Impacts of Industry 4.0 on Smart Manufacturing

Arvin Shadravan and Hamid R. Parsaei
Wm Michael Barnes '64 Department of Industrial & Systems Engineering
Texas A&M University
College Station, Texas, USA
arvinshadravan@tamu.edu , hamid.parsaei@tamu.edu

Abstract

The fourth industrial revolution, known as *Industry 4.0*, and its underlying digital transformation advances exponentially each year. People's lives and workplaces are radically changing due to this digital revolution. By methodically identifying specific sustainability roles of *Industry 4.0*, this paper adds to the existing corpus of literature on the subject. The study first explains the architectural design of *Industry 4.0* and reviews key design concepts and technological trends. The Internet of Things (IoT), Industrial Internet of Things (IIoT), cloud-based manufacturing, and smart manufacturing are the four driving forces behind Industry 4.0, and they all contribute to manufacturing processes becoming totally digital and intelligent. Manufacturing processes of separated and improved cells will be transformed into a fully integrated, automated, and improved production flow attributed to nine *Industry 4.0* pillars; (1) Big Data and Analytics (2) Autonomous Robots (3) Simulation/Digital Twin (4) Industrial Internet of Things (IIoT) (5) Augmented Reality (6) Additive Manufacturing (7) Cybersecurity (8) Cloud Computing (9) Horizontal and Vertical System Integration. As a result, conventional production connections between suppliers, producers, and customers, as well as between people and machines, evolve and become more efficient. This study also uses interpretive structural modeling to illustrate the relationships between the various *Industry 4.0* sustainability roles in their environment. The findings show complex precedence relationships between several *Industry 4.0* sustainability functions. The manufacturing sector and the economics of value creation are being transformed by *Industry 4.0*. The advantages of *Industry 4.0* technology for sustainable development have received much positive attention in recent years. Expectations for the opportunities that *Industry 4.0* technologies offer for smart manufacturing are very high, but a significant roadblock for companies pursuing digitalization and sustainable thinking is the need for a more accurate understanding of how *Industry 4.0* technologies enable sustainable manufacturing. This current study fills that knowledge gap by creating a road map that shows how *Industry 4.0* and its underlying digital technologies may be exploited to support and enable the triple bottom line of smart manufacturing.

Keywords
Industry 4.0, Digital Twin, Additive Manufacturing, Smart Manufacturing, and Sustainable Manufacturing.

1. Introduction
One of the primary industries that has a significant impact on a nation's economy and development is manufacturing. As a result, new technologies are always being developed to alter manufacturing procedures and enhance the output and quality of the final product. Recently, a new technology known as "smart manufacturing" has entered the manufacturing sectors. This technology can precisely predict product requirements and promptly identify faults, improving manufacturing processes and ultimately leading to the innovation of new products and services (Kusiak, 2018). Nowadays, this technology is essential for achieving better results with less human involvement, enhancing the efficiency and sustainability of production processes, and doing so at lower costs. The Internet of Things (IoT), which creates cooperative communication among machines and products and efficiently incorporates personalized instructions straight from clients, is used in the smart manufacturing process. This technology, known as a cyber-physical system (CPS), uses computer-based algorithms that combine and coordinate numerous physical and computational aspects to monitor the manufacturing process (Lee 2015).

Due to considerable decreases in sensor costs, improvements in sensing technology, and the use of highly effective analytical programs that study the data for subsequent decision-making, this technology uses smart devices and sensors to manufacture items, which is highly advantageous. The Industrial Internet of Things (IIoT) is the name used to describe this use of sensors in industrial applications. Smart manufacturing, in its broadest sense, refers to the full integration and execution of all manufacturing processes using data-based understanding, reasoning, and planning supported by cutting-edge sensing, analytics technologies, simulation, and modeling that react in real-time to achieve the constantly changing conditions and demands in the factory, the supply network, and customer needs (Lu et al. 2020). The ultimate goal is to provide goods and services that are individualized, clever, and environmentally sustainable. The fourth industrial revolution is also known as Industry 4.0, uses CPS to automate manufacturing processes and share information. Industrial control and Data mining have been greatly enhanced by technologies like IIoT, IoT, machine learning, AI, and big data analytics. These production facilities are also known as "smart factories" (Moghadam et al. 2018). The real-time interaction between machines, humans, and the entire production system is governed by using machine learning and cognitive computing in smart factories.

