the study, various publications and specialized documents were analyzed [52].

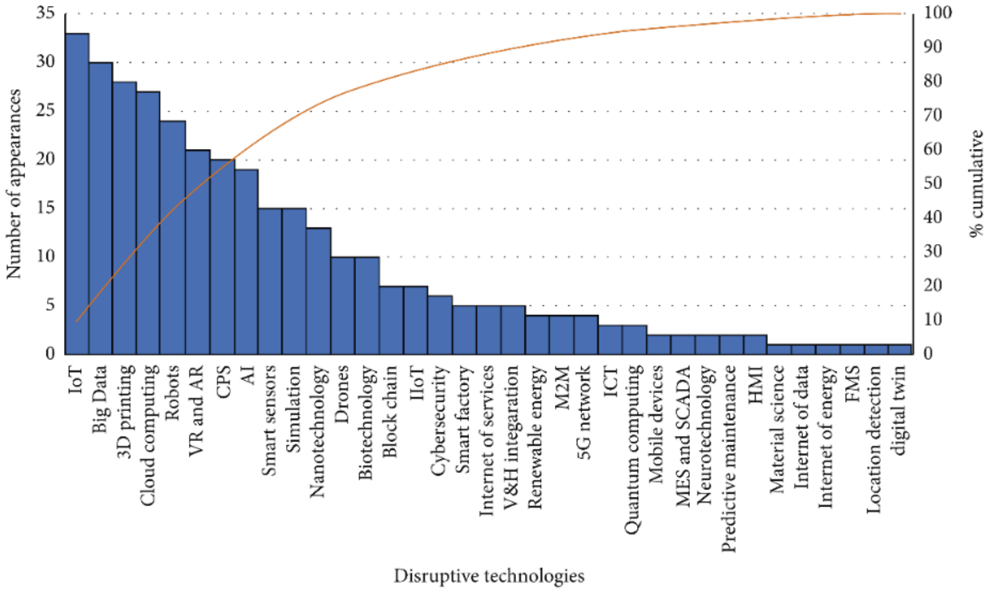

Figure 2. Disruptive technologies [52].

Other authors point out that the fourth industrial revolution is based on nine disruptive technological pillars, which are: Big Data, Cybersecurity, Additive Manufacturing, Horizontal and Vertical Systems, Augmented Reality, Simulation, Cloud Computing, Internet of Things and Autonomous Robots [53,54]. Figure 3 shows the technological pillars of Industry 4.0 [55].

Figure 3. Technology pillars of Industry 4.0 [55].

2.2. Mechanical Engineering and the Industrial Revolutions

Disruptive technologies are at the heart of the fourth industrial revolution. However, many of them and their applications have foundations in disciplines such as Electronics, Electricity,

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Computing, Control and Mechanics, among others. These disciplines do not have clear limits of application and can be combined with each other [56], for example, a classic combination between disciplines is Mechatronics (Integration of Mechanics, Electronics and Computing). Mechanical Engineering is essential in Industry 4.0, as many of the physical assets that are required for production are designed and developed with the Science and Engineering of Mechanics. The Science of Mechanics studies the movement of objects, while Mechanical Engineering is oriented to the development of physical assets or technology that have a specific function in human activity. In this way, with Mechanical Engineering, various physical assets are developed in industries, such as robots, belts, actuators, mechanisms, complex mechanical systems and machinery, among others, which are responsible for performing simple, complex and specialized tasks and movements. The functions and tasks of analysis, calculation, modeling, design and manufacturing associated with Mechanical Engineering have been present in all documented industrial revolutions and will surely continue to be active in Industries 5.0 and 6.0.

2.2.1. Mechanical Engineering and the First Industrial Revolution

The first industrial revolution was characterized by the generation of technologies associated with Mechanical Engineering, and was developed mainly in England and the United States by a strong inventiveness of many characters of that time. A list of the most important inventions and machines of the first industrial revolution can be found in [57]. Some of these relevant inventions were the following: 1) the steam locomotive, invented by R. Trevithick in the year 1804, 2) the Stirling engine, invented by R. Stirling in 1816, 3) the Singer pedal sewing machine, invented by the Singer Company in 1859, 4) the mechanical computer invented by C. Babbage in 1822 and 5) the Grain Thresher, invented by A. Meikle in 1784, among others. Many of the technologies that were developed at the time of the first industrial revolution or Industry 1.0, were emerging or disruptive as they transformed industries (textiles, manufacturing, food, etc.), agriculture, education, mining and construction, among others, which led to a large-scale economic, industrial and social development in society on a global scale. In the case of the first industrial revolution, the base technologies considered were the steam engine and mechanization [30,31].

2.2.2. Mechanical Engineering and the Second Industrial Revolution

The period from 1870 to 1914 saw the development of the second industrial revolution, the technological centre of which was the introduction of electric power, mass production and the assembly line [31]. However, great mechanical inventions were also developed in this period, such as the internal combustion engine invented by Nikolaus August Otto in 1876 and Carl Friedrich Benz applied for a patent for his automobile in 1886 [58]. These inventions gradually became part of industrialization and began to replace other technologies, for example, those systems that worked with steam engines were replaced by electric motors and internal combustion engines [57]. Hydro turbines, precision machine tools, and airplanes were also invented and developed in the second industrial revolution or Industry 2.0. All these inventions and mechanical products, along with electricity and mass production, brought about disruptive changes in industries, agriculture and transportation, among other fields of development.

2.2.3. Mechanical Engineering and the Third Industrial Revolution

The third industrial revolution or Industry 3.0 began in 1970 [33], and it led to the development of countless inventions and technological developments, such as computing, which has marked a before and after in science and technology since its appearance and has allowed the development of many applications in all fields of knowledge. Electronics were a driving force in industrial development and Information and Communication Technologies contributed to the development of countless applications. Industrial automation took a big boom in the third industrial revolution with the introduction of the PLC (Programmable Logic Controller) and the industrial robot accompanied by the development of electromechanical and mechatronic systems.

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In Industry 3.0, Mechanical Engineering had four driving forces [60]: 1) markets became more demanding and changing with respect to mechanical products, 2) due to automation there were changes in systems and forms of production, 3) Mechanical Engineering was associated with the disruptive technologies of that time, and 4) Mechanics was related to the basic sciences. In this sense, markets and consumers demanded new products and designs, which motivated the integration between Mechanics, Electronics and Computing, giving rise in Japan to the concept of Mechatronics [59], which was coined to meet the new requirements of industrial machinery. In the same way, the integration between Mechanics and Electricity gave rise to Electromechanics, whose applications revolutionized the forms of industrial production and allowed the construction of complex systems, such as airplanes and automobiles. The typical mode of manufacturing in the third industrial revolution was mass production, and changes in markets led to more varied and smaller quantity production. Mechanical Engineering at that time had to adapt to the changes.

On the other hand, the associations of Mechanical Engineering with the disruptive technologies of that time gave rise to a myriad of applications such as Computer Aided Design, the development of new materials, space applications, energy and biotechnology projects and maritime technology, among others [60]. In the same way, Mechanics was related to Mathematics and Physics, and the applications of both were enhanced, for example, the laser was developed, advanced machines were built and computer design and simulation were promoted to solve various industrial problems. The integration of computing, mechanics, electronics, electricity, and quality and material systems gave rise to the first cyber-physical systems conceived under the vision of Industry 3.0. The inventions and technologies developed in the third industrial revolution, as well as the integration of applied science, helped transform the society and industrial world of that time.

2.2.4. Mechanical Engineering and the Fourth Industrial Revolution

Industry 4.0, or the fourth Industrial Revolution, originated in 2000 [32]. The processes of change and transformations brought about by this new industrial paradigm are accompanied by new scientific and technological knowledge, and by diverse and varied technologies, of which 35 are considered disruptive technologies and 13 of them are of high relevance [52]. Large-scale digitalization and the use of Industrial Artificial Intelligence in various applications are two novelties that are accelerating the processes of change and transformation in industries and businesses. Technologies such as the Industrial Internet of Things, Industrial Networks, Cloud Computing and Big Data, among others, have allowed the development of new and powerful cyber-physical systems and have made it possible to update similar systems created under the vision of Industry 3.0. In the fourth industrial revolution, mass production systems are being transformed into customized manufacturing systems due to changes and new customer demands. This change in production allows consumers to have a say in the design of products, and companies must adapt their production processes to the new requirements. In Industry 4.0, cyber-physical systems and digital twin technologies enable the configuration of smart factories [61], in which hyperautomation and hyperconnectivity make autonomous production and manufacturing possible.

As in the previous three industrial revolutions, Mechanical Engineering makes important contributions in various fields of application of Industry 4.0. For example, Mechanics is related to many physical assets of digital twins and cyber-physical systems. In addition, he studies the properties of new materials and contributes to additive manufacturing in the design and manufacture of various products that are conceived within the vision of custom manufacturing. Collaborative robotics is another pillar of Industry 4.0 in which Mechanical Engineering is associated, and together with Mechatronics and Artificial Intelligence, they are responsible for the design of cooperative robots and the analysis of their movements. In the same way, Mechanics and Artificial Intelligence have come together to model and solve various complex problems that are related to multiphysics systems [16]. Mechanical Engineering also contributes to the transition from the third industrial revolution to Industry 4.0 as it is applied to perform Smart Retrofitting tasks, which consists of updating old machinery in terms of Industry 4.0 objectives [22]. This modernization process takes on relevance because many companies are in a process of technological reconversion and intelligent retrofitting is

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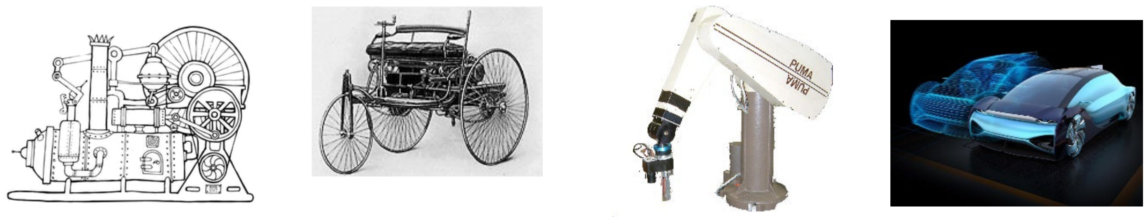
a viable option to operate in the vision of the fourth industrial revolution with old machinery at a lower cost.

