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Review Article

Industry 4.0 – Holistic Perspective: Modeling and Simulation Implementations in Manufacturing Systems

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Abstract

The simulation includes enormous technological tools and methods for the successful implementation of digital manufacturing as it allows product, process, system design, and configuration to be tested and verified. With the growth in the industrial sector, information systems and software products play an important role in the investments of technology in automation. The industrial sector has enabled the use of simulations to directly optimize the design and production of systems with computational growth. Modeling takes advantage of the integration of computing and controlling, enabling intelligent production and sustainability to greatly increase the efficiency of industrial systems. Recent technologies have been focusing on the development of solutions for increasing customer expectations, competition conditions, product and service providers. The information used for production is integrated with the simulation requirements in association with other software platforms in a flexible manner. In industry 4.0, various modeling and simulation techniques for automation of the industrial process in the integration of service-oriented architecture into contemporary management systems are presented and the modeling techniques available in the literature are discussed. Important milestones of simulation technologies in product, process and system design of digitized manufacturing systems have been investigated and the latest industrial and research approaches in basic manufacturing areas have been examined. It explores important milestones in the evolution of simulation technologies and the latest industrial and research applications and findings. Based on this review, future trends and challenges to be met in the field are summarized in order to reduce costs in current practices, increase quality and shorten the time to market of manufactured goods.

Keywords: Industry 4.0, digital industry, internet of things, modelling and simulation.

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1. Introduction

The first industrialization process known as the industrial revolution was observed between the 18th and 19th centuries. During this duration, water and steam-powered were the main energy sources. With the use of machines, the first industrial revolution started to become widespread. The second industrial revolution faced the electricity as an energy source in which electricity was produced using water, petroleum and chemical materials. As industrial development gained an important momentum, the first mass production was implemented. The third industrial revolution started in 1970, and has continued until today. The developments in electronics, information and communication technologies allowed automation systems in production with the support of computers and programmable logic controllers (PLC). The fourth industrial revolution includes cyber-physical systems, smart factories, autonomous systems, the internet of things and services [1-3].

The rise of digital industrial technology, namely industry 4.0 is a conversion that enables to collect and analyze information from machines, fast and effective processes to produce low-cost and high-quality products. This industrial revolution changes the competitiveness of regions by increasing productivity and promoting industrial growth [4]. Industry 4.0 plays an important role in the development of smart factory systems due to its large content such as a lot of automation systems, data exchange and production technologies. This revolution reveals more efficient models by collecting, observing and analyzing information from the production environment [5]. The evolution of industrial revolutions from the past to the present is presented in Fig. 1.