To improve decisions and increase production and yield, a lot of data is gathered from the manufacturing process, product flaws, customer feedback, market demands, and analytics. Moreover, cloud computing enables networked data management and storage, which may be used for off-site analysis. Users can access the results through a variety of mobile devices (Tao et al. 2018). The successful operation of smart factories can be achieved by following three basic objectives: (a) the collection of a wide range of relevant data from the equipment, (b) analysis of the data to generate useful information that can be used for operational as well as business decision-making, and (c) acting on process automation, system optimization, and informing business strategy. The components of a smart factory (Fig. 1) can be categorized into smart production, which deals with the effective association of tools, machines, and operators.

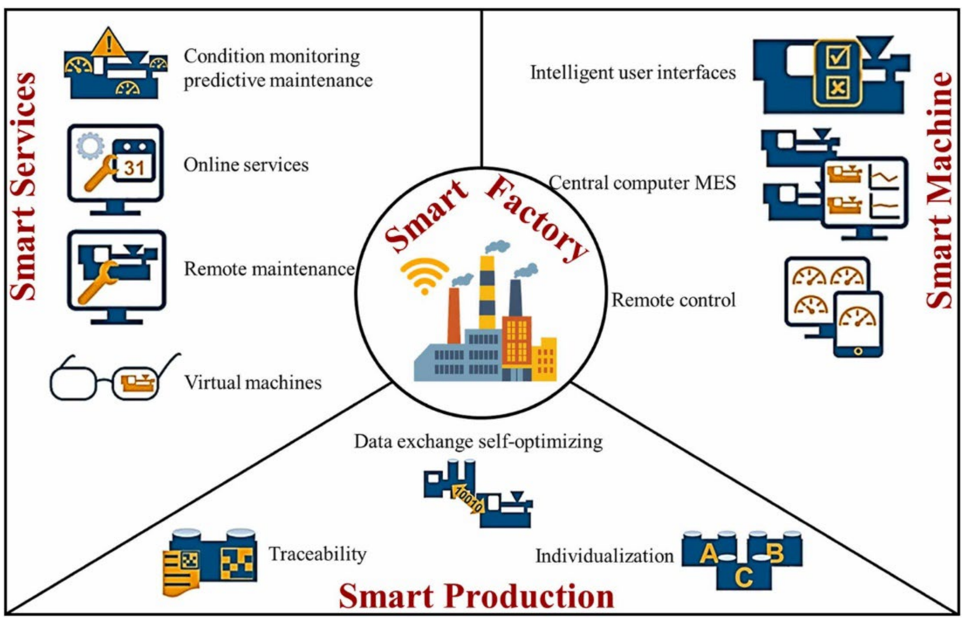

Figure 1. Smart factory's components (Sahoo et al. 2022).

2. Literature Review

2.1 Industrial Revolution

2.1.1 First industrial revolution (Industry 1.0):

Thomas Newcomen revolutionized industrial manufacturing in the 1700s by creating a prototype of the contemporary steam engine. The United Kingdom revolutionized manufacturing in the 1760s by using steam- or water-powered machines for the first time to produce items in large quantities, after a few earlier inventions. Then, between 1760 and 1820 or 1840, these industrial techniques were also adopted by all of Europe and America. The most cutting-edge manufacturing processes were originally used in the textile industry, which also drew significant investment. During this time, other industries including mining, agriculture, and the iron industry were also able to grow. The creation of coal and iron, the establishment of railroads, and the mass manufacture of textiles were the primary innovations of the first industrial revolution. The economic structure of society at the period was greatly impacted by such mechanization.