Today's Mechanical Engineering followed the same process as in the third industrial revolution [60], that is, it is characterized by four driving forces: 1) it is adjusting to the new requirements of the markets, 2) it is being reoriented to the new demands of manufacturing processes, 3) it is being associated with the disruptive technologies of Industry 4.0 and 4) it is related to the basic sciences. In general terms, cyber-physical systems can be conceived as the base technology of Industry 4.0 [33] and as evolutions of Information and Communication Technologies or integrations between computing, networks and physical processes [62]. Digital twins can be interpreted as evolutions of electromechanical, mechatronic, and simulation systems. Figure 4 shows the evolution of Mechanical Engineering in terms of the industrial revolutions and the technologies that underpin each of them.



Mechanics 1.0	**Mechanics 2.0**	**Mechanics 3.0**	**Mechanics 4.0**
Steam Engine Industrial Mechanization	Internal combustion engine Car	Electromechanical systems (Electric motor, MEMS) Mechatronic Systems (Robots, CNC Machines) Materials	Digital Twins Cyber-Physical Systems Smart Materials
1870	1900	1970	2000

Figure 4. Evolutions of Mechanics in the Industrial Revolutions and Base Technologies.

The potential of Mechanics in Industries 3.0 and 4.0 is found in integrations, such as Electromechanics and Mechatronics conceived in the third Industrial Revolution and in their evolutions in Cyber-Physical Systems and Digital Twins in the fourth Industrial Revolution. Therefore, the basic technologies of these two revolutions, conceived in terms of Mechanical Engineering, are the technological products that are derived from electromechanical systems, such as the electric motor and MEMS (microelectromechanical systems), and Mechatronics (industrial robot). In the same way, in the case of Industry 4.0, the base technologies are cyber-physical systems and digital twins, since both are characterized by having physical assets where Mechanics is present in an integrated way. In the same way, the development of materials has become crucial for the current and past industrial revolutions, and Mechanical Engineering takes a relevant role in their characterization, which is why it appears as one of the technologies of great importance in the evolution of Mechanics.

2.3. Mechanics 4.0

The concept of Mechanics 4.0 was proposed as the interrelation between Mechanical Engineering and Artificial Intelligence, whose purpose is to model and solve various problems related to multiphysics systems [16], which represent the basis of many applications in Industry 4.0. However, despite its importance, Artificial Intelligence is only one of the 35 disruptive technologies [52] that accompany the fourth industrial revolution in the process of transforming the industrial world. Therefore, defining Mechanics 4.0 only in terms of a disruptive technology minimizes the importance of Mechanical Engineering in Industry 4.0. It is possible to extend the concept of Mechanics 4.0 in terms of the four driving forces identified in Industry 3.0 [60], i.e. as a function of new consumer demands, new requirements in production systems and their relationships with disruptive technologies and basic sciences. Figure 5 shows a framework for Mechanics 4.0.

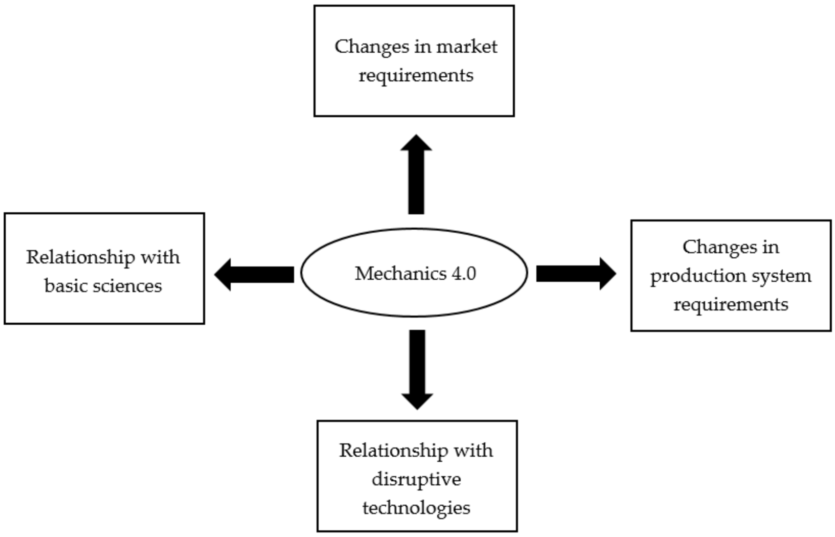


Figure 5. Mechanics 4.0 Framework.

2.3.1. Changes in market requirements

Physical assets or products related to Mechanical Engineering, including industrial machinery and various devices for production, are currently in high demand due to the diversity of applications of companies that have aligned themselves with Industry 4.0 and those that are in transition. As in the third industrial revolution, mechanical products must meet the requirements of Industry 4.0, for example: they must be precise, reliable, safe, comfortable, designed with greater accuracy and minimum weight, and they must be environmentally friendly, among others [60]. However, these requirements must be extended since the mechanical industrial products demanded by industries must be conceived under the integrations of Electromechanics and Mechatronics, in order to be more functional, for example, they must have: greater efficiency, energy efficiency, maintenance and availability, compactness and communication [63].

2.3.2. Changes in production system requirements.

Mass production was one of the most significant changes in the second industrial revolution and was introduced by the Ford company. At the beginning of the third industrial revolution, the paradigm of mass production changed and manufacturing was no longer massive, but developed in smaller quantities, but in a variety of ways. These changes were a consequence of the fact that the economy of the decade of the 60s and 70s of the last century was increasing, which caused and motivated greater needs for products and greater variability of them [60]. In the same way, the seller's market was transformed into a buyer's market, this was due to the intensification of the market in that decade. Non-mass production and product variation were the basis for what is now known as "mass customization", which is understood as the set of technologies and systems that make it possible to supply goods and services that meet the individual needs of customers with near-mass production efficiency [64]. This new production paradigm introduced important changes in manufacturing systems and in the elements and technologies that make them up. For example, to adjust to the customized demands of today's products, production systems must be flexible (Flexible Manufacturing Systems (FMS)) and reconfigurable (Reconfigurable Manufacturing Systems (RMS)) and this is possible if machinery and production systems are also flexible and reconfigurable. The reconfigurability feature allows companies to respond faster in global markets, as these types of systems adapt quickly to new product demands [65]. Therefore, reconfigurable manufacturing systems very frequently change the physical configuration of your machinery on production lines.

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Machines that are considered reconfigurable are designed taking into account the following considerations: 1) they are designed to operate in the environment of a Flexible Manufacturing System (FMS), specializing in a specific family of parts or products, 2) they are designed to operate under the criterion of customized flexibility, 3) the scalability of the machine is extremely important and 4) the machine must be designed under the criterion of modularity and 5) It requires that the machine can work in different places on a production line using the same basic design structure [66]. Mass customization is a new form of production in Industry 4.0 that involves designing production systems in such a way that they can be reconfigured in the face of changes in production volumes and product design. This involves the design and development of specialized, flexible and reconfigurable machines. Mass customization can be applied in four stages: 1) In order securing, 2) In design, 3) In manufacturing, and 4) In supply chain coordination [67].

2.3.3. Relations between Mechanics and disruptive technologies.

Mechanical Engineering has functional interactions with some of the disruptive technologies of Industry 4.0. Figure 5 shows the relationship of Mechanics to only six of the disruptive technologies shown in Figure 2.

According to Figure 6, the relationships between Mechanics and the selected disruptive technologies are bidirectional, since Mechanical Engineering provides knowledge, processes, methods, machinery and devices to disruptive technologies to achieve their objectives, and these in turn provide Mechanics with theoretical knowledge, experiences and technological support for its development. For example, Artificial Intelligence provides Mechanics with different algorithms for the solution of various complex problems related to multiphysics systems [16], while Mechanical Engineering contributes to the development of more specialized computer systems (Hardware) where it is possible to solve the methods of Artificial Intelligence to solve all kinds of engineering problems. The same interaction is followed for Cloud Computing and Mechanical Engineering, since the former provides technology for design (CAD), manufacturing (CAM), engineering (CAE) and manufacturing, to improve the processes of design, production and analysis of products, while Mechanics provides, together with other areas of knowledge, the computational devices that make up the servers. Additive Manufacturing and Mechanical Engineering are also interrelated, as physical prototypes of various mechanical designs, mock-ups and final products are provided by 3D Printing to improve designs and to manufacture machines, while Mechanical Engineering provides 3D printing systems with experimental methods to examine the mechanical properties and functionality of developed prototypes. Collaborative Robotics and Mechanics transfer knowledge and technologies, for example, the kinematic and dynamic models that are used for the control of movements, the physical configuration of robots, the analysis of operations and the movements of people, are supplied by mechanics to Collaborative Robotics, while the various problems that arise between robots and humans generate new challenges that Mechanics studies. In the same way, Renewable Energies and Mechanics support each other, since the former provides new knowledge about different energies that in turn are studied by Mechanics and, subsequently, Mechanics provides the development of systems for the production of non-renewable energies. Finally, Mechanics and Materials Science are related since the former provides methods and knowledge for the machining of new materials while the latter provides information on the existence of new materials that Mechanics is later responsible for characterizing for various applications.