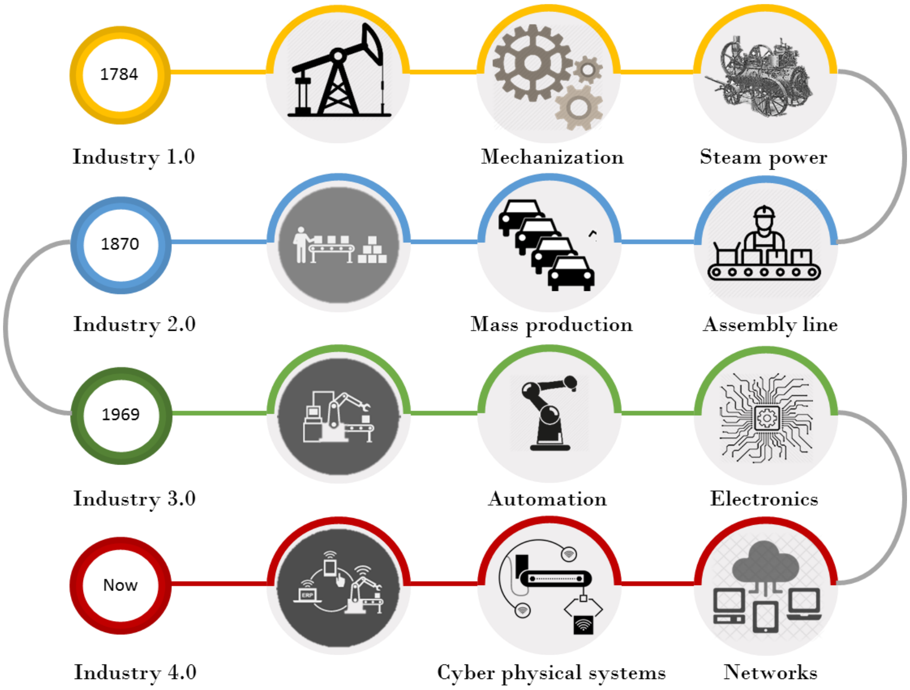

Figure 1: The hierarchy of relationships between the stages of the industrial revolution from industry 1.0 to industry 4.0. These industrial revolutions are described as 1st Industrial Revolution– Mechanical Production (Steam-based machines), 2nd Industrial Revolution – Mass Production (Electrical Energy-based mass production), 3rd Industrial Revolution – The Digital Age (Computer and internet-based knowledge) and 4th Industrial Revolution or Industry 4.0 - The Smart Factory (Artificial intelligence information technology)

The importance of simulation techniques in the manufacturing industry provides the development of an important area in the digitization and analysis of the industry [6, 7]. Simulation in transferring digital information such as advanced robotics, Internet of Things (IoT) technologies and 3D printing to the physical world encourages technological development of production and enables efficient work on the existing production system [8]. Computing tools are critical in fully understanding the dynamics of the manufacturing process and control operations and in analyzing new ideas. Therefore, the simulation serves as a complex, safe and fast analysis tool to analyze and evaluate production processes. Digital industrial transformation is digital, and most of the tools we use in our daily and business life, from smartphones to smart systems at home, to smart boards and projectors, to automating production processes. Although the process that started with factories since the beginning of the industrial revolution has mostly been replaced by business centers and plazas, we live in a developed industrial order. Transformation, on the other hand, has become a very common occurrence in our lives with the changes and transformations created by the increasingly digitalized technology in Fig.2.