Due to massive coal mining and the development of the steam engine, an extremely efficient energy source was produced. The production processes have been expedited by the expansion of railroads and a large increase in financial investments. The first industrial revolution had many disadvantages despite some benefits, including improvements in innovations, inventions, and related research, growth in the production of goods, building of new transportation networks, etc. These disadvantages included abhorrent working conditions, child labor, environmental pollution, and unhygienic living conditions (Phuyal et al. 2020).

2.1.2 Second industrial revolution (Industry 2.0):

The second industrial revolution, which took place between 1870 and 1914, is recognized for bringing existing manufacturing techniques to a new level. The invention of new combustion engines allowed the second World War to realize its full potential. After 1870, there was a tremendous increase in the transportation of goods, people, and manufacturing equipment due to the massive construction of railroads and electrical telegraph lines. This led to a new wave of globalization, which in turn sped up the manufacturing process and sharply raised production yield. Eventually, thanks to the production line and factory electrification, substantial advancements in electricity and telephone technology propelled the manufacturing sector to a highly advanced level. electric generators, vacuum pumps, transformers and gas lighting systems, and other devices all developed as a result of the widespread use of electrical power as a means of energy transfer. Due to the steel's escalating demand, the steel industry likewise started to expand dramatically. Synthetic fabric, colors, and fertilizer have also entered the scene thanks to new chemical synthesis techniques. The introduction of cars and commercial aircraft at the start of the 20th century altered transportation systems as well (Zhang et al. 2020).

2.1.3 Third industrial revolution (Industry 3.0):

With the profound effects of World Wars I and II, the manufacturing industries required a massive reformation, which came about in the wake of the digital revolution in 1969. Mechanical and analog electronic technologies have quickly evolved into digital electronics with the development of digital computers and digital record-keeping. The third industrial revolution, sometimes known as the digital age, is this period. This also heralds the start of the information age, which saw the invention of transistors and microprocessors as well as the widespread usage of computers and telecommunications. Miniaturized materials have been created because of the invention of new technologies, revolutionizing both biomedical and space research. This phase's key characteristic is production automation using industrial robots and programmable logic controllers (PLC). The development of the Internet and the World Wide Web gave the manufacturing process even more impetus (Zhou et al. 2016)

2.1.4 Fourth industrial revolution (Industry 4.0):

The Fourth Industrial Revolution, often known as Industry 4.0 or I4.0, was launched in Germany. The adventure started in 2011 with the promotion of the production process' computerization. Industry 4.0, which emphasizes IoT interconnectivity, machine learning, and real-time data processing, is built on the foundation of cyber physical systems (CPS). In order to exchange real-time information, the machines communicate via fusing IoT and industrial internet into the manufacturing system (Zhang et al. 2020). During the production process, the linked system algorithms support making wise judgments. The fourth industrial revolution has seen widespread and considerable adoption of artificial intelligence, augmented reality, flexible manufacturing automation systems, automated robotics, and additive manufacturing (Shadravan et al. 2021).

3. Methods

3.1 Technologies associated with smart manufacturing

Smart manufacturing processes require the effective coordination of numerous technologies. The most prominent ones are highlighted in Figure 2 and explained below.

Figure 2. Smart factory's components (Sahoo et al. 2022).

3.1.1 Immersive Technologies:
Immersive technology refers to new methods of creating, displaying, and interacting with apps, content, and experiences. The digital experience has been transformed by this technology by fusing the senses of sight, sound, and touch. Currently, there are three different categories of immersive technologies on the market: virtual reality, augmented reality, and mixed reality e.g., virtual reality, augmented reality and mixed reality (Baroroh et al. 2021).

3.1.2 Additive manufacturing
Smart manufacturing heavily relies on additive manufacturing (AM), which is essentially computer-controlled 3D printing of items. Industrial facilities have restrictions on creating samples for research and development (R&D). With a correct composition of the constituent materials and the design specifications, the fabrication of these 3D prototypes takes substantially less time (Shadravan et al. 2022). AM is very helpful for producing complicated components quickly and accurately for research purposes. This quickens the design process as well as mass customization, or the required adjustments in the following processes (Rad et al. 2015) (Tehrani et al. 2017). In general, 3D printing has the promise of enhancing the effectiveness, affordability, and performance of water purification systems such as 3D printed membranes (Gao et al. 2015).