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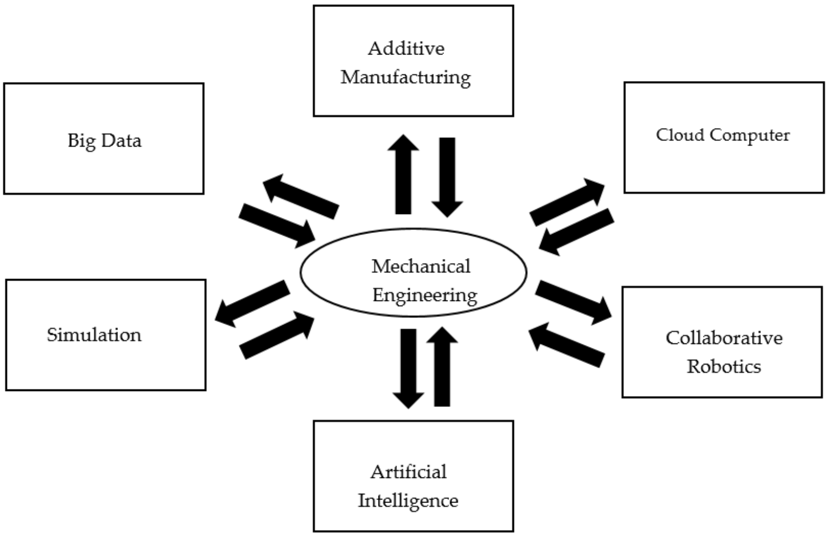

Figure 6. Relations between Mechanical Engineering and the technologies of the new industrial revolution. Improved and adapted from [60].

2.3.4. Relations of Mechanics with the basic sciences.

Mechanical Engineering is related to the basic sciences, but especially to Mathematics and Physics. Mathematics provides Mechanical Engineering with different tools for modeling and calculating various problems involving motion. Many problems in mechanics, such as the modeling of robots and mechanisms, generate systems of nonlinear equations. Numerical methods and Artificial Intelligence, both supported by mathematics, are used to solve the numerical models of robots [68]. In the same way, the development of the Mechanics of Continuous Media has given rise to modeling with partial differential equations various physical problems such as heat, thermo-elasticity, plasticity and mechanical vibrations, among others. These problems are solved by numerical methods and by interpolation by means of the Finite Element Method [69]. On the other hand, Physics has provided valuable knowledge for Mechanical Engineering since technologies such as plasma and lasers have been fundamental for the design of cutting machinery and for manufacturing processes [70]. In the same way, mechanics has contributed to the development of complex systems such as the quantum computer and the design of accelerators with which physicists study different processes and characteristics of particles. Mechanics also contributes to the design of devices for space exploration, such as telescopes and space probes, so that physicists can study other worlds and the universe.

Mechanics 4.0 seen from its relationships with disruptive technologies and basic sciences, and considering the market and changes in production systems, is more relevant and extensive than just associating it with Artificial Intelligence as proposed in [16].

2.4. Mechanical Engineering and Specialized Technical Fields

Mechanical engineering has an influence on some specialized technical fields, such as predictive maintenance, materials development, and tribology. Each of these fields and others are evolving in parallel to Mechanics by introducing the disruptive technologies of Industry 4.0 in its theoretical-practical development, analysis and technology processes. For this reason, terms such as Tribology 4.0 [71] and Materials 4.0 [72], among others, can be found in the specialized literature. Figure 6 shows some specialized technical fields that are related to Mechanics 4.0.

Figure 7 does not show all of the specialized technical fields that are associated with Mechanics 4.0. The technological changes and evolutions brought about by Industry 4.0 are present and active in many branches of knowledge and applications. These common evolutions (applications of disruptive technologies) allow each one, with the help of the others, to achieve objectives in a better way and with a wide potential. Each specialized technical field shown in Figure 6 uses disruptive technologies in its own way and delimits its application frontiers. However, Mechanics 4.0, by evolving in parallel with other specialized fields, can be integrated in a more direct and systematic way with these fields, thereby enhancing the construction of new knowledge and motivating the development of new specialized technological products. The vision and breadth of Mechanics 4.0 can be extended by operating in conjunction with the specialized technical fields evolved in the context of Industry 4.0. Described below are some of the specialized fields of knowledge related to Mechanical Engineering that have evolved due to the influence of Industry 4.0.

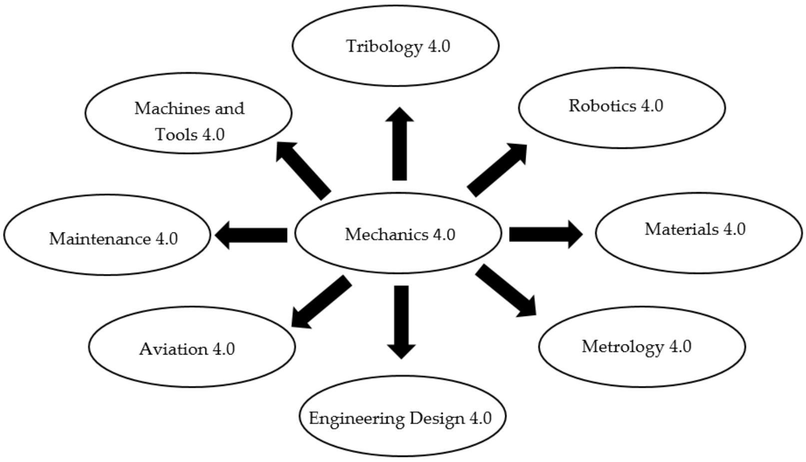

Figure 7. Mechanics 4.0 and specialized technical fields.

2.4.1. Tribology 4.0

Tribology 4.0 is the relationship between the disruptive technologies of Industry 4.0 and Tribology [73]. The most direct connection of Tribology is in terms of Information Technology and the Internet of Things, since tribological data (friction, wear and condition of lubricants) captured by sensors (Tribotronics) can be transferred via wireless connections and the internet to devices that can process the information for different applications [71].

2.4.2. Materials 4.0

Materials 4.0 can be considered as a novel paradigm that will revolutionize the research and development of materials, and that will surpass humans in basic tasks of coordination, search and analysis of the different knowledge and experiences that exist for the development of materials using the advantages and properties of cyberspace [17]. Materials 4.0 seeks to improve the development of materials through the use of the disruptive technologies that Industry 4.0 brings with it. Their objectives are to improve and develop infrastructures, promote the optimization of processes in terms of energy, and systematize, digitize and automate the life cycle of materials development. Materials 4.0 seeks to set digital standards, automate development labs, and offer greater digital security. The vision of Materials 4.0 is to develop cheaper sensors, build faster capture and analysis systems, and enable wireless connection systems to send and process information in the cloud and improve the manufacturing of materials. Materials 4.0 will transform traditional materials development and drive a digital revolution that will accelerate the discovery, innovation and validation of new materials [74].

2.4.3. Maintenance 4.0

Maintenance 4.0 is a new term that defines the next generation of production equipment maintenance [75]. This new approach to maintenance uses the disruptive technologies of the fourth industrial revolution to be able to carry out predictive analyses on equipment and machinery in industries. Predictive maintenance seeks to anticipate possible equipment failures through the use of various and modern technologies, such as the Industrial Internet of Things, Cloud Computing, Big Data, Digital Twins and Artificial Intelligence, among others. These technologies are used for monitoring, real-time measurement and analysis of sensitive variables and parameters of machinery or physical assets. Maintenance 4.0 is also known as smart maintenance and can be described as a subset of the smart manufacturing system represented by intelligent, self-learning machines that predict failures, perform diagnostics, and trigger maintenance actions [76]. Predicting failures in production systems reduces costs, improves efficiency in companies, and significantly reduces human error in asset maintenance activities and tasks.

2.4.4. Robotics 4.0

The new generation of robots in version 4.0 or Robotics 4.0, is a specialized field of robotics that joins various disruptive technologies to provide more advanced technical and operational capabilities to robots in terms of collaboration, perception and autonomy [77]. The Internet of Things, Cloud Computing, Sensorization and Artificial Intelligence are technologies that are already being applied in industries and their use will become commonplace, which will provide guidelines for the manufacture and operation of robots equipped with intelligence capable of making decisions and helping workers collaboratively [78].

2.4.5. Machine tools 4.0

Like many priority technologies in the industry, machine tools have been evolving and changing according to the guidelines set by the current development of the industry. The disruptive technologies of Industry 4.0 have been modifying the design and operation of machine tools, which has led to the generation of new, more advanced and sophisticated machines. In this sense, the concept of machine tools 4.0 describes a new class or generation of specialized machine tools that have new attributes, i.e., have better connectivity, have greater autonomy, have a certain degree of intelligence and more efficient adaptability [79]. Machine Tools 4.0 use the disruptive technologies of Industry 4.0 to conceive super-specialized manufacturing systems such as the Cyber-Physical Machine Tool that will be effective in the functionality of smart factories. Machine Tool 4.0 is identified as a generation of machine tools with a high degree of horizontal and vertical integration, and the relationship between product production and factory-level facilities is profound and unprecedented [80].

2.4.6. Aviation 4.0

The aviation industry is also applying various disruptive Industry 4.0 technologies to improve and optimize its processes and businesses. The term "Aviation 4.0" means the use of disruptive technologies in the aviation industry which are applied in three major areas [81]: 1) ground services, 2) maintenance and production and 3) unmanned aerial vehicle technology [81]. One of the characteristics of today's advanced aviation systems is their cyber-physical configuration, i.e., various physical and computational assets are associated and work together and synergistically to achieve objectives. In this sense, Aviation 4.0 also refers to the design and operation of sophisticated cyber-physical systems, where one of its functions is to assist aerospace workers to operate autonomously, to be able to make decisions and to be integrated with cyber-physical components into future aeronautical information systems [82].