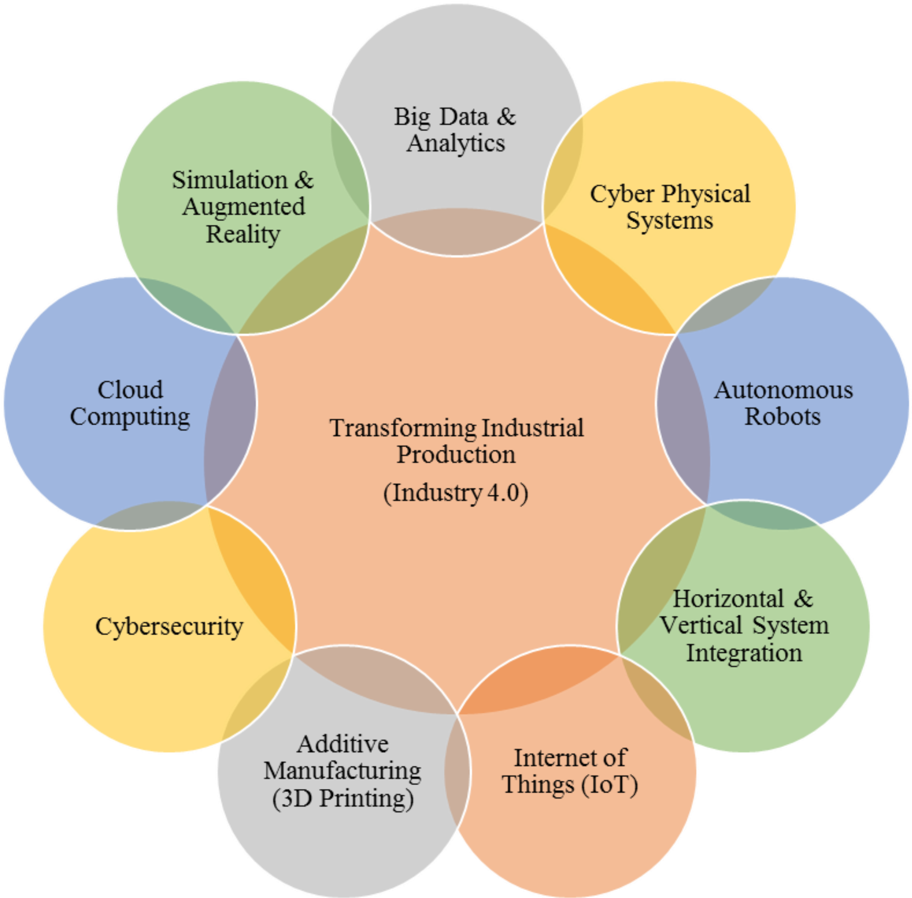

Figure 2: The services and components of the industry 4.0 concept.

Big Data and Analytics: Big Data is defined as a general name for huge, endless, defined or undefined data. It includes a variety of data types such as shopping, transactions, e-mails, social media sharing and traffic data. It corresponds to a large amount of data recorded in meaningless and meaningless structure. Analyzing and interpreting all these data, creating certain examples and trends play a crucial role in making strategic plans for the future of the companies, solving existing problems effectively and developing their products in line with the needs and preferences of their customers [9].

Cyber-Physical Systems (CPS): Cyber-physical systems are one of the most important components of production systems and are defined as systems that enable the physical world to be connected to cyberspace via a network. It is a network that emerges as a result of the integration of the physical world with the virtual structure. The real objects that build the network communicate and interact with each other via digital communication channels. Hence, Cyber-physical systems are software-based production systems that can intercommunicate with each other and other materials using the internet. These sensor-supported systems provide the interaction between objects by collecting the movements in the physical world through a network [10].

Autonomous Robots: Robots, which currently have vital importance in the production processes of factories, have played a greater role in the industry with speed and ease, and they have become a common workforce today. In previous periods, it is strongly believed that robots working independently will come across humanoid robots that interact with each other at the same time. Robots have high flexibility in terms of adapting to changing conditions as their ability to detect, collect and analyze data is quite high [11].

Horizontal and Vertical System Integration: Industry 4.0 enhances the importance of horizontal and vertical integration producing the backbone on which the smart factory is built. One of the biggest factors that hold a role in the growth of companies is the integration of systems. Horizontal integration is the merger between different companies with the same customer type. The main purpose of this merger is to increase the market share of these companies that address the same customer type. On the other hand, vertical integration is the form of merging of companies with customers in the same sector but in different sub-sectors [12].

Internet of Things (IoT): It is a global network of objects that are formed among themselves and can be defined as the communication of objects in this network with a specific protocol. In our daily life, it is widely used in agriculture, smart city and home concepts, energy, security and health. IoT takes an important part of this structure as industry 4.0 envisages efficient usage of resources, design and logistics processes in the manufacturing environment where interconnected automatic machines and robots cooperate and to link this structure with other companies in the value chain. IoT not only allows people to communicate with each other via the Internet, but also includes all objects such as materials, products and machines. The interconnectivity of objects with the detection systems in almost every object has led to the emergence of a new era of industrialization, namely industrial 4.0 or industrial internet [13-14].

Additive Manufacturing (3D Printing): New generation technologies permit a part to be produced with a 3D geometric model in material layers. 3D printers that can use many different materials such as plastic derivatives, metal, cork, resin wood as building materials can be used in aerospace, aviation, military applications, industrial manufacturing, medicine and health, energy, architecture, machinery manufacturing, food manufacturing. With basic logic, the 3D writing process can be defined as layer-by-layer writing on a tray with high precision, for example by melting the plastic. 3D printers enable the production of the prototype before the actual production in highly-cost projects, minimizing the possible errors. For instance, in orthopedic surgery operations, risks can be minimized by making operation demos with models produced by the 3D printer before surgery. Critical equipment used in production can be produced at any time thanks to 3D printers. Models drawn with software developed in accordance with 3D model designs can realize many innovative product options. It is frequently used in areas such as medical, dental, automotive parts supply, engineering and architecture through 3D printers [15].