3.1.3 Big data analytics
The immensely complicated nature of the smart manufacturing network creates additional difficulties. The door is now open for innovative research and development projects. Big data analytics is a method that has a big impact on smart manufacturing through the gathering and analysis of a lot of data from the production units, customer feedback, and product request system, which aids in real-time decision making (Phuyal et al. 2020).

3.1.4 Industrial Internet of Things (IIoT)
With the developing Industry 4.0, the Industrial Internet of Things (IIOT) is crucial. In this technique, sensors are affixed to every step of a manufacturing line to track both the efficiency of the machinery and the results of the process. To enable the fusion of all the process phases, the sensors are connected via the cloud over the Internet. With smart process control of tool and material optimization, preventive maintenance, finding machine defects, and improved human-machine interaction, this integration aids in better production planning (Cook et al. 2022).

3.1.5 Artificial intelligence

The adoption of artificial intelligence (AI) has allowed for greater robot usage and a significant decrease in the presence of humans in danger areas. AI also aids in improving maintenance of the production line and identifying equipment or product faults. AI-powered systems can make their own decisions, optimizing their own performance, responding automatically to alterations in the production schedule and machine failures, swapping out any machine parts automatically, and transmitting alarms for any unmanageable conditions. High levels of automation, mass customization, the use of intelligent machines and robotics, etc. are all made possible by AI technology. AI technology can be used to boost efficiency, regulate product costs, optimize processes, and improve manufacturing performance. By introducing predictability and operations, machine learning-based predictive and prescriptive analytics successfully enhances the life of assembly employees (Lee et al. 2018).

3.2 Influence of AI in smart manufacturing

3.2.1 Quality checks

Since they can eliminate undesirable items from the production process before they reach the market, quality inspections are the most crucial step in a manufacturing process. Finding efficient methods to carry out precise quality inspections is difficult, though. Manual inspections take a lot of time, and because human error is inevitable, they may lead to erroneous and inconsistent product quality. Hence, as inspections are carried out in the production line, highly sophisticated quality checks along the entire supply chain are crucial for customer happiness and loyalty. Machine vision is a type of imaging-based inspection technology where machines, robots, and autonomous devices can automatically recognize, detect, and analyze images. They can also automatically check the quality of products and provide data from the production line to the warehouse fulfillment center to the distribution center (Yang et al. 2021).

3.2.2 Maintenance

Smart factory floors are outfitted with sensors that collect massive amounts of data and record a variety of activities in the era of Industry 4.0. To make decisions and provide inputs to reduce unplanned downtime in a production line, improve manufacturing efficiency, automate production facilities, forecast likely market demand, optimize inventory levels, and enhance risk management, the collected data are analyzed in real-time by analytical capabilities. AI is used to control Prognostic and Health Management (PHM) systems to determine whether any equipment is having issues under normal operating conditions or when a defect develops. Significant advancements in AI systems performance have been identified thanks to the expanding data available over time and recent developments in machine learning and deep learning (Biggio et al. 2020).

3.2.3 Reliable design

By supplying the previous design issues, fundamental dimensional dimensions, maximum weight it must support, mechanical strength, and constituent material options, AI is also employed in modern smart manufacturing to develop hundreds of possible designs of any entity. Generative design is the process of using AI-based software to explore every design combination depending on the input data. A select few businesses, including Airbus, Under Armour, and Stanley Black & Decker, use such design technologies to create design concepts that go beyond what the human mind can imagine. Such designs offer a wide range of design alternatives that can lower the weight and quantity of materials needed for a product while retaining its strength and price (Miles et al. 2022).