2.4.7. Design in Engineering 4.0

Product design is an essential task today and is supported by Industry 4.0 technologies and various methodologies, including Design Engineering and the Design Process. Product design activities are multidisciplinary and there must be digital platforms or sophisticated technological environments that enable the creation of systems that involve specialized designs. Design Engineering 4.0 is understood as an approach within Industry 4.0 that represents the human, cybernetic and physical vision of an ecosystem that is used for the realization of systems and provides an environment conducive to the development of complex systems [18]. Such an environment or ecosystem would have the following characteristics: 1) An association between the flows of information about the performance and use of a product, and digital twins over the entire life cycle

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of a product's design and development, 2) have the ability to incorporate rapidly changing technologies, and 3) possess mechanisms that make it possible to explore and facilitate the creation of new opportunities for product design, processes, services and systems. A platform created under the concept of Design Engineering 4.0 is called PDSIDES (Platform for Decision Support in the Design of Engineered Systems) which is designed to facilitate end-to-end digital integration, customization, agile collaboration networks, open innovation, co-creation, crowdsourcing and servitization of products. and all as a service [83]. Product design decision-making is of paramount importance in industries, and disruptive technologies and Design in Engineering 4.0 platforms or ecosystems provide support so that design engineers can have relevant information and better options to make correct decisions about product design.

2.4.8. Metrology 4.0

Metrology is an essential field of knowledge for Industry 4.0 and, like other areas of application, it is being improved and enhanced by disruptive technologies and the development of new and novel measurement techniques and procedures. The mass customization of production, digitalization, cost reduction, and process improvement and optimization are some of the new requirements that the fourth industrial revolution imposes on manufacturing processes and their metrology. Artificial Intelligence applied to Metrology makes it possible to cover some of the requirements mentioned above and originates concepts such as "intelligent metrology systems". Metrology, which associates the tools of the fourth industrial revolution with their applications and development, is known as Metrology 4.0 or Metrology of the Future [84]. This progressive vision of Metrology is changing the philosophy and organization of measurements carried out from the generation of new knowledge and the development of modern measurement techniques. Metrology 4.0 will revolutionize calibration processes by reducing time and costs, and will be able to process measurement information in real time [85].

2.4.9. Ergonomics 4.0

Worker labor is essential in those companies that have transitioned to smart manufacturing, particularly when complex and precise tasks are required in production processes and when manufacturing is customized. Due to the specialization of work, a product of the Industry 4.0 vision, it is necessary to improve workspaces in companies so that operators can perform their tasks in the best way and with the maximum possible safety. Ergonomics has as its central axis the adaptation of the work environment to man [86]. The disruptive technologies of Industry 4.0 are introducing changes and transformations in the safety and working conditions of company workers. These technologies have led to the formation of the concept of Ergonomics 4.0 and other terms such as Operator 4.0, Safety 4.0 and Mining 4.0 [87]. The introduction of disruptive technologies in companies and workplaces leads to new challenges and new considerations in the context of occupational risk prevention. The vision of Ergonomics 4.0 seeks to integrate knowledge in Ergonomics into the study of the digital work environment and seeks to develop techniques and methods to increase the safety and efficiency of human-machine interaction in the digital environment.

2.5. Relationships of Mechanical Engineering with background technologies and retrofitting

This section presents some relationships and examples between Mechanical Engineering and three disruptive Industry 4.0 technologies, called background technologies, which are: 1) cyber-physical systems, 2) digital twins and 3) Artificial Intelligence. In addition, the importance of Mechanical Engineering in Smart Retrofitting is described.

2.5.1. Mechanical Engineering and Cyber-Physical Systems

Mechanical Engineering is related to Cyber-Physical Systems as they are composed of various assets, including mechanical physical assets, such as machinery, infrastructure, and various devices. Cyber-Physical Systems represent the technological basis of Industry 4.0 [33] and are made up of physical assets and digital systems that are intertwined with each other through communication technologies and wired and wireless networks, to perform various actions. There is no single definition for this technology. One of the definitions is described below: *A Cyber-Physical System combines in the same frame of reference two systems, one physical and the other digital connected to the network, where the tasks and activities of the physical system can be controlled, analyzed and supervised from the networked digital system, using the communication of a feedback loop between both systems* [88]

Mechanical Engineering is responsible for the design and operation of various physical systems that carry out operations in companies and provides mechanical physical models for the control of the actions of production devices and machinery. Mechanics was one of the areas that gave rise to mechatronic systems in the 70s of the last century and that are now vital in modern machinery. In fact, today, mechanical systems have become mechatronic and electromechanical systems, and these, in turn, have become cyber-physical systems [89]. It is also possible to consider that Mechatronics was an evolution of electromechanical products and that Cyber-Physical Systems come from an evolution of cybersystems. Cyber-physical systems and mechatronic systems have similarities and differences, which are shown in Table 1.

Table 1. Similutides and Differences Between Mechatronic Systems and Cyberphysical Systems [90].

Mechatronics systems	**Cyber-Physical Systems**
Heterogeneous and cross-domain systems	
Functional, multi-domain and multi-disciplinary integrated systems	
Dynamic physical interactions	
Fixed structure	Adaptive structure
Centralized architecture	Decentralized organization
Can be physically integrated in a compact volume	Geographically distributed
	Human in the loop
	Functionally open
	Large communication real-time processing

Cyber-physical systems are made up of various mechanical, electromechanical, and mechatronic systems, which constitute and make up physical assets (see Figure 8). In some of these systems, it is possible to integrate digital twins, which are considered to be cyber-physical assets [91]. The physical assets that make up today's cyber-physical systems, such as machines, devices, actuators, industrial belts and various mechanical devices, must meet the demanding demands of customers who request new and complex solutions every day. In this way, physical assets must be more operationally efficient, energy efficient, designed for better maintenance, and have communication systems [63]. In addition, assets must be more precise and accurate, safe and reliable, and nature-friendly [60]. One technology that interacts with the physical assets of a Cyber-Physical System (CPS) is the Internet of Things (IoT), which is responsible for transforming machine information through sensors, processing it and sending it to cloud systems. The Internet of Things gives physical assets the characteristic of being communicable and is more closely related to physical assets [92].

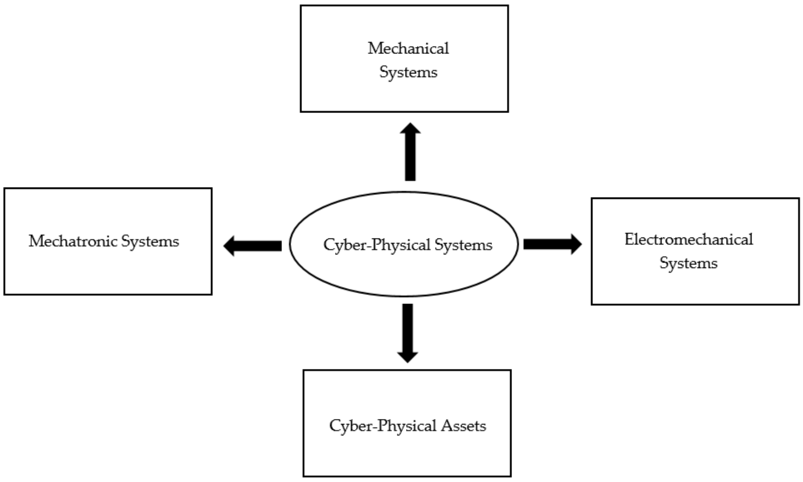

Figure 8. Cyber-Physical Systems in terms of physical assets in which Mechanical Engineering intervenes.

Figure 9 shows a schematic of a CPS, showing physical assets, virtual assets, and cyber-physical assets, which, for this example, is a digital twin of a robot.

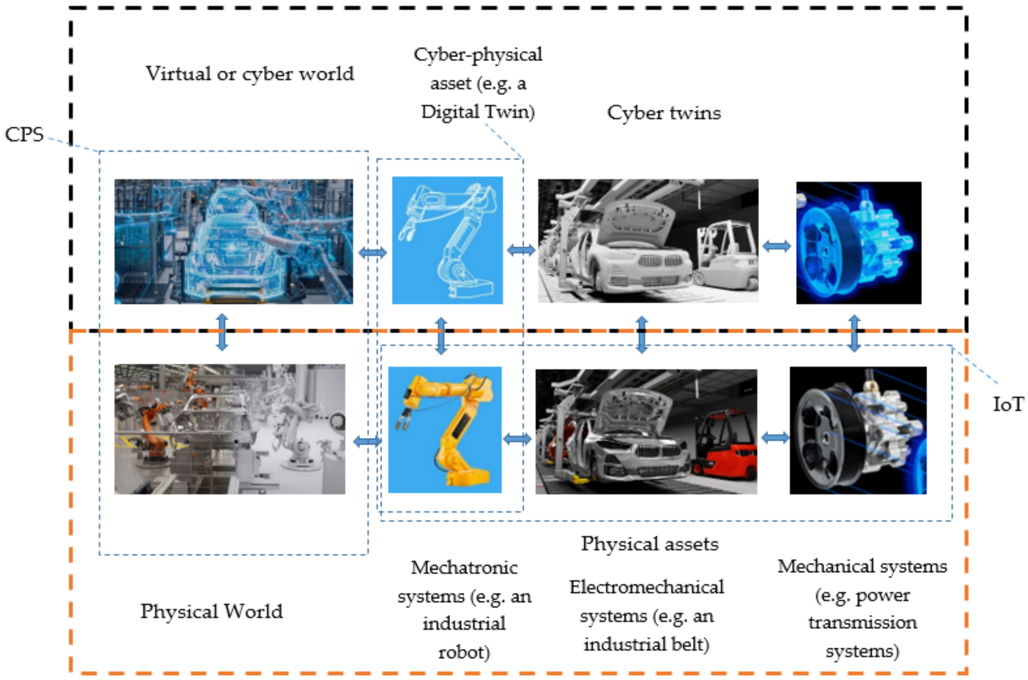

Figure 9. Cyber-physical system, IoT, and system assets. Taken and improved from [92].