Cybersecurity: Nowadays, IoT or industry 4.0 applications continue to become widespread, making it increasingly inevitable to connect a growing number of devices to networks. This trend tends to increase the productivity of firms with industrial systems. IoT brings a necessity to consider the risks posed by cybersecurity threats. Cybersecurity, which enables to establish secure devices and networks in industrial applications, can meet the needs of companies. The wide network and high-rate data sharing that come with Industry 4.0 rapidly increase the cybersecurity demand of companies. In the age of industrial internet (IIoT), in order to be protected from cyber attacks, systemic information should be closed to the outside, to adopt that physical security is one of the building blocks of defence, external threats should always be taken into consideration, and security measures should be taken against any adversities that may occur from inside [16].

Cloud Computing: It is a technology that handles problems such as file storage and access to files. This concept, which refers to the internet-based computing approach, enables common information sharing by communicating between devices with computer features. It makes possible to use the intelligent technologies that come into our lives more actively and efficiently, eliminating the loss of files and data, providing access to the data without interruption at any time, and ensuring all of these parts without being dependent on any device. Cloud computing services, called public cloud or private cloud, make the information publicly available [17].

Simulation & Augmented Reality: Simulation is the imitation of a real-life system or process in a computer environment. Simulation allows the generation of the artificial history of the system and the observation of this history to make inferences about the characteristics of the actual system. Virtual reality is a term defined in computer-based 3D environments where users experience the feeling of being in the designed environment. Simulation and virtualization in industry 4.0 occur when a virtual replica of intelligent factories is connected with sensor data from systems through virtual facility and simulation models [18-19].

2. Methodology and Methods

The 4th industrial revolution, commonly referred to as Industry 4.0, enables companies to better monitor their industrial processes and identify potential problems at early stages. In recent years, the industrial development and rise in the production technology, strengthening world economy have been a threat for countries which are pushed to search for new models to fasten the speed of products to market, to provide more flexible production structure, the capability of producing personalized products and more productivity in production [20-21]. As a result of these searches, smart manufacturing and intelligent factories are being built increasingly. Smart manufacturing is defined as productivity of all actions, energy usage, situational awareness, optimization of economic performance, real-time decision-making, flexibility, the ability of early diagnosis and treatment and working in connection with the environment and other systems. Industry 4.0 can be defined as a whole technology group that allows this smart manufacturing process. The Smart factory is described as a complete system structure with the ability to control the production from a centralized point and remotely through industrial computers. The main difference of smart factories from traditional systems is to avoid the problems encountered by a human in manual operations so that it can produce more efficient and effective products at every stage of production by the automatic controls by machines.

In this study, we conduct an evaluation of simulation technologies in which it will enable to reduce the human power, greatly reducing costs by reducing work areas, increase profitability with production and keeping customer satisfaction at the highest level by producing high-quality products. New production methods, intelligent process optimizations and the importance of simulation studies for higher machine availability in industry 4.0 are studied in this paper. Simulations are extensively used to reflect the physical world through a virtual model that introduces real-time information in factory operations, machines and products. These simulations allow operators to test and optimize machine settings for the next product in the virtual world before physically changing, reducing machine setup times and improving quality. Simulations methods are powerful techniques to optimize the production processes and making more intelligent decisions about the system. Most of the organizations across the world implement a variety of simulation software to raise productivity and decrease costs [22].