3.2.4 Reduced environmental impact

Without a doubt, the manufacturing industry accounts for close to 50% of the total global energy use. The majority of the waste comes from low-quality goods and wastage of raw resources in the production process. The International Energy Agency claims that energy demands are rising over time. Yet, a paper by Microsoft and PwC claims that AI may significantly improve environmental sustainability and direct the manufacturing industry toward becoming more environmentally and energy conscious. By optimizing the creation of scrap trash and balancing out the uneven distribution of energy resources across the logistics, AI may address problems like decreasing the excessive use of some materials that are bad for the environment (Pratt et al. 2022).

3.2.5 Factory integration

By using IIoT, IoT, and AI, delivery is being integrated. A few businesses are also combining various manufacturing plants to boost total yield at the same time. To automate material supplies, maintenance, and other manual tasks for significant time and energy savings, data collected from one manufacturing line can be examined and shared with other plants. They are made possible by the interaction of people and machines throughout all of the factories. This system facilitates the continual delivery of value to clients of a business by integrating customer expectations, process design, and products (Calderone et al. 2022).

3.2.6. Post-production support

AI can also be used to inform customers on the performance of a product. KONE, a maker of elevators and escalators, monitors and forecasts the real-time state of its elevators and escalators from the associated sensor data using an IoT platform and AI tool. They can use this not just to anticipate failures but also to demonstrate to customers how their products are used in actual situations. To identify equipment condition usage patterns and any subsequent failures, the data are processed and analyzed in a cloud platform. With KONE 24/7 linked services, artificial intelligence (AI) can forecast when a collapse is likely to happen and/or when any servicing is required (Horo et al. 2022).

3.3 Challenges in smart manufacturing

No matter how sophisticated a system is, there are always significant security risks. Enterprises still encounter several difficulties even after using new, cutting-edge technologies in numerous plants to achieve smart manufacturing. As smart manufacturing capabilities are built on levels of technical integration, complexity, and automation much beyond those of traditional manufacturing processes, there will always be new hazards. It is also concerning that there is no consensus on security. The increase in cyber-attacks in smart factories shows that even present systems are vulnerable to several poorly understood security vulnerabilities. As a result, businesses are ill-equipped to deal with current security threats. Due to their limited resources, SMEs particularly struggle to overcome such challenges (Mittal et al. 2018).

3.3.1 Data security

Adoption of smart factories, where IIoT and IoT are widely utilized to integrate operational technology (OT), information technology (IT), and intellectual property (IP), is dependent on data security. Interoperability and real-time operation are made possible in smart factories by the mix of physical and virtual technologies. Nonetheless, there is a chance for cyberattacks. When data is shared online, there is always a chance of a data breach. The manufacturing industry is constantly vulnerable to major threats from the misuse of these highly classified data. According to one survey, 65% of businesses believe that IoT technology primarily increase cybersecurity concerns (Bakuei 2022).

3.3.2 System Integration and Interoperability

Modern technology is frequently included into the machineries of smart factories. However, there may be problems with compatibility between older and newer devices. Establishing machine-to-machine (M2M) communication is the most difficult challenge. For instance, the modern production systems operate best with IPv6 connectivity and support several devices connected at once, which may not be possible with equipment from a prior generation. The ubiquitous M2M communications and machine comprehension are the main issues with autonomous machine interactions in the context of smart manufacturing. Moreover, manufacturers are discouraged from making significant investments because they lack a clear grasp of the return on investment (ROI) of the new technology (Phuyal et al. 2020) (Lu et al. 2020).

3.3.3 Safe human-robot collaboration

Cobots, or collaborative robots, are a key component of Industry 4.0 and greatly increase factory productivity by lowering human mistake rates. Even in a production setting, cobots can engage directly and safely with people, potentially enhancing human-machine interactions. In smart factories, these cobots are typically designed to carry out duties. But, if any of the cobots fail, there may be serious concerns about the safety of the nearby personnel. If the staff is not adequately taught for collaboration and work with the cobots, there is also a risk from the human side.