2.5.2. Mechanical Engineering and digital twins

Another disruptive technology that Mechanical Engineering is related to is the digital twin. These are composed of a physical asset and its virtual replica, and are interconnected with each other in a two-way relationship of real-time exchange of evaluated data and information. The idea of the digital representation of the physical asset is that it is possible to have a better understanding of the dynamic and operational behavior of the asset by solving mathematical models of multiphysics systems previously programmed and fed with real-time information from sensors installed in the physical asset. Like CPS, digital twins don't have a single definition. One definition is as follows: *a digital twin is a non-physical model that has been designed to faithfully reflect an artificial or physical system, in which sensors are placed to acquire a series of data relating to different aspects related to the operation of the*

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system [93]. Digital Twins (DTs) represent the differentiating technologies in companies, so the study of them is essential in Industry 4.0.

Mechanical Engineering provides physical assets, information, and multiphysics models for the construction, control, and operation of DTs. The operation of a digital twin is shown in Figure 9. The DT has a physical asset (PA) and a virtual entity or replica of the physical asset (VE) and are interconnected by two functions: f: PA→VE and g: VE→PA . The first function represents the sending of real-time data generated by sensors of sensitive parts or parts of interest from the PA to the VE and the second function represents the sending of analyzed, modeled and improved information from the VE to the PA.

Figure 10 shows the flow of data between the physical asset (Robot) and the virtual entity (Robot Models) and a series of states, which are explained below: In state 1, the physical asset is considered to operate normally and interact with the environment around it. State 2 represents a generation of signals obtained by means of sensors placed at sites of interest in or on the physical asset. State 3 is associated with the sending of the signals generated by the sensors to the virtual entity (f: PA→VE) and state 4 represents the information sent by the sensors and is processed by IoT elements and the operating history of the physical asset. Status 5 describes the internal processing of data under multiphysics and prediction models, among others, using various tools such as Artificial Intelligence and Data Analytics. In this state, the processed information is generated and will be returned to the physical asset, and state 6 represents the transfer of the evaluated information g: VE→PA. Finally, state 7 represents the control or command elements that receive the processed information and are in charge of giving the necessary orders to execute the improvements in the physical asset.

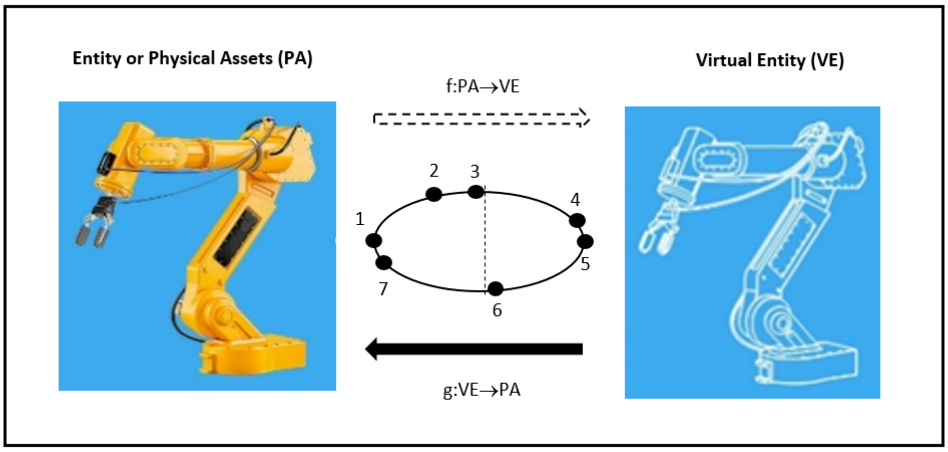

Figure 10. Operation flow of a DT. Taken and improved from [30,94].

Mechanical Engineering, together with Mechatronics, provide important elements for the design, construction, control and operation of digital twins, since they are two fields of knowledge responsible for providing physical assets, multiphysics models, control and relevant information on their operation and design. Therefore, Mechanical Engineering supports Industry 4.0 by being related to the design and operation of cyber-physical systems and digital twins, and forms a part (real object) of the so-called "cyber-physical asset" which is defined *as an object that exists in the real world and in the digital world with an end-to-end connection between the two worlds (state synchronization with a cyber-physical bridge). State changes that occur in one world are automatically reflected in the other, so that real and virtual objects are inseparably linked* [91]. Digital twins and cyber-physical systems, as well as Non-Fungible Tokens (NFTs), are some examples of cyber-physical assets. Figure 11 shows an example of a robot-related digital twin that performs perforations in parts [95].

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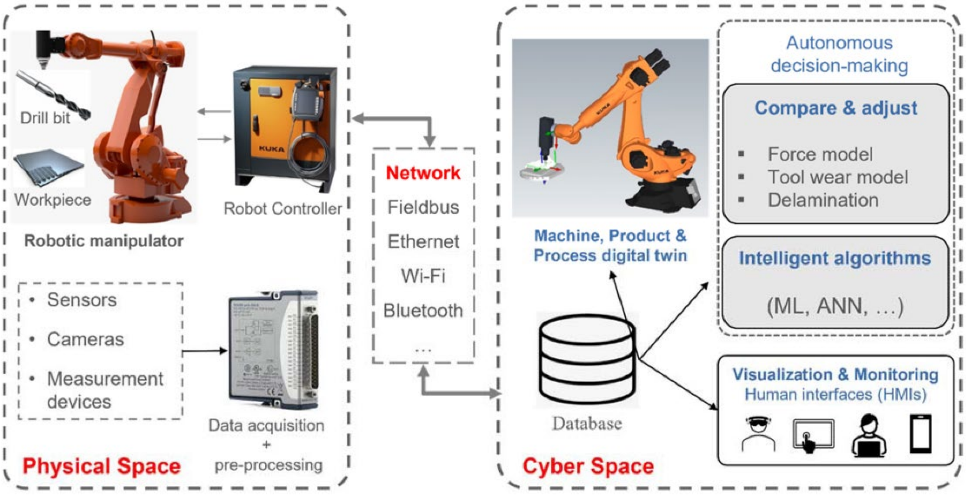

Figure 11. Example of a DT related to a robot that punches parts. Taken from [95].

The figure above better describes some of the elements that make up a DT and the generic operating cycle shown in Figure 10. The robot is the main element of physical assets and is considered to be a mechatronic system. This system is sensorized and the information captured by the cameras and sensors is sent to a data acquisition system and pre-processed, to later be transferred to the digital or virtual entity through wired and wireless networks. In the digital world, information is integrated and processed according to pre-established mechanical and manufacturing models, and Artificial Intelligence systems such as Machine Learning (ML) and Artificial Neural Networks, among other algorithms, are integrated. The processing of the information can be visualized by means of the Human Machine Interface (HMI). The processed information is sent to the physical asset for adjustments and changes to be made [95].

2.5.3. Mechanical Engineering and Artificial Intelligence

Artificial Intelligence is a disruptive Industry 4.0 technology [52], which has partnered with Mechanical Engineering to solve a number of problems, some of them highly complex. Decision-making and the design of physical assets are some of the tasks in which Artificial Intelligence helps Mechanics in Industry 4.0 applications. In the case of decision-making, cyber-physical systems or digital twins require information on the states of mechanical systems that are characterized by physical systems, in order to operate and meet objectives. The analysis of physical systems or multiphysics systems can be carried out using some methods of Artificial Intelligence [16]. Computational simulation is another disruptive Industry 4.0 technology that has benefited from the relationship between Mechanical Engineering and Artificial Intelligence, for example, human behavior has been simulated in the operation of machines and devices through Artificial Intelligence, and machine language (Machine Learning) has been applied in various problems. for example, in the development and characterization of materials, in the prediction of the mechanical behavior of parts manufactured by additive manufacturing, in the optimization of production systems, to reduce rejects, to improve product quality, and to detect and reduce errors, among other important tasks [96].

Neural networks, fuzzy logic, and genetic algorithms have been applied to the analysis of the movements of machines and robotic systems, especially for the solution of kinematic problems [68], and have been extended to the study of robot dynamics and control [97]. The analysis of the behavior of fluids and gases has also been studied using CFD (Computational Fluid Dynamics) and with Artificial Intelligence methods, such as genetic algorithms and artificial neural networks [98].

In the context of Industry 4.0, mechanical analyses of various components or machinery must be done quickly and efficiently. Although tools and methods have existed for decades to perform computational analysis of the mechanical behavior of elements of machinery or mechanical systems, such as finite differences or the well-known finite element method, the calculation carried out with these tools leads to thousands and millions of computational operations. In some applications, such as in manufacturing operations such as orthogonal cutting [69], the models to be solved are complex and require a high computational cost and a considerably high time to have solutions. In today's production processes and supply chains aligned with Industry 4.0, fast and precise solutions are required in the mechanical studies of parts or components to be manufactured. Artificial Intelligence is useful for developing methods of study and analysis quickly and with precise adjustments to solve and predict the behaviors of mechanical systems that make up various physical assets and that are necessary for the design, operation and control of cyber-physical systems and digital twins that are applied in the different technologies for production [16].

2.5.4. Mechanical Engineering and Smart Retrofitting

Some of the equipment strategies that various companies are using to migrate from their current state to Industry 4.0 is the use of methods for technological reconversion or modernization of their production systems. This is due to the fact that the infrastructure and the new machinery equipped with systems for digitized and connected production is expensive and difficult to acquire. In the same way, some companies acquire equipment planned to work for a long time and due to the technology with which they were built, it is difficult to integrate them into the vision of the fourth industrial revolution. Modernization or retrofitting projects for industry 4.0 or Smart retrofitting are not easy to carry out because the technologies that are located in a production line do not have the same technological level, so it is necessary to design particular retrofitting methods for each machine, device or system. In fact, Smart Retrofitting can be applied to machines, production lines and cyber-physical systems and even factories, and is highly dependent on the Industry 4.0 goals that the company aims to achieve [22].