Simulation allows the production of the artificial history of the system and the observation of history to make inferences about the characteristics of the real system. In industry 4.0, simulation is created by connecting sensor data and simulation models from systems to create virtual copies of smart factories. It is predicted that these technologies will be utilized in the near future to improve factory and warehouse architecture, particularly for intelligent inventory management [23]. Using simulation-based methods to improve production, cost-efficiency and a deeper understanding of the process, the return and duration of a project are seen as significant parts. Studies such as reducing capital cost with better design, reduction of pilot plant cost, material and energy optimization and safety/environmental management provide pre-production benefits to the manufacturer with simulations.

2.1. Simulation in Industry 4.0

In a production where processes and different behaviours are modelled, organizations, supply chains, machines, tools and information systems are required. For example, as in production simulation, modelling is required to support operations beyond the production area (Fig. 3). Evaluating the manufacturability of product designs, supporting the development and validation of process data for products and their impact on overall business performance is highly significant. Planning alternatives, analyzing the order and flow of materials within production areas and lines, performing capacity planning analysis, determining production and material processing requirements, training production and support personnel on systems and processes are vital for the development and verification of simulation models. The important steps for simulation modelling is shown below [24].

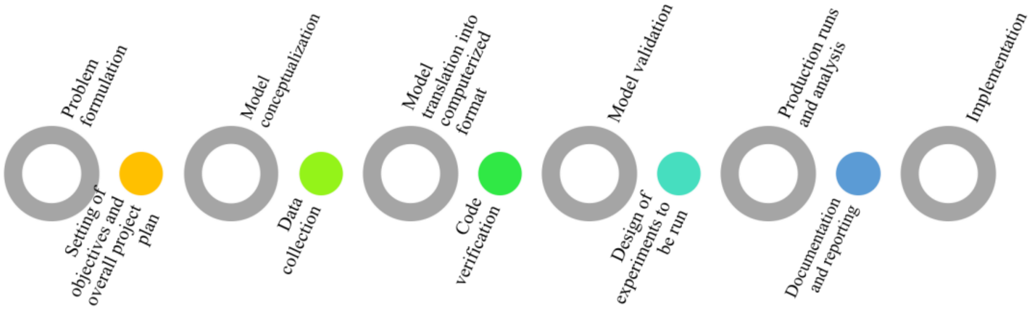

Figure 3 : Simulation and modelling for design and operation of manufacturing systems

Modelling and simulation are currently a way of understanding and improving processes to meet increasing productivity demands in the manufacturing industry and remain competitive in the industry. Simulation has become an important enabling technology in decision-making, engineering and operation, covering the entire life cycle of a production line. In order to obtain better performance from the simulation results, high-performance computing (HPC) systems are employed. The HPC system is the main platform for supporting visualization and animation of production. It is to solve the complex computing problems with the use of workstation and parallel processing techniques. HPC technologies allow faster and more accurate processing of scientific and technical issues based on computer simulations and modelling [25]. The importance of engineering and scientific studies on new computer-based algorithms and technologies has increased in many fields such as education, industry, aerospace, chemistry, physics, medicine and manufacturing with HPC technologies. Examples of HPC modelling and simulations include financial calculation, weather forecasting and climate modelling, computational physics, computational chemistry, structural cardiovascular modelling, genetic and DNA modelling, collision simulations, and so on [26].

In order for the solution of interdisciplinary problems, HPC is analyzed by comparison of an algorithm flow, numerical analysis and parallel processing. In HPC, running and visualizing the simulations is being a great hope to improve the future applications in bioengineering, intelligent technologies, nanotechnology, industry 4.0 requiring more computing resources [27]. There is an important need of simulation tools for parallel simulation of large-scale modelling, use of machines with very high performance, allocation of high memory and high-speed processors of HPC systems [25]. Therefore, simulation techniques are highly implemented to conceptualize the sustainability of the industry 4.0 and to solve problems that have many variables requiring detailed analysis. As a result, the utilization of efficient methods in simulation-based HPC systems for improving production provides significant benefits. These benefits can be achieved through intangible possibilities such as cost-savings and a deeper understanding of the process. With simulation applications, a number of great results can be achieved and examples of the results are reducing capital cost with better design, reducing the time for design and commissioning, reducing the cost, size and complexity of the pilot plant, improved productivity and efficiency with material and energy optimization, extending equipment life and environmental management.