Moreover, because mobile cobots are powered by batteries, they could run out of power mid-task, seriously disrupting production for the manufacturer (Kadir et al. 2018).

4. Discussion

4.1 Future prospects of smart manufacturing in the global market

Manufacturers have shown a strong need for remote work and increased supply chain agility since the COVID-19 epidemic, which can be accomplished by deploying smart manufacturing technologies. In a recent poll conducted in 2021 with about 300 manufacturers, 83% of them stated that implementing smart manufacturing technology and processes is their top goal, and more than 60% of them intended to start doing so within the following year. Employers in the manufacturing industry would prefer candidates with the necessary technical expertise and adaptability to new technologies to effectively manage smart factories (Plex and Hanover Research Group 2022). The most crucial abilities are adaptability, critical thinking, teamwork, communication, and knowledge of cutting-edge technologies. SMEs are likely to use smart manufacturing technology in the near future.

The adoption of the smart manufacturing process will be much simpler if it adheres to a framework that includes (i) identifying the manufacturing data that the SME has access to, (ii) evaluating the SME's readiness for smart manufacturing among the data-hierarchy steps, (iii) creating custom smart manufacturing goals for the SME, and (iv) identifying the appropriate tools and practices that will help the SME reach the custom goals. Using this paradigm would encourage SMEs to develop a culture of data-driven decision-making. Yet, many modern factories still lack the key elements of smart factories, such as self-optimization, self-configuration, predictive maintenance, and decision-making. Big data analysis and cloud manufacturing will undoubtedly benefit from edge computing and 5G technology. End users can directly request services based on their own needs with the aid of IoT. Networked manufacturing services thus facilitate wise choices. Big data analytics will also hasten the extraction of pertinent information and knowledge from voluminous production data in order to enable targeted decision-making. Deep machine learning (DML) and artificial intelligence (AI) are examples of advanced technologies or algorithms that will be crucial in the same. Also, in the era of climate change, manufacturers are dedicated to reaching carbon neutrality because it is one of the key characteristics of smart factories to be ecologically friendly. Companies should run their facilities with smart management, computer simulation/modeling, and highly effective manufacturing processes to reduce carbon emissions.

5. Conclusion

The fourth industrial revolution carries the promise of customization according to the end user, greater product quality, and increased factory productivity, and smart manufacturing is a key paradigm in this movement. In this article, we examine how industrial manufacturing technologies have developed through time as well as the state of smart manufacturing today, which is a key component of Industry 4.0. We have also gone into detail about several smart manufacturing technologies and shown how AI technologies have an impact on the entire manufacturing process. Also, current issues are explored, which can give academics and practitioners ideas for future study directions. To eliminate the need for human labor and speed up production, manufacturers are choosing complete factory automation. AI-driven quality inspection solutions are also essential for enabling the highest caliber products to be sold. Moreover, innovative ideas like CPS, IIoT/IoT, additive manufacturing, and immersive technologies have had a big impact on improving manufacturing processes that use smart manufacturing systems. The majority of manufacturing sectors do not, however, use these technologies frequently, leaving a significant gap between the theoretical smart manufacturing system and the actual manufacturing system. This may be a result of the challenges and lack of understanding involved in integrating smart manufacturing technology, as well as the potential returns on those investments. Smart manufacturing can be difficult to adopt at first, but once it has been implemented, both businesses and end consumers can greatly benefit from it.

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Biographies

Arvin Shadravan is a doctoral student in the Wm Michael Barnes '64 Department of Industrial & Systems Engineering at Texas A&M University, College Station, TX, USA. He received his M.S. from the University of Technology in Malaysia (UTM), Johor, Malaysia.

Hamid R. Parsaei is a Professor in the Wm Michael Barnes '64 Department of Industrial & Systems Engineering at Texas A&M University, College Station, TX, USA. His recent book Reconfigurable Manufacturing Enterprises for Industry 4.0 (co-authored by Dr. Ibrahim Garbie) received the 2022 IISE Joint Publishers Book-of-the-year award.