A viable proposal for the introduction of companies to Industry 4.0 is to implement the so-called "smartification" of machinery, which refers to the improvement of machines or physical assets with digital technologies and services [99]. There are two methods of technological conversion: 1) Intelligent Retrofitting and 2) Traditional Retrofitting. These methods differ from each other, as the first refers to the conversion of technology oriented towards Industry 4.0 objectives and the second only seeks to expand the potentialities of a system or machine [22]. Although in practice, intelligent and traditional retrofitting are both applied in the conversion of machinery, since the former depends on the latter. Mechanical Engineering is involved in both processes of technological reconversion, since it is generally necessary to improve or change elements, links, gears or mechanical systems that exist in operating machinery and even in non-operational or old machinery that is to be reconverted to enhance its performance or to meet Industry 4.0 objectives. The relationship between Mechanical Engineering and the Internet of Things (IoT) is crucial for Smart retrofitting projects, since the sensorization placed in or on the improved physical assets or part of them and the processing of signals generated by the sensors, are related to the IoT and smartification.

Mechanical Engineering and Mechatronics provide Smart Retrofitting with machinery improvement, mechanical system design engineering to meet new requirements, energy systems analysis, motion modeling and control, automation (PLC and microcontrollers) and sensorization of key parts in machinery, among other tools and methods, while IoT offers communication networks. routers or gateways and communication software, among other technologies. Finally, the cloud offers applications such as monitoring, data analytics, and Artificial Intelligence services, among others. Figure 12 shows a diagram showing the relationships between Smart Retrofitting, traditional Retrofitting and the Industrial Internet of Things (IIoT).

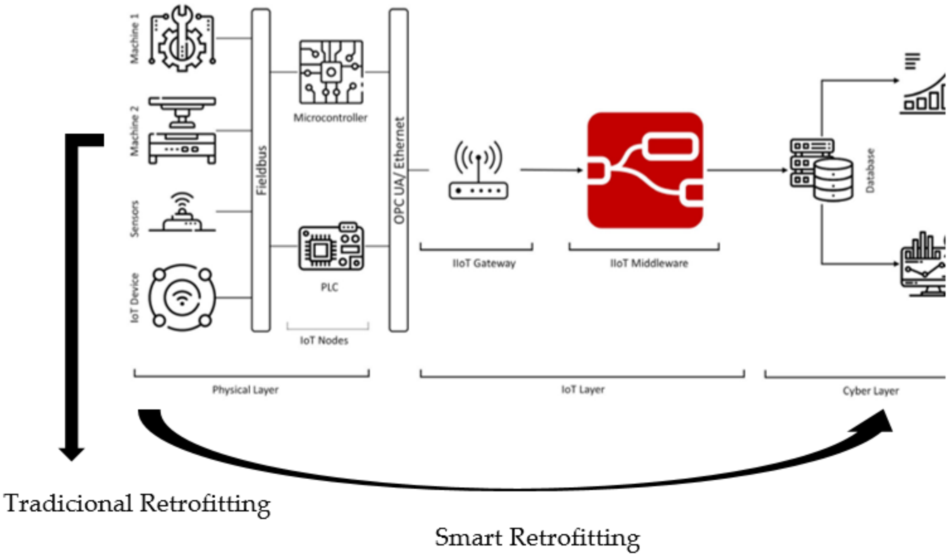

Figure 12. Smart Retrofitting, Traditional Retrofitting and IoT . Tomada y mejorada de [100].

2.6. Mechanical Engineering Education in the context of Industry 4.0

This section presents an overview of Engineering Education in the context of Industry 4.0, with special emphasis on Mechanical Engineering Education and related fields.

2.6.1. Education 4.0

Industry 4.0 has not only brought about changes in production systems and businesses, but it is also transforming educational systems. To face the challenges brought about by the fourth industrial revolution, the concept of Education 4.0 has been proposed, which can be considered as an educational paradigm or revolution that transforms and interprets the concepts of teaching and learning, analyzes the new roles of students and teachers, and studies the role played by the university in the vision of Industry 4.0 [101]. Education 4.0 was also conceived by the application of the disruptive technologies of Industry 4.0 to the teaching and learning process in educational institutions. Today, technologies such as Augmented Reality, Virtual Reality, Artificial Intelligence, Educational Robotics, Simulation, the Internet of Things and Additive Manufacturing, among others, have implications for education in general and are transforming the educational dynamics in schools. In general, this new educational paradigm is based on four pillars: 1) Technologies, 2) Processes, 3) Teaching methods, and 4) Competencies [102].

Education 4.0 is not only based on the insertion of the disruptive technologies of Industry 4.0 in educational processes, but also adopts new teaching and learning methods, some of them are: 1) Project-Based Learning, 2) Competency-Based Education, 3) STEAM (Science, Engineering, Art and Mathematics) and 4) Gamification, among others [103]. The availability of disruptive technologies and educational methods or approaches provide schools, teachers and education administrators with valuable tools with high potential to improve teaching and learning in students, and help university management and administration to improve educational processes. Figure 13 shows a schematic showing some of the disruptive Industry 4.0 technologies that are impacting education and some learning methods that are being applied today.

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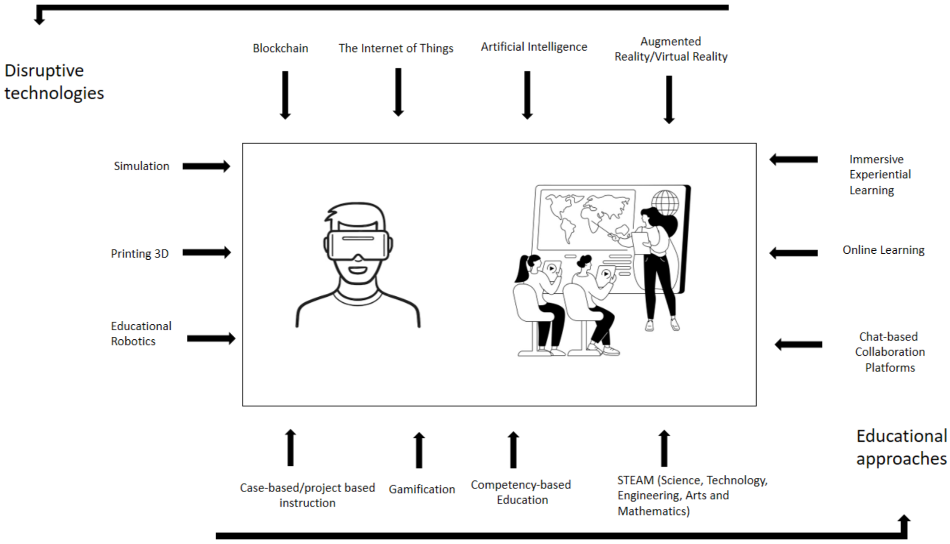

Figure 13. Disruptive Technologies and Pedagogical Methods in Education 4.0. Taken and improved from [30].

2.6.2. Engineering Education 4.0

Industry 4.0 seeks for universities to train engineers with the necessary skills and competencies to meet the needs of today's companies that seek to orient themselves to the digital age and to be more competitive in the fourth industrial revolution. The training of modern engineers is the task of Education 4.0 and of industry-university relations. Engineering Education 4.0 is a subsystem of Education 4.0 that is aimed at training engineers who must align themselves with the challenges of the Industry. 4.0. The theoretical and practical application of physical and mathematical laws or principles in tasks such as design, manufacturing, maintenance, technology integration, system control, materials study and software application are some of the activities that new engineers must master in order to align with the requirements of Industry 4.0 [104].

Engineering Education 4.0 seeks to transform engineering studies to meet the demands of specialized knowledge companies. Due to the complexity of the new challenges, today's engineering must be multidisciplinary and comprehensive, becoming aware that Engineering Education 4.0 will be the basis of the fourth industrial revolution and future industrial revolutions. The education of engineers must take place in the technological and educational context that predominates, for example, the role of the teacher has changed, he is no longer the center of the classes, but has become a facilitator or collaborator of the students. In the same way, the role of students has gone from being a passive actor to being active and independent and capable of building their own learning, in other words, the engineer must understand that today's education is student-centered. In the same way, engineering graduates must be aware that although titles, academic degrees or certifications are important in jobs, the skills and competencies acquired during their training are even more important. Engineers must be skilled in the use of Information and Communication Technology tools, since these, together with the technologies of the Internet of Things, have replaced the physical printing of documents, classic calculators and even the use of the Internet. In the same way, information is concentrated in online sources and there are tools such as Artificial Intelligence that are used to enhance searches and printed textbooks and other traditional didactic tools have been left behind. Traditional classrooms are shifting to physical spaces and individual or shared cybernetic systems [105]. Engineering students need to know the concepts of connectivity, digitalization, and virtualization to further extend the possibilities for better learning.

Engineering Education 4.0 seeks to transform the curricula of engineering according to the social, economic, political, industrial and technological context of the moment, that is, in the direction of Industry 4.0, to achieve the training of engineers needed by companies and industries. To achieve this change in curricula, better and greater multidisciplinary and interdisciplinary collaboration between faculty and researchers from different specialties, including industry, is required [106]. Modernizing engineering laboratories is another goal of Engineering Education 4.0. These must allow the management of didactic infrastructure oriented to Industry 4.0 and must be able to be managed remotely in order to share experiences and projects with students from other institutions. The disruptive technologies of Industry 4.0 help in the reconversion of academic laboratories, for example, Augmented and Virtual Reality, when combined with the physical or remote laboratories of universities, create innovative tools for engineering education [107].