2.2. Simulation Working Principles

Simulation is an animated model that simulates the processing of an existing or proposed system, such as the daily work of a bank, the work of a factory, or the assignment of personnel to an organization. Simulation can compose the visual structure of the process, similar to creating a flowchart using the software. Simulation can show the actual process correctly by adding new rules to tasks, sources and limitations of systems [28-30]. As the industrial requirements change rapidly with the advances of technology, the need for a more efficient production system design and the requirement to investigate alternative system solutions are more intense. Production systems simulation is a powerful tool for designing and evaluating a production system due to its fast analysis and low risk and cost features.

Simulation provides a strong, evidence-based approach for decision-making. To test the influence of process changes, an approach which ensures the best results can be explored using a virtual representation. The most important feature of the simulations is that they have a realistic effect and are modelled to mimic the real environment. For example, when a customer arrives at a cashier in a market, all possible behaviours (whether a cashier is in place or he is busy, how many people are in the queue) can be seen by simulating and adding more customers to the store database. It can be then determined to find the number of staff to be employed, and the prediction of behaviour of a big supply including hundreds of factories with thousands of products and workers [31, 32].

To give another example, time, temperature and humidity ratios are very important for preventing the deterioration of the drying approaches of the fruits as well as theoretical approaches to moisture movement considering the climatic conditions. This information will be very beneficial to optimize the production process of dried tropical fruits. Therefore, in the commercial food industry, it successfully changes mathematical simulation to represent the process of water uptake in the sense of heat and mass transfer within tropical fruits. By mimicking the behaviour of every piece of the process in association with different parts of the system, it can be understood that how the entire system is performing and attempts various solutions to ensure resource capacity or innovative ways to provide better performance.

2.3. Fundamental Features of Simulation

As a common rule, systems with a process flow containing events could be simulated. Hence, you can simulate any process with a drawable flowchart. When the change of business process is combined with industry tools such as Simulation and Optimization, the measurement of productivity can be increased easily. Simulation is to design a model of a real system understanding its behaviour to experiment on a model to evaluate various strategies. Optimization is a technique that provides the most efficient use of resources (such as labour, time, capital, raw material, capacity and equipment) in a system, minimizing costs and maximizing profit and capacity utilization. The processes that you will benefit at maximum are the processes that involve change over time, variability and randomness. For instance, before spending time and money, it is necessary to evaluate the validity of capital in the project by evaluating the return on investment. Large business challenges can be solved by arranging novel processes, strengthening business situations with a visual, collaborative, evidence-based approach and simulation modelling processes [32, 33], as illustrated below in Fig. 4.

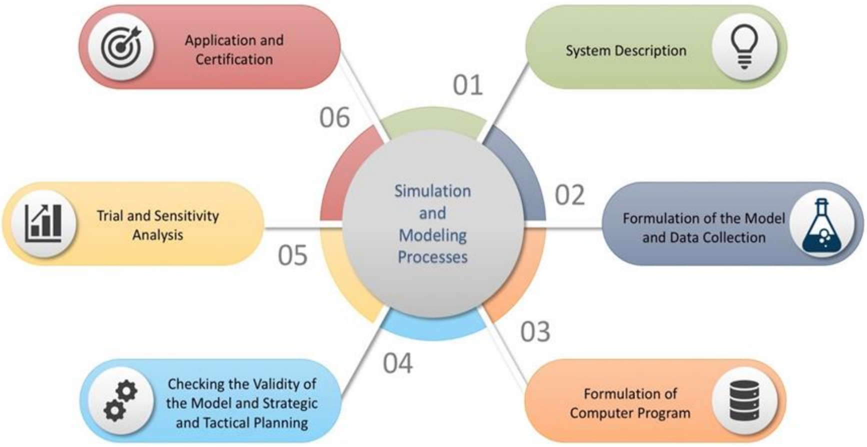

Figure 4 : Simulation modelling processes: The process of creating and analyzing a digital prototype of a real-world physical model

2.4. New Trends in Manufacturing Systems

Simulation in environmentally-friendly and sustainable production, real-time data monitoring, system intervention before failure occurs, high efficiency, reduction of production costs, decrease in market exit time of the product, increase in flexible production are very important for sustainability of the enterprise. Performing experiments in the real world or a research laboratory increases a number of potential costs. The industrial uses of simulation methods cover a wide range of areas such as education, health, service, manufacturing, operation, management and marketing.