On the other hand, Industry 4.0 seeks to ensure that today's engineers have the necessary skills and competencies to face the challenges of a differentiated, specialized and hyperconnected world. In this sense, one of the objectives of Engineering Education 4.0 is to promote the design of the competencies and skills of today's engineers. Companies are promoting in their engineers and workers a culture of continuous learning that allows them to understand the importance of knowledge and the need to improve their skills and competencies. This is due to the fact that Industry 4.0 is causing innovation in competencies and skills for work and that universities cannot train graduates to the necessary extent, especially in specific competencies. The skills for the job revolution being brought about by the fourth industrial revolution will mean that engineers will have to learn continuously, in part because there will be new specialized jobs and because technologies are changing rapidly. For these reasons, workers and engineers must have the capacity for Learnability [108], that is, the ability to continuously develop their skills without the need for the company or university to do so. In order for engineers to be considered by Industry 4.0-oriented companies, they need to develop the ability to learnability. There is no consensus among researchers and educators for the definition of the skills and competencies required in Industry 4.0. The following competencies have been proposed: 1) failure analysis, 2) forecasting, 3) adaptation to change, and 4) management of technologies, among others [109]. Engineers will have to use creativity in conjunction with the skills they possess to solve problems in industries.

Engineering Education 4.0 focuses on the improvement of curricula and laboratories, the development of competencies, and the insertion of disruptive technologies into the teaching and learning process. A more general proposal on the pillars that make up Engineering Education in the Fourth Industrial Revolution is shown in Figure 14.

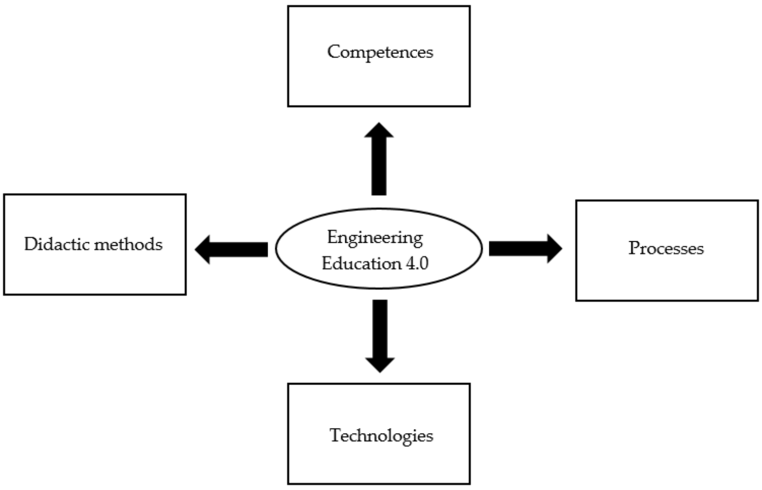

Figure 14. Pillars of Engineering Education 4.0. Based on [102].

2.6.3. Mechanical Engineering Education in Industry 4.0.

The Science of Mechanics and Mechanical Engineering make important contributions to Industry 4.0 and are related to various disruptive technologies, to other areas of knowledge such as computing and electronics, and to specialized fields of application. The strong relationship between Mechanics and the Fourth Industrial Revolution makes the education of mechanical engineers a priority. The introduction of new didactic methods to teaching and learning processes, the improvement and automation of educational processes, the adoption of disruptive Industry 4.0 technologies to teaching and the development of engineering competencies are the most important guidelines that Mechanical Engineering Education must follow in order to align itself with the needs and requirements of the fourth industrial revolution. Therefore, Mechanical Engineering Education should follow the guidelines of Engineering Education 4.0 and in general the vision of Education 4.0.

The tradition in Engineering Education until now is that the educational process continues to depend on the teacher, which complicates the insertion of new didactic proposals in teaching and student learning. From the perspective of educational approaches and teaching methods, educators in Mechanical Engineering must initiate transformations from teacher-centered teaching to student-centered learning. One educational approach that enables this transition is Competency-Based Education [24,110]. This educational model focuses on results and integrates various proposals for teaching practice, and promotes evaluation methods which focus on giving a central value to student learning and on their evaluation, promoting the application of learned knowledge and interpersonal competencies [111]. The implementation of the competency-based approach in Mechanical Engineering Education is a challenge due to the resistance to change of teachers and students. Learner-centered education requires the use of active methods to boost learning. These methods are used by teachers with the purpose of changing or transforming students' passive processes, tasks, and activities into active processes and tasks, with the aim of leading them to their own meaningful learning [112]. An active method that is naturally applied in the processes of engineering teaching and learning is Project-Based Learning [110]. This method uses projects to develop learning and encourages students to seek and find solutions to real-life situations or problems or applied projects, where it is possible to generate a product or prototype [113]. There are other active methodologies that can be used in engineering teaching and learning, such as Problem-Based Learning and the Case Method, among others. Active methodologies such as Project-Based Learning and Problem-Based Learning, as well as the competency-based approach, are applied in Education 4.0 [103], and should be promoted and applied in the teaching and learning of Mechanical Engineering.

On the other hand, with the help of disruptive technologies, it is possible to improve and automate the educational processes of teachers and students, such as the grades of exams and projects, the review of assignments, repetitive activities and checking class attendance, among others. These day-to-day tasks of teachers are often long and tedious, and they take up time. Automation can help improve the management of activities that teachers perform and improves attention to students, saving valuable time and costs.

Mechanical Engineering Education must adopt the disruptive technologies of Industry 4.0 necessary to facilitate and improve the training of engineers. These technologies can be applied in two ways in the educational process: 1) in combination with some educational method to facilitate and improve learning and 2) as a knowledge base in the applications of Mechanical Engineering. For example, Artificial Intelligence can be used as a pedagogical support in the search for information by using tools such as ChatGPT and virtual assistants [114], and it can also be used as a subject of study when applied to solve various multiphysics problems [16] that are necessary for applications in Industry 4.0. Virtual Reality and Augmented Reality are two disruptive technologies that are used to motivate, facilitate and improve student learning by using electronic devices such as glasses or smartphones to perform animations and simulations in virtual environments that facilitate the experimentation of educational content in an immersive way. Augmented Reality has been used in conjunction with the STEAM methodology to help students improve their skills and abilities in solving math problems, particularly in the subject of geometry [115]. Augmented Reality and Virtual Reality are applied for evaluation processes of part assemblies in industries [116]. In the same way, digital twins are used in conjunction with Project-Based Learning to boost the learning of engineering students [117], and in the field of applications Digital Twins are used for applications in Mechanics, for example, in aircraft maintenance [93]. The Internet of Things has also been applied in Education, for example, this technology has been used in conjunction with Project-Based Learning to carry out a quantitative evaluation of learning and to know the perception of students about the experience they

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have had in relation to the learning learned [118]. The Internet of Things is also applied for activities in which Mechanical Engineering is involved, such as the refurbishment of machinery [100]. Robotics is another Industry 4.0 technology that has been applied in conjunction with the didactic technique called Learnig Factory, which promotes learning in the workplace, to develop hard and soft skills related to Industry 4.0 and creativity [119]. Robotics is a topic of conceptual and practical study in Mechanical Engineering. In this way, the disruptive technologies described in Figure 2 are associated with pedagogical methods and with the teaching of content and applications in the training of engineers.

On the other hand, the design of competencies is another pillar of Education 4.0 and the education of mechanical engineers. The fourth industrial revolution has caused a transformation and a radical change in the dimensionality or scope of engineering competencies, so it is necessary to improve, design and implement already established or new skills and competencies in mechanical engineers so that they can be incorporated into Industry 4.0. There is no consensus to define a single class of Engineer 4.0 or Industry 4.0 engineer competencies. The following 10 competencies can be associated with Engineer 4.0: 1) social intelligence, 2) virtual collaboration, 3) resilience, 4) novel and adaptive thinking, 5) cognitive load management, 6) meaning-making, 7) new media literacy, 8) design thinking, 9) transdisciplinary approach, and 10) digital and computational skills, among others [120]. These competencies can be transferred to the training of mechanical engineers and must be complemented by the design of specific competencies in which universities and companies must unite to clearly define them and apply them in the workplace. The development of competencies must be directed under an educational approach, as is the case of Competency-Based Education and active methodologies for learning, such as Project-Based Learning and Factory Learning.

Other aspects that Mechanical Engineering Education must address is the improvement and development of the topics and contents of the subjects offered in universities, as well as the improvement and modernization of laboratories. With regard to content, some subjects, such as the design and manufacture of mechanical components, must integrate aspects of additive manufacturing and 4, 5, 6D printing [121], as well as applications of smart materials, since several current uses are based on these technologies. In the same way, Artificial Intelligence should be promoted in the topics of classes in Mechanical Engineering, since it has various applications in Mechanics, such as, for example, the solution of various multiphysics systems [16] and in the analysis of mechanisms and robots [122], among others. Design and manufacturing topics must be taught in the context of design and digital manufacturing, for which engineering students must learn to handle different types of software and programs, such as CAD (Computer Aided Design), CAM (Computer Aided Manufacturing), CAE (Computer Aided Engineering), CAPP (Computer Aided Production Planning) and CIM (Computer Integrated Manufacturing). among others [123]. Updating the class topics of Engineering curricula is crucial for the training of mechanical engineers who will operate under the vision of Industry 4.0. On the other hand, the teaching laboratories of Mechanical Engineering must be modernized so that students can carry out practices and projects, and so that they can improve their learning by participating remotely in projects with other universities.