It uses simulations to test different ideas under the same conditions, to determine the long-term impact of process changes, to give an opportunity thinking about every aspect of a process, to collaborate with stakeholders, to identify innovative methods and to improve processes. Industry 4.0 is a promising solution when it comes to declining costs of industrial production. With industry 4.0, production costs can be reduced by 10-30%, logistics costs by 10-30%, and quality management costs by 10-20% [34-35]. In order to reduce production costs in the industry, factors such as bringing new products to the market in a shorter time, more flexible and more efficient usage area should be considered [36].

Advantages of industry 4.0 simulation technologies are increased productivity in production, reliability and quality, low operating costs, flexibility and innovation, customer experience, high-profit margins and revenue. Industry 4.0 connects all parties involved in business processes in the manufacturing and process industries. Devices and machines independently manage production - flexible, efficient, resource-saving. Simulations are foreseen to be used in the near future, especially for improving factory architecture and intelligent inventory management. The illustration (Fig. 5) shows the future and results of industrial 4.0 studies based on these predictions.

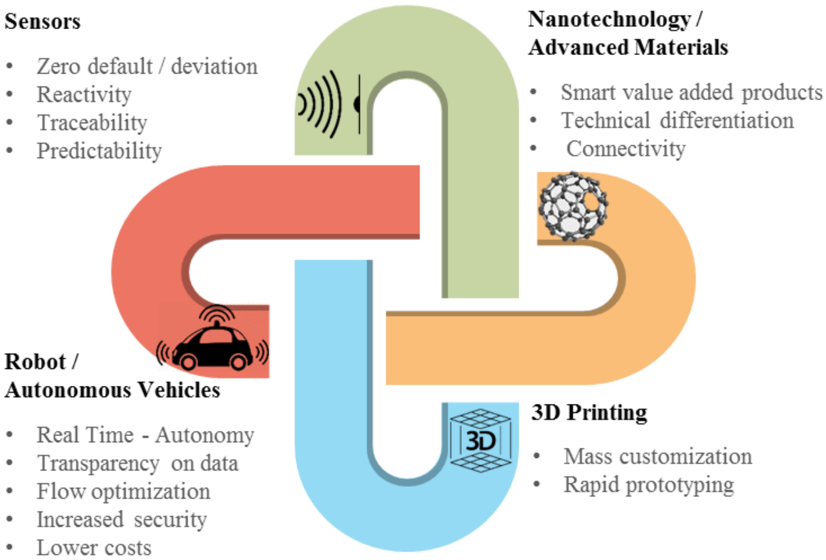

Figure 5 : Some sustainability results in Industry 4.0 using computer modelling and simulation for manufacturing processes.

With the introduction of digital industrial transformation into our lives, highly-improved versions and technologies continue to be added to the technologies mentioned above. The digital industrial transformation has reflections in almost every sector such as health, energy, security systems, education, marketing and information technologies [37]. Reflections combine requirements and opportunities between sectors such as sales-marketing, after-sales service, quality management and R&D. By adapting to these technologies, not only large–scale and well-established organizations but also medium and small companies will ensure that the distance between them is widened in their competition. Thus, they will also benefit from the opportunities of digital transformation. In this sense, it would be appropriate for companies to follow a few critical steps to achieve and protect success against the dizzying pace of digital industrial transformation.

3. Discussion and Findings

In the production processes of the digital industry, there are machines and production systems that operate autonomously to reduce the need for human factors. Creating self-managed production processes where production systems and factories become smarter, minimizing human-induced errors and achieving a full standardization in production processes are subject to simulation and modelling. Key areas such as 3D simulation and measurements, robotics simulation and modelling. sensors and controlled devices, 3D printing are thoroughly studied within the scope of industry 4.0 paradigm. Simulations and modelling. need to be considered in the large capital investment and production processes of industry 4.0. There is no single plan approach to building a factory in each production system. Manufacturers are using most simulation software to prototype the implementation of industry 4.0 principles and make sure decisions before making any investment. [38-39]. The functions of machines, distributions, communication between all objects and inter-product network equipment from the industrial area are contained basic simulation and modelling principle of industry 4.0.

Simulation, one of the technologies indicating the advancements of Industry 4.0, is a computer model that can mimic the operation of any real or proposed system. Simulation models such as application, system and process design, material handling system design, operations planning, scheduling, real-time control, maintenance management, ergonomics, knowledge management are the best way to layer value for an organization and better predict before investment [40-42]. The main reason in which a simulation process achieves such results is that it can explain the behaviour of individual tasks and resources by measuring what will happen in a production system over a period of time. Simulation can also be preferred due to its risk-free environment, which is another important feature. Therefore, in the literature review, the investigations regarding the simulation in production and manufacturing have been recently detailed. The aim is to create a summary of simulation applications in the industry and discuss the results such as when the simulation applications can be used, their usage advantages, how the processes related to their basic features contribute to the company. In addition to these, state-of-the-art analysis of simulation in the context of Industry 4.0 has been investigated.

4. Conclusion

Simulation is the core technology of Industry 4.0 to support the development of new models to optimize decision making, design, and operations of complex systems. However, developments and technologies in Industry 4.0 bring new challenges to the simulation field due to the increasing complexity of the systems to be modelled. Numerous studies have been conducted for the developments offered by industry 4.0, highlighting the interaction between the virtual and real worlds. In this article, with the modelling of industry 4.0, the construction process of digital structuring for complex manufacturing events, analytical, decisive and creative knowledge shows the modernization of industry. This information is the main focus of current research on industry 4.0 to design and implement production systems from a simulation perspective. In industry 4.0, ever-expanding embedded systems in the advancement of these manufacturing systems will assist in performance and rapid decision-making (e.g. cyber-physical systems) in specific modelling systems. In this study, the industry 4.0 holistic perspective, the historical development of the concept of industry 4.0, the uses and advantages of simulation and modelling processes in industry are presented.

Simulation-based digital manufacturing technologies are the focal point of digital production solutions as they allow different product, process and production system configurations to be tested and verified. The simulation tools and developments examined in this research are guiding the production systems and the future trends of digital technologies have been conveyed. As a result, a more efficient research area has emerged with the development of simulation tools. All issues can be addressed through the development and use of multi-disciplinary and multi-domain integrated simulation tools. The findings obtained from this study have implications for researchers, practitioners and administrators. Moreover, the use of simulation techniques, opportunities to evaluate Industry 4.0 principles and technologies in a virtual environment to help organizations improve their technology investment decision-making and transition to the 4th Industrial Revolution are summarized below.

• It provides industrial system analysts with more general and broader thinking. The behaviour of the system under changing conditions and new situations can be examined.

• The real-time of dynamic systems can be examined within a reduced or extended time. Simulation methods can close this gap when system data is insufficient or missing.

• Since the data required for simulation is often very easy to obtain, it offers a complete value chain, from direct production to suppliers to customers, business functions and services of the enterprise.

• Once the simulation model has been installed in industry 4.0, it can be used for the required time to examine the different states of the system. After finding analytical solutions with mathematical models, simulation can be used to verify the accuracy of analytical solutions.

• In industry 4.0, applied to the production and industrial environment, Internet of Things, big data, cybersecurity and similar components provide the opportunity to analyze and simulate real-time data collection.

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