2.6.3.1. Mechanical Engineering Education 4.0

Figure 15 shows a scheme that places Mechanical Engineering education in the context of Engineering Education 4.0 and Education 4.0. Mechanical Engineering Education 4.0 *can be conceived as that subsystem of Engineering Education 4.0 that adopts the disruptive technologies of Industry 4.0 and modern educational approaches to train mechanical engineers in the skills and competencies required by the fourth industrial revolution, and that inherits the four pillars of Education 4.0. that is, 1) competencies, 2) automation of educational processes, 3) technologies and 4) didactic methods.*

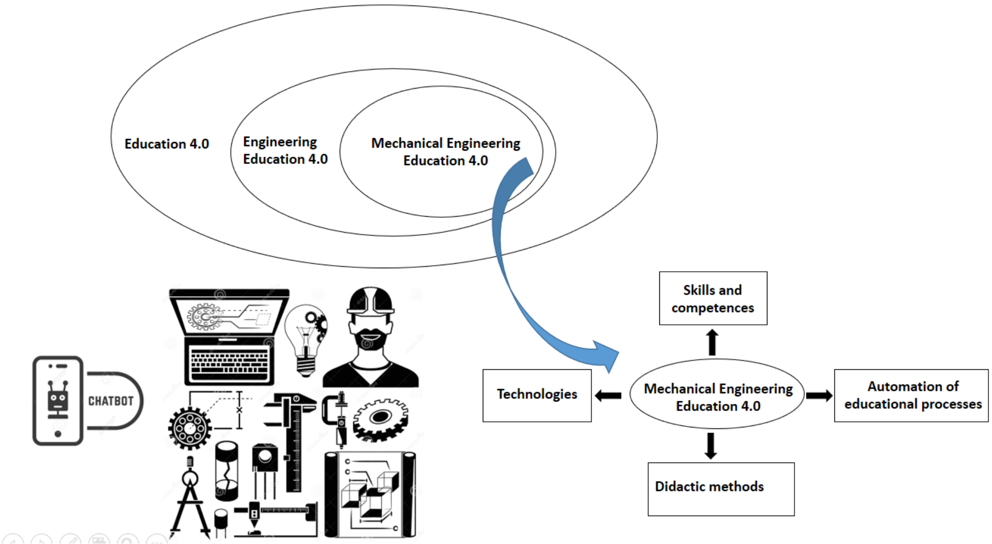

Figure 15. Conceptualization of Mechanical Engineering Education 4.0 .

3. Results and discussion

Mechanical Engineering is an important field of study for the fourth industrial revolution. In fact, in a recent survey of companies, it was highlighted that knowledge of technical mechanics is necessary and essential when developing projects related to Industry 4.0 [124]. The treatment that Mechanical Engineering has received from researchers since the emergence of Industry 4.0 in 2011 has been poor and not very widespread, and they have magnified digital tools and Information and Communication Technologies even more. However, as described in this work, Mechanical Engineering has been present in all industrial revolutions and its contributions have been important and revolutionary. By sharing knowledge, methods and analysis tools with other fields of study, such as Electricity, Electronics and Computing, it has been possible to conceive machines and devices that are based on electromechanical and mechatronic systems, which together with Information and Communication Technologies and the Internet of Things, they form the basis of cyber-physical systems and digital twins, which represent the heart of Industry 4.0.

Mechanical Engineering is applied to the development of various physical assets that are used for production in smart factories whose production lines are governed by cyber-physical systems and digital twins. These technologies require physical assets in operation and their multiphysics models to know the mechanical states of machines and production systems in real time, for monitoring, communication and control of operational events and to optimize processes and machinery operations through services available in the cloud. In this sense, mechanics and mechatronics make important contributions to Industry 4.0 as they are responsible for the design and operation of various physical assets. Some of these assets are considered smart because with Artificial Intelligence and its various methods of autonomous learning it has been possible to build intelligent machines, such as cobots.

On the other hand, Mechanical Engineering is a fundamental part of the technological reconversion projects of machinery and systems whose operations seek to align with the objectives of Industry 4.0. Smart Retrofitting is the key for various companies that do not have the economic capacity to acquire modern digitized machinery to participate in Industry 4.0 projects by improving their current and old production systems and putting them in operational condition according to the new production requirements. In the application of Smart Retrofitting, Mechanics together with mechatronics and the Industrial Internet of Things, make important technological contributions by improving and connecting physical assets with the virtual assets of cyber-physical systems and digital twins operating in factories.

On the other hand, the concept of Mechanics 4.0 has been proposed as an alliance between Mechanical Engineering and Artificial Intelligence to solve various complex problems [16]. However, as described in this work, the contributions made by Mechanical Engineering to Industry 4.0 are

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diverse and varied, and it is not limited only to a relationship with a disruptive technology, as is the case of Artificial Intelligence [52]. In order for it to become more relevant, the concept of Mechanics 4.0 must be extended. To expand this concept, the four driving forces identified in the third industrial revolution related to the evolution and importance of Mechanical Engineering were taken as a reference in this work [60]. These forces are: (1) the demand for new products, (2) new production requirements, (3) the association with disruptive technologies, and (4) the relationship with the basic sciences. Therefore, Mechanics takes these driving forces in order to explain part of its influence on Industry 4.0. The other part is built with the interaction of Mechanics with specialized fields such as Robotics 4.0, Metrology 4.0 and Ergonomics 4.0, among others, which have been evolving in parallel with Mechanical Engineering due to the influence of the disruptive technologies of Industry 4.0. In this context, it is possible to construct an expanded concept of Mechanics 4.0 in which it would be as follows: *Mechanics 4.0 refers to the applications of Mechanical Engineering in projects that meet the requirements and objectives of Industry 4.0, and takes as a reference for the development of applications, the current demands of the products, the new production requirements, the disruptive technologies of the moment and the relationships with the basic sciences and the specialized fields of application.*

In relation to Mechanical Engineering Education, it must be transformed and adopt the disruptive technologies and pedagogical methods available to train engineers with the skills and competencies required by the Industry. There is currently resistance on the part of teachers and students to change the educational model, i.e. from the teacher-centred teaching model to the student-centred learning model. Despite the fact that many universities have implemented competency-based educational approaches to transform the educational model, this approach is rarely applied in the teaching and learning practice of Mechanical Engineering, precisely because of the reluctance of the teaching staff to change. However, the existence of information banks, intelligent search engines, digitized teaching systems, the complexity of the problems to be solved and the new requirements of Industry 4.0, will put pressure on educational changes in engineering, so that it is possible to implement active methods, such as Project-Based Learning, Factory Learning, etc. Problem-Based Learning and the Case Method, among others, to train engineering human resources with the vision of the fourth industry 4.0 revolution.

The introduction of disruptive technologies in teaching processes will greatly improve the learning of Mechanical Engineering students, since it will be possible to improve classes and laboratories, as well as improve learning experiences with the application of Augmented Reality and Virtual Reality, among others. In the same way, the contents of the subjects of the Mechanical Engineering career must be updated with topics in accordance with Industry 4.0, in particular topics of Artificial Intelligence, Big Data, and Cloud Computing, among others, and it is necessary to transform the basic contents of the topics of design and manufacturing to topics of personalized manufacturing and digital design and manufacturing. motivating students to the widespread use of the software in their applications. Disruptive technologies can also improve administrative processes that take up teachers' time. This is achieved by automating processes and training teachers in the use of the tools.

Mechanical Engineering must build, together with companies, new competencies or improve existing ones so that it is possible to adequately train new engineers who will support Industry 4.0 projects. The design of competencies is essential to educate engineers and foster in them the need for collaboration, teamwork, autonomous and continuous learning, resilience and antifragility, creativity in problem solving, and mastery of computational skills, among others. Mechanical Engineering Education 4.0 will be the guiding concept that will help trainers, teachers and administrators in Mechanical Engineering to create the necessary conditions to train Engineers 4.0 who apply knowledge in Mechanics for projects of the fourth industrial revolution.

4. Conclusions

In this article, the implications of Mechanical Engineering in Industry 4.0 have been discussed and the concept of Mechanics 4.0 has been extended. The main conclusions are summarized in the following points:

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- Industry 4.0 has been described in terms of the insertion of disruptive technologies into production processes. However, there are fields of knowledge that also contribute to the development of Industry 4.0 that are rarely mentioned in the literature, such as Mechanical Engineering. In fact, most of the literature has given more importance to Information and Communication Technologies in the contextualization of the fourth industrial revolution than to other fields of study. However, as described in this work, Mechanical Engineering makes several important contributions to Industry 4.0, as it is responsible for the design and operation of many physical assets that make up cyber-physical systems and digital twins, and is essential in Smart Retrofitting projects, among other important contributions.
- Given the importance of Mechanical Science and Engineering in Industry 4.0, the concept of Mechanics 4.0, recently proposed in [16] as a relationship between Artificial Intelligence and Mechanical Engineering, was extended in this article. To achieve this, the four driving forces with which Mechanical Engineering developed in the third industrial revolution were taken into account [60]. The driving forces considered were: 1) the market, 2) production requirements, 3) relationships with disruptive technologies of the day, and 4) association with basic sciences. With this foundation and considering the specialized fields such as Metrology 4.0, Robotics 4.0 and Ergonomics 4.0, among others, it was possible to redefine and extend the concept of Mechanics 4.0.
- Mechanical Engineering must operate with other fields of knowledge, such as Mechatronics and Communication and Information Technologies, among others, in order to respond to the requirements of Industry 4.0.
- To align with the demands and requirements of Industry 4.0, Mechanical Engineering Education needs to be reformed. To this end, a real change in the educational model in universities is needed where it is possible to transform teacher-centred teaching into student-centred learning. The insertion of disruptive technologies in the teaching and learning process, Competency-Based Education and active methodologies, can be great allies to make changes in Mechanical Engineering Education.
- Modern Mechanics education must follow the guidelines of Engineering Education 4.0 and its pillars, which are: 1) competencies, 2) automation of educational processes, 3) technologies and 4) didactic methods, to successfully achieve the training of mechanical engineers of Industry 4.0. Mechanical Engineering Education 4.0 will be the new concept that will align disruptive technologies and modern educational approaches to train competent mechanical engineers who will face the challenges of the fourth industrial revolution.

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